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Potential Improvements to the Nuclear Safety and Launch Approval Process for Nuclear Reactors Utilized for Space Power and Propulsion Applications

A Report to the Nuclear Power & Propulsion Technical Discipline Team

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February 2019

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Nomenclature

ANS	American Nuclear Society
DoD	Department of Defense
DOE	Department of Energy
DSA	Documented Safety Analysis
EIS	Environmental Impact Statement
EOL	End of Life
EPA	Environmental Protection Agency
FSP	Fission Surface Power
GDC	General Design Criteria
GEO	Geostationary Orbit
HEU	High Enriched Uranium
IAEA	International Atomic Energy Agency
INSRP	Interagency Nuclear Safety Review Panel
KSC	Kennedy Space Center
LANL	Los Alamos National Lab
LEO	Low Earth Orbit
LEU	Low Enriched Uranium
LOCA	Loss of Coolant Accident
MEI	Maximally Exposed Individual
MOU	Memorandum of Understanding
NASA	National Aeronautics and Space Administration
NEPA	National Environmental Policy Act
NERVA	Nuclear Engine for Rocket Vehicle Application
NIMS	National Incident Management System
NPAS	Nuclear Power Assessment Study
NRC	Nuclear Regulatory Commission
NRF	National Response Framework
NTP	Nuclear Thermal Propulsion
OSTP	Office of Science and Technology Policy
OSU	Oregon State University
PRA	Probabilistic Risk Assessment
RPS	Radioisotope Power Systems
RF	Respirable Fraction
RHU	Radioisotope Heater Unit
RORSAT	Radar Ocean Reconnaissance Satellite
RPS	Radioisotope Power System
RTG	Radioisotope Thermoelectric Generators
SAR	Safety Analysis Report
SER	Safety Evaluation Report
SNAP	Systems for Nuclear Auxiliary Power
SP-100	Space Power 100
STPI	Science and Technology Policy Institute
UN	United Nations

Executive Summary

This study examines potential improvements that could be made to the nuclear safety and launch approval process for fission reactors to reduce the associated uncertainties in cost and schedule while continuing to ensure public safety and environmental protection. It concentrates on the launch approval and mission safety of fission power and propulsion applications of nuclear energy. Improvements to the launch approval process for radioisotope power systems (RPSs) are being considered elsewhere but are acknowledged throughout the report. The study considered technical, process, and organizational improvements to the launch approval processes.

The study exclusively evaluated reactors that would not be started up prior to achieving a "sufficiently high orbit," per United Nations (UN) Resolution 47/68.Potential criticality accidents were considered that could occur during a launch failure or abort or during reentry. Numerous scenarios were examined that might involve one or more Earth flybys as well as potential transportation missions that could intentionally return an active, or previously active fission reactor to Earth orbit.

The Study Group was guided in its deliberations according to a number of fundamental principles. These included the paramount importance of adequate and appropriate levels of public safety and environmental protection as well as the importance of the inclusion of independent scientific, engineering, and safety reviews of the applications and proposals as a critical part of the process. Also considered was the need for the development of launch approval processes that might be different, depending upon the source of the application for launch approval, whether it be derived as a governmental launch, a commercial launch, or a hybrid/combination of the two. It is clear that all launches of nuclear reactors into space should have similar safety requirements; however, the safety review effort and the details of the analysis that are required should be commensurate with the potential hazards and the actual risk, which may differ based on the reactor design and its intended purpose. Finally, the study aimed at ensuring that whatever processes and procedures are developed should maximize the sufficiency, simplicity, and transparency of the processes.

The Study Group reached five Conclusions and makes thirteen Recommendations. The Conclusions and Recommendations presented here are extensions of those presented previously in other studies. This report attempts to add specificity to the actions that need to be taken in order to move forward with successful space fission reactor programs. Without action to address the perceived and real problems in the launch approval process, designers and mission managers will be reluctant to commit the resources necessary to make space fission reactors a reality.

Conclusions:

Conclusion 1: Progress has been made in the launch approval process for RPS; however, more work is needed especially for fission reactors.

Conclusion 2: Accidents involving cold reactors pose little risk without criticality.

Conclusion 3: Reactor designers need clear design guidance and acceptance criteria.

Conclusion 4: Roles and Responsibilities are unclear and have evolved over time, leading to redundancy of efforts and uncertainty in achieving approval.

Conclusion 5: Significant work will be required to implement a new launch approval process.

Recommendations:

Recommendation 1: Continue to improve the launch approval process in a manner that complements activities in the RPS program.

Recommendation 2: Implement a graded approach that requires minimal effort for non-critical accidents.

Recommendation 3: Explicitly address criticality in design and safety criteria.

Recommendation 4: Adopt a set of General Design Criteria (GDC) for space fission reactors, such as presented in Section 5. These criteria should be reviewed by both the power and propulsion teams at NASA and examined relative to anticipated designs and missions. These GDCs provide a high-level framework for safety, while numerical risk criteria per recommendations 5 and 6 help determine when the implemented safety strategy is adequate.

Suggested GDCs might include:

- The reactor shall not be operated prior to space deployment, except for low-power testing on the ground, for which negligible radioactivity is produced.
- Inadvertent criticality shall be avoided for both normal conditions and credible accident conditions.
- The radiological risk and consequences on Earth's surface of a release from an accident shall be insignificant.
- The reactor shall not be operated below a "sufficiently high orbit" per UN Resolution 47/68.
- In-space disposal shall be limited to sufficiently high orbits or extra-terrestrial planetary surfaces where not precluded by planetary protection requirements.

Recommendation 5: Adopt a set of Safety Criteria for space fission reactors, such as presented in Section 6. These criteria should provide levels of safety commensurate with other U.S. government nuclear activities. Begin sample studies to develop the safety case for near-term designs.

Recommendation 6: It is recommended that a high-level, readily understandable safety criterion be adopted such that:

> ***The likelihood of a space reactor accident shall be very small, and even if it occurs, will pose little threat to the public.***

This criterion includes two parts, one associated with likelihood (or probability) of an inadvertent criticality, and one associated with health effects. The recommended likelihood criteria contain two parts considering both inadvertent criticality and unintended hot reentry following reactor operation:

> ***The conditional probability of an inadvertent criticality, given the occurrence of an accident, shall be no more than 1E-3.***

> ***The probability of an unintended hot reentry after reactor operation shall be less than 1E-4 over the life of the mission.***

The recommended health effects criterion is:

> ***For any credible space reactor accident, doses to members of the public shall remain less than 25 rem at 1 km from the reactor.***

For this criterion, *credible* is defined as having a probability that is greater than or equal to 1E-6. For launch and ascent, this means 1E-6 per launch, while for hot reentry this means 1E-6 over the mission life.

The Study Group considered the possibility that the criterion could take into account the magnitude of the criticality event. That is, only criticalities that could generate a threshold number of fissions, e.g., greater than 1E20 fissions would be counted. It can be argued that events generating fewer fissions than this threshold value are unlikely to result in significant public health effects away from the accident or crash site. However, it is important to note that even "small" criticalities may require extensive cleanup, cause hazards to adjacent personnel, and generate negative public perception. Therefore, even if the magnitude of the criticality event were to be included, any GDC should drive designers to aim for designs that are unlikely to become critical during an accident and include positive means to prevent inadvertent criticality.

Recommendation 7: Develop standards for acceptable methods and analyses to determine compliance with the adopted safety criteria.

Recommendation 8: Continue to support efforts at Office of Science and Technology Policy to clarify and improve the launch approval process.

Recommendation 9: Develop clear roles for applicants, reviewers, and regulators.

Recommendation 10: Include independent technical review in the process, with clear guidance for the review process.

Recommendation 11: Develop a process that is consistent for government and commercial launches.

Recommendation 12: Utilize the regular technical and engineering standards development process for the development of safety and launch approval criteria.

Recommendation 13: Begin now to identify and update the procedures and processes inside and outside of NASA that may require modification.

1.0 Introduction

1.1 Objectives

This study examines potential improvements that could be made to the nuclear safety and launch approval process for fission reactors to reduce the associated uncertainties in cost and schedule while continuing to ensure public safety and environmental protection. In this report, the focus is on nuclear fission reactors for a variety of applications including electric power generation for both in-space power and surface-powered missions as well as for nuclear thermal propulsion, although many of the ideas presented could also apply to other nuclear systems, including radioisotope power systems (RPS).

1.2 Scope

The study and this report concentrate on the launch approval and mission safety of fission power and propulsion applications of nuclear energy. Improvements to the launch approval process for RPSs are being considered elsewhere but are acknowledged throughout the report. The study considered technical, process, and organizational improvements to the launch approval processes.

Numerous missions powered by radioisotope systems have been launched by the U. S. over the years, and these have undergone rigorous analysis and review to achieve launch approval based upon Presidential Directive/National Security Council-25 (PD/NSC-25) that was developed in the late 1970s and evolved through the 1990s.[1] However, only one nuclear fission reactor, Systems for Nuclear Auxiliary Power (SNAP) 10A, was launched by the U.S., back in 1965, well before the official launch approval process was developed through PD/NSC-25. While an extensive safety program was developed and executed for this electric power-producing reactor, all of the work was conducted prior to the release of PD/NSC-25. Further fission reactor development programs over the years, including the nuclear thermal propulsion programs Rover and Nuclear Engine for Rocket Vehicle Application (NERVA) (which pre-dated PD/NSC-25), and the Space Power 100 (SP-100), Topaz II, and Prometheus electrical power programs also incorporated extensive launch and mission safety programs. However, since none of these programs culminated in an actual launch, none of them progressed completely through the process established by PD/NSC-25.

A wide variety of topics were considered during this study. The study team exclusively evaluated reactors that would not be started up prior to achieving at least a safe orbit. Potential criticality accidents that could occur during a launch failure or abort or during reentry. Numerous scenarios were studied that might involve one or more Earth flybys as well as potential transportation missions that could intentionally return an active, or previously active fission reactor to Earth orbit. The differences between reactors that would use either high enriched uranium (HEU – 20% enriched uranium or greater) or low enriched uranium (LEU – less than 20% enriched uranium) were also considered, as well as various reactor types and configurations. In general, it was determined that the fuel type affects security issues but has little impact on safety. Further, the recommendations proposed for safety criteria are intended to be independent of the particular reactor design. A set of general design criteria (GDC) are proposed for space reactors, along with a set of risk criteria to guide designers and decision-makers. The study also considered the distinctive organizational roles and responsibilities within the current launch approval process for RPSs and evaluated the differences between civilian science and commercial missions. The study reflects upon possible changes to PD/NSC-25 and other governmental processes that would enhance the launch approval process for fission reactors and discusses any possible implications for the RPS launch approval process.

A number of important areas were not included in the scope of this study. These include consideration of reactors that are operating or were operated prior to their achieving a safe orbit, e.g., for possible propulsion missions. The security or nonproliferation issues related to civilian space reactors that use HEU or national security driven missions that might be subject to different policies were not evaluated as part of this study.

1.3 Methodology

In order to conduct this study and evaluation, a Study Group of experts was formed to analyze and assess the current nuclear system launch approval process and to examine changes that could benefit future potential launches. The members of the Study Group are the authors of this reports and are listed in Appendix A. The Group divided the full launch approval process into functional categories that describe the current and future launches for distinctive applications, materials, and systems. The study also examined various launch types and objectives, and grouped them into three general categories:

1. Current launch approval processes for existing RPSs including existing and historical radioisotope thermoelectric generators (RTGs), radioisotope heater unit (RHUs), multi-mission radioisotope thermoelectric generator, etc. based on PD/NSC-25 and extensions.
2. Future launch approval processes for Fission Power Systems, including both missions for in-space electrical power generation and missions that require fission surface power (FSP) on other Solar System bodies.
3. Future launch approval processes for Fission Propulsion Systems, including both missions that simply leave Earth orbit and never are intended to return and missions that could include at least one return to Earth orbit.

The Study Group did not discuss, or directly consider, future launch approval processes for new RPSs including potential new designs, fuels, and systems. Some changes to the launch approval process for these applications and devices have already been adopted by NASA's RPS Program, while others are being considered directly by the Office of Science and Technology Policy (OSTP), and the interested reader is pointed to the results of the OSTP deliberations when they are completed and released.

The Study Group's effort began with a study to identify and understand primary principles and key features of the current launch approval processes, and then identified the commonalities and differences between launch types and objectives. The Group then attempted to identify any potential opportunities to improve the launch approval processes and identify any entirely new advances that could be used to simplify the launch approval processes while retaining all of the safety imperatives. The Study Group targeted its efforts to achieve a graded approach to the analysis of potential launch and operational accidents. A graded analytical approach would enable the effective consideration (and elimination) of the possible accidents that involve cold reactor fuel, without criticality, and make possible the use of conservative or bounding analyses for many other accidents.

The Study Group was guided in its deliberations according to a number of fundamental principles. These included the paramount importance of adequate and appropriate levels of public safety and environmental protection as well as the importance of the inclusion of independent scientific, engineering and safety reviews of the applications and proposals as a critical part of the process. Also considered was the need for the development of launch approval processes that might be different, depending upon the source of the application for launch approval, whether it be derived as a governmental launch, a commercial launch, or a hybrid/combination of the two. It is clear that all launches of nuclear reactors into space should have similar safety requirements; however, the safety review effort and the details of the analysis that are required should be commensurate with the potential hazards and the actual risk, which may differ based on the reactor design and its intended purpose. Finally, the study aimed at ensuring that whatever processes and procedures are developed should maximize the sufficiency, simplicity, and transparency of the processes.

2.0 A Brief History of Safety for Space Reactors

The current power and propulsion space reactor programs are built from the foundation of previous programs. Past space reactor programs include SNAP, SP-100, Topaz, Prometheus and other smaller programs such as FSP, and past nuclear reactor rocket programs include Rover, NERVA and Timberwind.[2] The safety issues and design specifications for each program are directly tied to the specific mission for each program. Safety needs to be an integral part of a program and incorporated into the reactor design as early as possible to limit the possibility of major and costly design changes later within the program. This section provides a short overview of the missions and corresponding safety criteria for earlier space reactor programs to provide a foundation for the proposed safety criteria.

Table 2-1. Mission areas for space reactor safety by program.

Program	**Ground Testing**	**Launch and Ascent**	**Cold Reentry**	**Hot ReEntry**	**LEO - Operation**	**High Orbit Disposal**	**Earth Flyby**
Historical Programs							
SNAP	✓	✓	✓	✓	✓	✓	
Rover	✓	✓	✓	✓	✓	✓	✓
SP-100	✓	✓	✓	✓	✓	✓	✓
Topaz	✓	✓	✓			✓	
Prometheus	✓	✓	✓				✓
Current Programs							
Kilopower	✓	✓	✓				Not currently planned
NTP	✓	✓	✓	Currently Under Consideration	✓	Currently Under Consideration	✓

As noted above, the design and safety criteria are mission specific. If a reactor system is not designed to operate in low Earth orbit (LEO) and does not include flyby or return-to-Earth scenarios, then issues associated with hot reentry of the reactor and post-operational criticality are not applicable and greatly simplify the safety analysis and test program. Table 2-1 provides a list of the past and current space reactor programs for both power and propulsion and their operational mission areas. Table 2-2 includes the power levels, mission operating space, and safety strategies for each program.

Table 2-2. Overview of power, mission operating space and safety strategy by program.

Program	Power	Proposed Mission Operation	Safety Guidelines for Criticality and LOCA	Reentry
		Historical Programs		
SNAP	0.5 to 350 kWe	LEO or geostationary orbit (GEO), planetary, or deep space operation.	Beginning of life critical in water; resulting in dispersal or chugging within controlled area. End of life (EOL) reentry criticality not allowed.	Hot reentry considered plausible for some missions: boost to higher orbit, high altitude burnup or intact reentry.[3]
Rover		LEO or Earth flyby operation. High orbit disposal.	Criticality not allowed for launch pad or space operations. Poison wires or active destruct proposed.	Uncontrolled reentry, active destruct considered. Due to limited oxidation of fuel considering intact reentry.
SP-100	100 kWe base design; 5-1000 kWe	LEO-GEO, planetary, or deep space operation. High orbit disposal.	Designed to remain subcritical in water. Ensure minimum core melt due to LOCA* in LEO.	Cold or hot reenter intact with aeroshell.
Topaz	6 kWe	High Earth orbit operation and deep space disposal	Subcritical in water; anticriticality device for launch or pre-ascent.	Proposed cold reactor reentry dispersal
Prometheus	100-200 kWe		Subcritical in water	Cold reactor reentry dispersal
Kilopower	1-10 kWe	High Earth, planetary, or deep space operation.	Subcritical in water	TBD
NTP		High LEO-medium Earth orbit operation	TBD	TBD

*LOCA – loss of coolant accident due to a puncture of the primary coolant loop.

Ground testing is project and reactor specific and will depend on where and who tests the reactor and should be handled accordingly. It is not the subject of this study on reactor launch safety.

As cited in the Topaz report on cold reentry accidents,[4] the dispersal of a cold reactor is a very low consequence event and should not require extensive analysis or safety requirements. The area of concern for this phase of a mission is inadvertent criticality of the reactor from impact on land or water. Although low consequence, inadvertent criticality received attention from every U.S. reactor program. The goal was to design in safety such that inadvertent criticality was reduced to a low probability.

The other areas of launch safety are mission dependent. Operation in LEO and possible hot reentry should be covered by launch safety if they are part of the mission set. Past space reactor programs with missions in LEO had to face a number of technical challenges and consider potential solutions to ensure the space reactor or nuclear rocket could meet the safety criteria. Operation in LEO has to include design for EOL disposal and the possibility of hot reentry. In the SP-100 Program, concerns over the nuclear system being struck by space debris, losing coolant, and melting the core resulted in a new criterion to ensure the core maintained its physical integrity.

To allow the decay of the fission products prior to reentry into the Earth's biosphere, reactors operating in LEU must be boosted to higher orbits after shutdown to ensure longer reentry times of several hundreds to thousands of years. After operation in LEO, the former Soviet Union would boost their Radar Ocean Reconnaissance Satellite (RORSAT) nuclear reactors to high orbit for final disposal. After Cosmos 954 accidently reentered in 1978 and scattered radioactive material over a broad area of northern Canada the Soviets added an automatic backup system that would eject the core to ensure the fuel would burnup if the EOL boost failed resulting in an accidental reentry.[5] Operations for the cleanup of radioactive debris by the Canadians and the U.S. was called Operation Morning Light. After 1980, the Soviet RORSAT reactors that were boosted to a higher orbit ejected their cores resulting in a significant increase in space debris from the release of the sodium-potassium coolant.[6] Therefore, it is not advisable to eject the core except for planned dispersal and burnup for accidental reentry.

Near-Earth flyby is very mission dependent and could be included for any mission to the outer planets. The need for a near-Earth flyby, whether the reactor is turned on, and how close the flyby is to Earth, will be key in understanding the level of analysis needed to ensure safety. If the reactor is cold, then clearly it would be covered by other launch safety analyses. If the reactor is operating or has been operated, then appropriate analysis is required. Similar concerns exist for return-to-Earth scenarios, such as might occur for a reusable space tug.

2.1 Systems for Nuclear Auxiliary Power (SNAP) Program

The SNAP Program began in 1955 and continued until 1973. The objective of the Atomic Energy Commissions SNAP Program was the development of compact, light-weight, reliable atomic electric devices for space.[7] The SNAP Program was the genesis for both RTGs and space nuclear reactors. Under the early SNAP Program, a number of RTGs were launched for both NASA and military applications.

The SNAP Program developed, built, and flew the only space reactor in U.S. history, SNAP 10A, in April of 1965. There were multiple SNAP reactors developed throughout the program with varying power levels, fuel types, and power conversion systems. Potential missions included operation in LEO, planetary power, space station, and deep space operation.

The SNAP Program had an extensive safety program, the Aerospace Safety Program that included both analysis and testing. Safety was integral to the design of the reactor system from the beginning of the program. The following areas of reactor safety were extensively analyzed with a robust test program:[8]

- Reactor reentry analysis
- Reactor disintegration upon reentry
- Reentry theory
- Fuel ablation and fuel element burnup on reentry
- Reactor impact experiments and analysis
- Reactor disposal in high orbit
- End of life shutdown analysis
- Reactor transient analysis

- Reactor transient (reactivity insertion) analysis
- Destructive reactor reactivity insertion experiments (SNAPTRAN-2 and 3)
- Critical configurations experiments
- Fission product release experiments

Two of the primary safety concerns for the SNAP Program were accidental reentry and remaining subcritical under accident conditions. Reentry during launch ascent or post-operational from LEO presented one of the greatest challenges to the SNAP reactor program. The goal was to have the reactor disperse and burnup in the upper atmosphere for accidental reentry. Early test results indicated that reentry heating would be adequate, but later tests demonstrated that the fuel elements would not be released from the reactor vessel at a high enough altitude to ensure that the fuel elements would ablate.[9,10] The project was cancelled before a definite solution was found to address accidental reentry.

A poison sleeve was designed to ensure that the reactor would remain subcritical for all prelaunch activities. For launch abort or EOL reentry a series of studies were being completed to determine if spectrum dependent thermal neutron absorbers in the fuel element and core reflector interface region or modifications to the core and reflector geometries could result in intrinsic subcriticality under accident conditions.[9] Experiments were conducted to measure the reactor's response under transient conditions. The tests, the SNAPTRAN series, provided invaluable information on the reactor response and radiological distribution.[9,11] By the end of the program, means of ensuring that the reactor remained subcritical under accidental reentry for both pre-operation and post-operation were not completed, but concepts were proposed. At the end, they concluded that "Destructive nuclear excursions of SNAP reactors are not entirely precluded under certain launch accident or reentry impact conditions."[9]

2.2 Rover/NERVA Thermal Nuclear Rocket Program

The Rover Program to develop a thermal nuclear rocket also began in 1955 and ended in the early 1970s. The Rover program established a safety program early in the life of the project that required increasingly more conservative safety and design requirements as the program advanced.

Since ground testing was integral to the development of the reactors, ground test safety was an early focus of the Rover safety program. Most of the launch and in-flight safety was attached to the NERVA Program. The NERVA engine was required to incorporate "means of preventing accidental criticality during all ground and space operations. An anticriticality destruct system shall be provided for launch and ascent."[12,13] Poison wires that could be removed from the core and a destruct system were both considered to address the criticality requirement.[14] They were to incorporate the means for self-destruct during launch and ascent to assure sufficient dispersion of the reactor fuel to prevent nuclear criticality with the fuel fully immersed in water.[15]

For a possible accidental hot reactor reentry, passive burn-up of the fuel elements was considered,[16] as well as a post-operational explosive destruct system.[14] Testing and analysis demonstrated that the oxidation of NERVA fuel materials did not result in adequate burnup of the fuel material, and therefore they were considering an intact reentry to be preferred over an explosive destruct.[17] Westinghouse reported that "The potential need for intact reentry is leading to changes in materials of construction and control system design."[17]

Safety requirements for the Rover/NERVA Program evolved over time as analyses and test data provided insights into the operation and response of the nuclear rocket under accident conditions.

Ensuring that the reactor remained subcritical under all phases of the program and ensuring that post-operational reentry did not result in unacceptable health affects to the public provided the guidance for the design and test program.

2.3 Space Power 100 kWe (SP-100)

SP-100 was a general-purpose space reactor to meet a range of power needs from 5 kWe to 1 MWe for NASA and Department of Defense (DoD). The reference flight system was designed to produce 100 kWe. DoD missions that required an SP-100 system were primarily in LEO to support the Strategic Defense Initiative. The NASA missions varied but focused on deep space missions. The SP-100 Program began in 1982 and was cancelled in 1994. Safety was a key aspect of the program throughout its development.

The key areas examined by the program are similar to those examined by both SNAP and Rover programs:

- Ground test safety of a reactor up to 2.5 MW thermal to obtain lifetime and operational data,
- Launch safety accidents including:
    - Explosions and fires
    - Inadvertent criticality during launch and ascent (land or water impact)
    - Impacts of material dispersion other than nuclear materials
- Operational Accidents
    - Loss of cooling
    - Issues with reactivity control and shutdown
- Hot reentry of the reactor
    - Reactor burnup in atmosphere versus intact reactor to Earth
    - Reactor impact
- Boost to higher disposal orbit

Generalized nuclear safety criteria were proposed by the Department of Energy (DOE) in 1982.[18] These nuclear design criteria provided guidance on safety, including such criteria as: "the reactor should be designed to not go critical on a launch accident." The safety criteria were further defined by Los Alamos National Lab (LANL) throughout the program as analysis and testing were performed. Numerical acceptance criteria were not established under the SP-100 Program.

The initial guidance for the SP-100 reentry specified that the designer had "the option to design for either assured high-altitude aerosolization of the reactor or essentially intact reentry" while ensuring that the reactor remains subcritical.[19] The safety guidelines became more specific with the design of the Generic Flight System, which specified that the designer was to assure intact reentry for specified inadvertent events, maintain the reactor subcritical during accidents, and assure an essentially buried impact following inadvertent reentry.[20] The decision to design for an intact reentry was made in part based upon the results of the reentry programs for the SNAP and NERVA Programs. Both the SNAP and NERVA Programs established high altitude dispersion and burnup for possible accidental reentry scenarios. They established extensive programs to prove the fuel would be released from the reactor vessel and burn up, but the safety testing and analysis demonstrated that the fuel might not release or adequately burn up prior to reentering. A final reentry solution was not proposed for the SNAP reactors prior to the program ending. It impacted the safety program in two ways as the reentry dispersion ensured that the reactor would not go critical, and they had to consider other options, including burnable poisons, to address the question of accidental criticality.[9] The NERVA Program was considering active dispersal methods for accidental reentry, but they had not gone beyond the concept stage.[21]

An aero-shell was incorporated into the reactor to ensure intact reentry as the preferred option. Ensuring that a hot reactor remains intact was a result in part due to the failure in 1977 of the Soviet RORSAT space reactor, Cosmos 954, to achieve orbital boost resulting in the reentry of the reactor. The Soviet Union designed the reactor to burnup upon reentry but a number of solid pieces of the reactor were retrieved including small samples of the fuel. The Soviet Union modified their design to include a core pusher that would separate the fuel from the core vessel if there were an inadvertent reentry to ensure that the fuel would burnup upon reentry. This system worked as demonstrated by Cosmos 1402.[22]

The SNAP reactor program findings related to fuel burn-up during reentry also influenced SP-100 security protocols. Since, SNAP concluded that the fuel would not adequately burnup upon reentry, the decision to keep the reactor intact for SP-100 also helped to ensure that the highly enriched uranium fuel would be in one piece for retrieval.

2.4 Topaz II

The Topaz II reactor was a Russian reactor to be flown as part of a joint U.S./Russian mission. The project began in 1991 and ended in 1994, about the time that the SP-100 Program was also closing down. Topaz II used much of the information generated by SP-100, but there were some notable issues that arose during the project related to launch safety.

Initial calculations showed the Topaz II reactor would go critical if immersed in water. The U.S./Russian team opted to use the same policy as in SP-100, namely, “Inadvertent criticality must be precluded for all credible accident conditions.”[23] Therefore, the team designed an anti-criticality device to ensure that the reactor would remain subcritical if submerged in water. Critical mockups of the core were run simulating water submersion at the Kurchatov Institute in Moscow that verified the anticriticality device would function properly.

Second, there was a significant amount of debate within the Topaz II project on whether or not to include the use of an aero-shell for hot reentry or to consider high altitude dispersal.[7] An alternative solution considered was to preclude LEO missions from the mission set and thus preclude “hot” reentry through operational constraints and design modification, which would have made hot reentry accidents not credible.[24]

Finally, for cold reentry the issue of an aero-shell was also debated.[25] The analysis by the safety team concluded that no risk reduction was realized in assuring a radiologically cold reactor to reenter intact.[4] Consequently, the safety team reached a decision not to establish a functional safety requirement for cold reentry accidents and this became the preferred option for the project.[9]

2.5 Prometheus

Prometheus was a project to build a 200-kWe reactor as a power source for an electric ion thruster propulsion system for a mission to Jupiter’s icy moons. The project officially began in 2003 and was cancelled in 2005, although reactor design work began several years before in 2003. The project performed early studies on safety, but the design was not completed to a detailed level before the project was cancelled.

Safety was of the "absolute highest priority"[26] within the program. Initial safety requirements included:[26]

1. Minimize potential for inadvertent startup during all potential launch accident scenarios,
2. Maximize use of non-nuclear testing in all phases of development,
3. Restrict NASA applications to outbound trajectories and use in deep space,
4. Develop planetary protection requirements,
5. Require highest commitment of safety throughout all phases of development, deployment, and operation, and
6. Engage the public to assure that safety concerns are addressed.

Therefore, while the system did not move forward beyond the preliminary design phase, safety was considered to be a critical part of the overall design process.

2.6 Historical Efforts to Prevent Inadvertent Criticality

Previous designs have taken various measures to prevent inadvertent criticality during various stages of the mission. Some of these previous methods are included in Table 2-3 and could be considered by designers for future space nuclear reactor applications and would need to be specifically tailored to the particular mission profile.

Table 2-3. Examples of past methods deployed to ensure that the reactor remains subcritical under accident conditions.

Method	Mission Phases	Reactor Concept	Value Provided
Launch Vehicle Destruct	Preoperational: prelaunch, launch and orbital ascent	SNAP; NERVA	Destructive separation of the reactor ensures that the reactor cannot go critical.
In-core poison wires	Preoperational: prelaunch, launch, orbital ascent and orbital injection	NERVA	The in-core poison wires ensure that the reactor would not go critical under accident conditions and were removed once the operational orbit was achieved. The poison wires could not be reinserted once removed and therefore could not be used for post-operational reentry.
High Altitude Dispersion and Burnup	Preoperational or post-operational: orbital injection, in-space operation, mission completion and long-term disposal	SNAP NERVA Soviet RORSAT original guideline	Separation of the fuel pins from the reactor, dispersion at high altitude and burnup would ensure that the reactor could not go critical upon reentry. Proved to be ineffectual for SNAP, NERVA and RORSAT systems. The Topaz II U.S./Russian project considered full, partial or intact reentry to be acceptable.
Reactor length-to-diameter modifications and in-core thermal neutron poisons.	Preoperational or post-operational: orbital injection, in-space operation, mission completion and long-term disposal	SNAP	The SNAP Program was considering multiple options that were inherent and passive to the reactor design.

Automatic Core Ejection at High Altitude Dispersion and Burnup	Post-operational in LEO: orbital injection, in-space operation, mission completion and long-term disposal	Soviet RORSAT	Active separation of the fuel elements from the reactor vessel resulting in dispersion at high altitude and burnup.
Active Dispersal at High Altitude and Burnup	Post-operational in LEO: orbital injection, in-space operation, mission completion and long-term disposal	NERVA	Several active means of dispersing the core upon post-operational reentry were considered by the NERVA Program.
In-core control and shutdown rods with a reentry shield for intact reentry	Preoperational or post-operational: orbital injection, in-space operation, mission completion and long-term disposal	SP-100	The SP-100 was designed with a reentry shield to ensure that the reactor remained intact with in-core shutdown rods that would ensure the reactor would remain subcritical under accident conditions.
Launch with fuel pellets external to the reactor	Preoperational: prelaunch, launch, orbital ascent and orbital injection	U.S. and Russian Topaz Flight	The reactor would remain subcritical for all postulated accidents with a percentage of the fuel external to the core during launch. The fuel was to be placed back into the core once the operational orbit was reached.

2.7 Summary

The U.S. has developed a number of different space nuclear reactor technologies for power and propulsion. In each program, safety played a key role in the design of the system and in establishing a test program. Safety analysis and testing has been one of the major costs in each of the earlier programs. In both the SNAP and Rover/NERVA Programs, the test results drove the programs to consider alternative ways of meeting the safety goals when it was clear that the original safety design assumptions would not work. For example, with the proposed reentry scenarios it became clear from the test results that the fuel would not adequately burnup prior to Earth return thereby requiring alternative safety methods be incorporated to assure compliance with the safety goals.

2.8 Impacts to Current Programs

Past programs chose to focus on the establishment of verbal safety requirements (see GDC in next section) and technical ways of ensuring that these requirements are met. In contrast, the Kilopower safety program is examining the use of both verbal safety requirements (GDCs) and the use of risk-based safety criteria recommended in this document. The current mission set for Kilopower assumes its use on extra-terrestrial surfaces or on interplanetary probes that operate beyond LEO.

The Nuclear Thermal Propulsion (NTP) Program has not yet established a safety program and is considering different ways to ensure that safety is incorporated into the design and operation of the system given the unique mission set. That mission set includes an initial reactor startup in LEO and a successful engine firing to achieve orbit departure and may include a LEO return if the NTP stage is designed for reusability.

Establishing risk criteria that meet or exceed current risk criteria established by the Nuclear Regulatory Commission (NRC) for commercial nuclear power plants and DOE operating nuclear facilities places the risk of launching and operating a space reactor into the proper context. Based on the previous 50+ years of space reactor design and development, there are a few key lessons learned that should be incorporated into future missions. Specifically,

- All phases of a mission, including reentry, must be explicitly considered,
- Reactors should remain off prior to reaching a safe altitude, and
- Designs should include a positive means to prevent inadvertent criticality.

3.0 Current Launch Safety Process

3.1 Launch Process Overview

There are many safety-related requirements that must be met for a nuclear launch, including the National Environmental Policy Act (NEPA),[27] the National Response Framework (NRF),[28] the National Incident Management System (NIMS),[29] and PD/NSC-25, as amended.[1] NEPA requires preparation of an Environmental Impact Statement (EIS) while NRF and NIMS require emergency planning in preparation for possible accidents. The NEPA, NRF, and NIMS requirements are generally well understood and, while significant and important, are usually not the primary source of uncertainty in obtaining launch approval. PD/NSC-25 is the greatest challenge, and therefore the focus of much of this study effort.

As noted above, PD/NSC-25, as amended in 1995, provides guidance for obtaining approval for launching a nuclear reactor into space. This document specifies that "The President's approval is required for launches of spacecraft utilizing reactors" PD/NSC-25 is reinforced by the 2010 National Space Policy which states:[30]

> *Approval by the President or his designee shall be required to launch and use United States Government spacecraft utilizing nuclear power systems either with a potential for criticality or above a minimum threshold of radioactivity, in accordance with the existing interagency review process.*

Presidential approval is typically delegated to the Director, OSTP and is based on a subjective judgment balancing the benefits of the mission against the risks. While PD/NSC-25 is a simple memo, the path to approval has proven to be long and arduous. The Nuclear Power Assessment Study (NPAS)[31] provides discussion of the approval process, which is depicted in Figure 3-1. Multiple organizations are involved, most notably NASA, the Environmental Protection Agency (EPA), and DOE. NASA provides detailed technical information regarding the proposed mission, DOE is responsible for a detailed safety analysis, and each participating agency reviews the material prior to NASA requesting approval from OSTP. The NASA administrator also empanels an Interagency Nuclear Safety Review Panel (INSRP) with representatives from NASA, DoD, EPA, and DOE, along with technical advisory support from the NRC. The INSRP produces an independent Safety Evaluation Report that is provided to the participating agencies and the White House OSTP. Following the launch, the INSRP is dissolved, and a new INSRP is assembled for each mission. For nuclear missions, such as Cassini, Pluto-New Horizons, or the Mars Science Laboratory, significant quantities of hazardous Pu^{238} are used to power the on-board RPS. Given the level of hazard, detailed and thorough safety assessments are performed. The process involves both testing and detailed analysis. The tests and experiments for previous RPS safety documentation have included:

- Explosive-Overpressure Tests
- Fragment Projectile Tests
- Drop Tests
- Solid Propellant Fire Tests
- Bare Clad Impact Tests
- General Purpose Heat Source Impact Tests
- Large Fragment Tests
- Flyer Plate Test
- Edge on Flyer Plate Tests
- RPS End-On Impact Tests
- Solid Propellant Fire Characterization Test

Figure 3-2 shows the detailed computational process followed for the safety assessment of past RPS missions.[31] The complete set of analyses and experiments can take 3-5 years to complete and cost tens of millions of dollars, with no assurance that presidential approval will be granted at the end of the process.

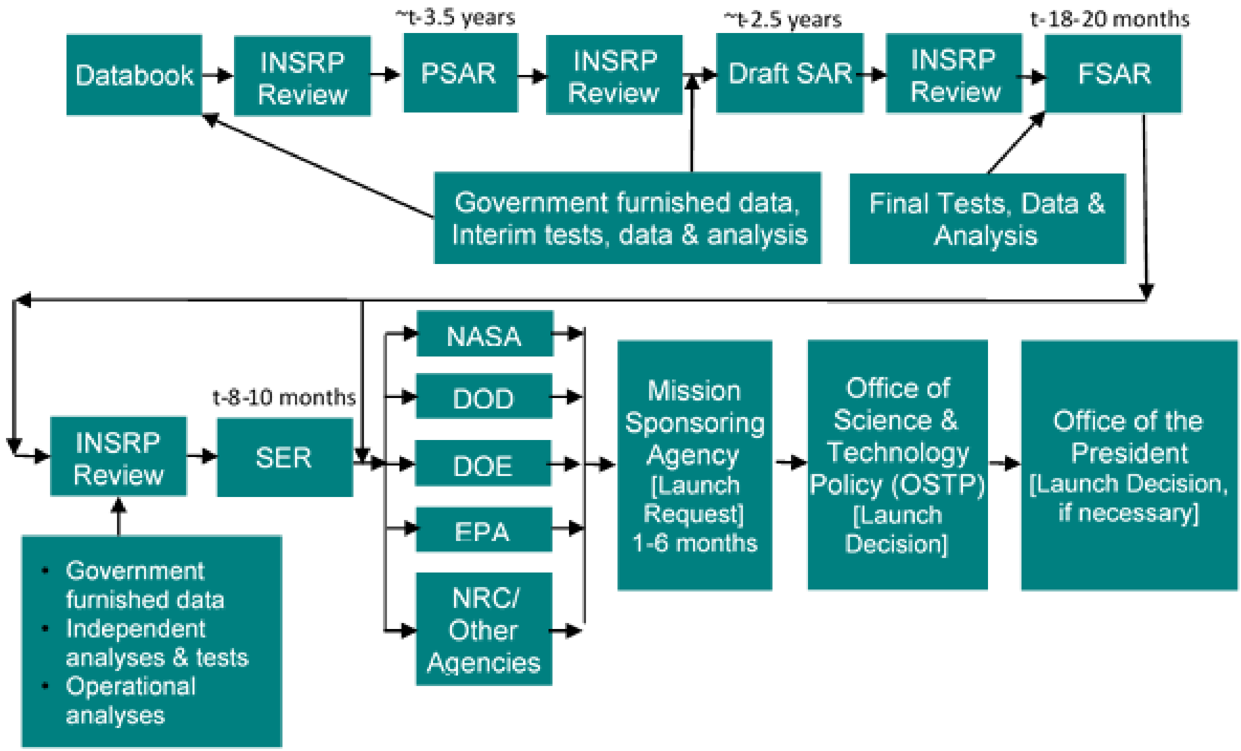

Figure 3-1. The U.S. safety review and launch approval process for nuclear-powered space missions.

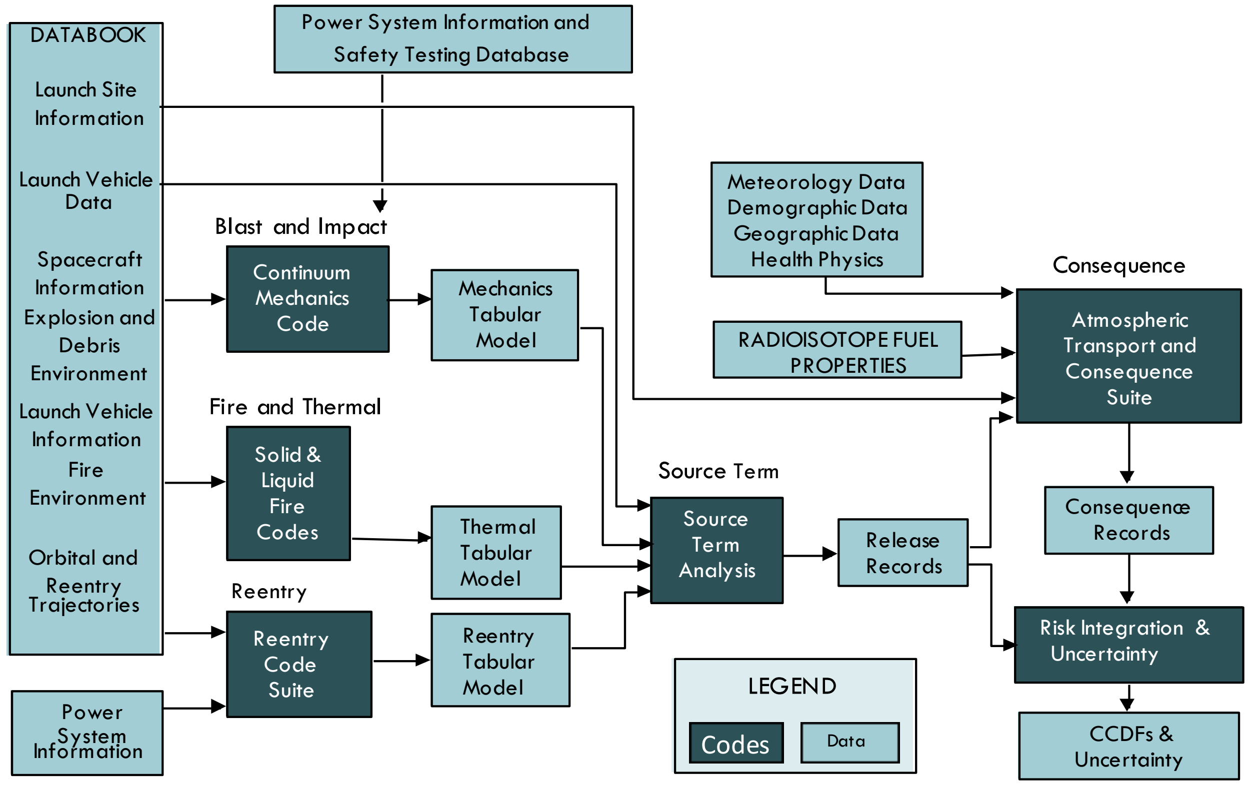

Figure 3-2. Computational flow for the launch approval safety analysis.

As a result of the complex processes discussed above, mission planners are understandably reluctant to include nuclear options in their plans. Space missions often have fixed launch windows and fixed budgets, and nuclear approval processes add uncertainty to both. The discussions below attempt to address these issues for launching small nuclear reactors.

3.2 Considerations for Fission Reactors

A typical nuclear launch safety assessment considers a number of mission phases, including prelaunch, launch, ascent, and reentry. As noted previously, numerous RPS have been approved for launch. Because a nuclear reactor does not present a radiological hazard unless it achieves sustained criticality, there will be important differences compared to RPS. The current approach to launching nuclear reactors precludes operation prior to achieving a safe orbit or beyond, although this is not legally prohibited. United Nations (UN) Resolution 47/68 sets out non-binding principles for space nuclear power systems, including "Nuclear reactors shall not be made critical before they have reached their operating orbit or interplanetary trajectory."[32] This is consistent with NASA working group recommendations for nuclear propulsion for the Space Exploration Initiative:[33] "The reactor shall not be operated prior to space deployment, except for low-power testing on the ground, for which negligible radioactivity is produced."

Assuming that no criticality occurs, the key advantage of launching cold uranium fuel (either HEU or LEU) is that the health effects of dispersed uranium are small when compared, for example, to Pu^{238} contained in RPS. A 50-kg HEU-fueled reactor will have an activity of approximately 3 Ci, with most of that coming from the U-234 component of the fuel. Such a reactor is likely to include an additional neutron source for safety and control that will add an additional 0.5 to 1 Ci.

Calculations presented in Appendix B show the low radiation doses that result from dispersing cold fuel for a typical reactor design.

Therefore, while not an explicit requirement, it is assumed that the U.S. will launch a subcritical reactor with "cold" uranium fuel, and that the fuel will remain cold through any likely reentry scenarios. That said, the possibility that a launch accident could lead to a criticality event still should be considered, and national security requirements are likely to require the prompt recovery of the core, particularly if it involves HEU.

While it is clear that the public health risks from launching cold uranium reactors are very low, questions about criticality and security remain. Criticality events could result in high, localized radiation doses and also present a challenging recovery and cleanup process. Criticality could occur through change in fuel geometry, loss of neutron absorbers, immersion in water, burying in sand, or perhaps other events. Criticality is not possible for RPSs, and thus RPS accidents present different consequences than a fission power reactor.

Reentry scenarios tend to be particularly controversial, with debates about the virtues of intact reentry versus reentry burnup, and the difficulty in predicting the health consequences of these events. Reentry scenarios involving cold fuel are expected to be of much less concern from a safety viewpoint, but criticality accidents must still be considered.

The issues discussed above for nuclear reactors have been examined previously for the programs identified in Section 2, and various solutions have been proposed. However, beyond the requirement for INSRP and OSTP review, there are currently no explicit requirements to assure launch safety for fission reactors, and no previous approvals that can be used as a template for going forward.

4.0 Assessment of Areas for Improvement

As discussed in Section 3, the current launch approval process is complex and costly. It is important to identify those areas most suitable for improvement, while maintaining adequate public and environmental safety. In considering these areas, past work provided a foundation for the effort, along with additional discussions among the study team and others.[31,34,35,36,37,38] Generally, the concerns and issues regarding the current process fall into the following areas:

4.1 Duplication

The current process generally produces multiple analyses with similar types of information. As noted in Section 3, this includes an EIS, multiple Safety Analysis Reports (SARs), and the Safety Evaluation Report (SER). It is important to consider the value added by each of these analyses. Figure 4-1 shows that, for a number of recent missions, the uncertainties in the assessments are larger than the differences among the assessments. For example, the figure shows the EIS estimate, along with the associated 5^{th} and 95^{th} percentiles. The difference between the 5^{th} and 95^{th} percentiles is identified as the uncertain range in the figure. The corresponding SAR and SER values lie within the uncertainty range. A full set of values for the Mars 2020 mission is not yet available.

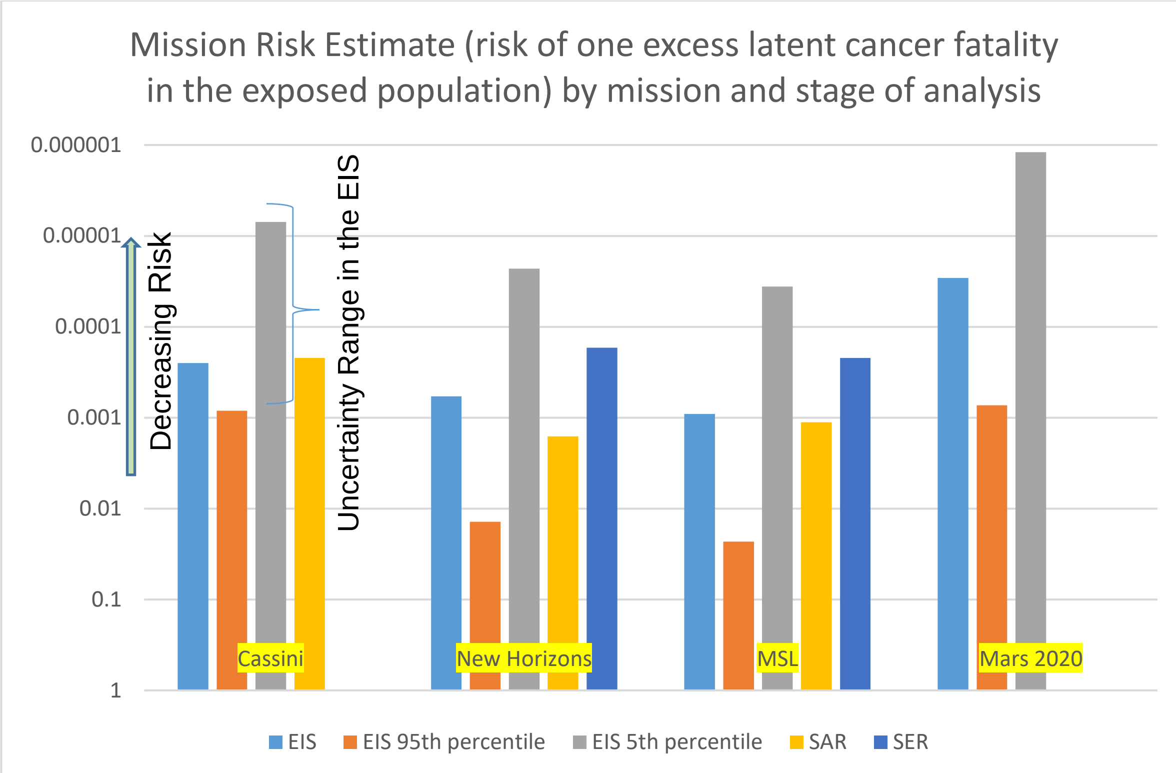

Figure 4-1. Comparison of multiple analyses for recent missions.

In each of the missions identified in Figure 4-1, none of the additional analyses provided risk information that changed a launch decision. Having said that, it is unlikely that a single analysis can meet all necessary requirements, although that may be a worthy goal. NEPA requires an EIS, and there is certain information that must be included. Changing NEPA requirements would be very challenging and is likely not the best area to focus on for change. However, an SAR is provided for the EIS that then evolves further for the INSRP review. Reducing the number of iterations of the SAR may be achievable and should be examined.

Additionally, the INSRP generates a SER, which reports the results of their independent review. Most recent SERs have included significant independent analyses. However, a SER can be generated based on a thorough review of the SAR, without generating duplicate analyses. For example, the NRC often generates SERs without performing duplicate analyses. It is important that someone perform an independent technical review, but such a review can be limited in its scope to that level of review necessary to inform decision makers. Appropriate reviews should be carried out by experienced nuclear safety experts and can be guided by review plans that specify such things as ensuring the use of approved analysis tools, validated data sets, quality controls, and consistency checks.

Another example of duplication occurs when a previous analysis is repeated for similar systems and missions. It should be possible to substantially reduce the level of effort by referencing previous work and only performing new analyses that address any significant new information. The measure for significance should be whether the information has the potential to change a launch approval decision. Otherwise, past analyses should be considered sufficient, and approval of reference designs should be possible.

4.2 Complexity

Complexity can exist in both the analysis process and in the approval process. In either case, the level of complexity should be commensurate with the level of hazard involved. Currently, small sources, such as RHUs can be subjected to similar process as RPS systems. This is due to the arbitrary use of low A2 radioactivity levels as a threshold or trigger level for entering the detailed review process. Significant complexity can be removed for many missions by setting appropriate activity levels to trigger the approval process, and in many cases, performing simple environmental assessments instead of full EISs. An INSRP type review should not be necessary for potential accidents involving activity levels of a few tens of curies or less.

When significant radioactive hazards exist, such as for RPS or criticality events, there is still room for simplification. Current SARs are very thorough and produce a wealth of information about safety and risk. Maintaining technical quality in the analyses is important. However, a great deal of information is produced that is interesting academically, but generally does not factor in to final launch decisions. An example of this is the generation of complementary cumulative distribution functions. These curves are of interest to professional risk analysts, but are of little value to decision makers, and are generally not understood by the public. Generating a few simple measures of safety or risk will increase the transparency of the process. Section 6 provides recommendations for such measures.

4.3 Roles and Responsibilities

The current process was described previously in Section 3. Multiple agencies are involved, along with the INSRP and the White House/OSTP. With few exceptions, a detailed launch approval process has never been defined; it remains a largely ad hoc process. Memorandums of Understanding (MOUs) exist between certain agencies, but no single document reflects a comprehensive process. As a result, there is sometimes question about where authority resides, and where there may be potential conflicts of interest.

Changing the roles and responsibilities of organizations will be complex and difficult. Nevertheless, it may be necessary, particularly since the prospect of commercial launches must now be considered. Fundamentally, the launch approval process is a form of a regulatory process. Generally, a regulatory process involves an applicant, who is responsible for the design and making a safety case, along with a regulator who has the authority to make decisions according to a prescribed set of regulations. The regulator may engage an independent technical review, either within or outside the agency. Such a review group may be a standing body, as opposed to an ad hoc group, to allow for continuity and consistency of decision making.

While a cumbersome set of regulations is neither necessary nor appropriate for nuclear space systems, the lack of clear decision criteria is problematic for both designers and decision makers. It is entirely appropriate for an analysis to be considered complete when it can be demonstrated that the criteria are met, even though there may be outstanding technical questions. For example, if a bounding analysis meets the criteria, the fact that there are technical uncertainties associated with best estimate analyses is not relevant.

National security was in important part of early nuclear space activities. As a result, it was entirely appropriate for the White House to maintain authority over nuclear launches. The discussions in this report apply to science and commercial missions. Classified national security missions are subject to a different risk-benefit perspective and are not addressed here. Such missions may be required and approved even if the proposed safety criteria are not fully satisfied.

5.0 General Design Criteria

The use of GDC, General Design Criteria, etc. has a long history in the nuclear safety community. The most famous of these criteria are the GDC for light water reactors codified in 10CFR50 Appendix A.[39] For consistency the term "General Design Criteria" or GDC will be retained.

Generalized nuclear safety criteria were promulgated by the DOE in 1982 for space reactors as part of the SP-100 program.[40] These criteria were nuclear design criteria that provided verbal guidance on safety, such as "the reactor should be designed to not go critical on a launch accident." They were not numerical acceptance criteria. However, the guidance was a change from previous programs where no such criteria were codified.

GDCs were used in all space reactor programs after SP-100 including Topaz II and the Jupiter Icy Moons Orbiter. After review of each of these programs, the following are the suggested GDCs for space reactors. These criteria are modified from those developed for the Topaz II program by Al Marshall at Sandia National Laboratories.[41] The suggested GDCs are then:

- The reactor shall not be operated prior to space deployment, except for low-power testing on the ground, for which negligible radioactivity is produced.
- Inadvertent criticality shall be avoided for both normal conditions and credible accident conditions.
- The radiological risk and consequences on Earth's surface of a release from an accident shall be insignificant.
- The reactor shall not be operated below a "sufficiently high orbit" per UN Resolution 47/68.
- In-space disposal shall be limited to sufficiently high orbits or extra-terrestrial planetary surfaces where not precluded by planetary protection requirements.

The use of GDCs will provide guidance to designers for achieving adequate nuclear safety. The criteria are purposely written in a non-proscriptive fashion to allow designers the opportunity to pick their own individual path to achieving safety. These GDCs provide a high-level framework for safety, while numerical risk criteria help determine when the implemented safety strategy is adequate.

6.0 Safety Criteria

6.1 Need for Explicit Criteria

There are currently no explicit safety criteria for launch approval of nuclear systems. PD/NSC-25 merely requires the White House/OSTP to evaluate the risks versus the benefits of the mission.[1] No U.S. reactors have gone through the current launch safety approval process, since the SNAP 10A launch occurred before the current policies were established. RPSs have been approved though the process at a cost of several tens of millions of dollars per mission.[31,34,38] Reference 34 states for RPS systems: *The NASA and DOE safety and support costs for use of RPSs and RHUs is sufficiently high to limit their use for all but flagship-level missions.*

To date, no RPS mission has failed to receive launch approval, although the time and cost can vary significantly. While these missions have been approved, in each case the mission planners proceeded on the hope that approval would occur without actually knowing that their design was adequate, since adequate was never defined. Some confidence is obtained by having precedent from previous missions; such precedent does not exist for fission reactors.

Given the long lead time to design and build nuclear systems, an uncertain launch approval is a major impediment to choosing a nuclear reactor for space missions. NASA mission managers are understandably reluctant to consider nuclear reactors even when alternative approaches compromise mission goals. While federally funded programs will sometimes take on high risk missions, uncertainty in launch approval is even more problematic for possible commercial missions. Specific acceptance criteria are needed so that designers and mission planners can treat nuclear reactors in a manner similar to other engineered systems and have predictability of cost and schedule.

The benefit of reducing approval uncertainty is exemplified by the experience of the U.S. commercial nuclear power industry. In the 1980s, that industry faced numerous challenges following the Three Mile Island accident. Of particular importance was the constantly moving regulatory landscape, in which frequent new regulatory requirements were leading to increasing costs and an inability for utilities to plan. At the urging of the industry, Congress, and others, the NRC finally explicitly addressed the question "How safe is safe enough?" by issuing the 1986 Safety Goal Policy.[42] This policy statement, along with related regulatory changes, significantly influenced the regulatory environment such that over the next two decades, nuclear plant availability and profitability increased dramatically,[43] while plant safety continued to improve.

6.2 Approach to Development of Safety Criteria

As a wide variety of nuclear missions were being considered in the early days of space flight, flexibility was an important part of the launch approval process. Many different systems were considered for many different missions, and at the height of the Cold War, national security played a key role in balancing risks versus benefits of particular missions. Flexibility is important in the launch approval process to accommodate new designs, and the White House or their delegate will be the final arbiter for nuclear missions, particularly missions involving national security. However, much has been learned since the 1960s that can be applied to develop standardized approaches that might apply to the majority of launches, and fission power reactors in particular.

While PD/NSC-25 is an elegant document in its simplicity, it requires a subjective judgment by the White House regarding the benefits of a mission compared to the risks. It makes no attempt to define those terms or how they should be measured. The benefits to society from NASA space missions are substantial, but they are admittedly difficult to quantify. On the other hand, it is possible to specify acceptable methods and metrics for evaluating launch safety, thus going a long way in reducing the uncertainty in achieving approval.

PD/NSC-25, by itself, contains no mechanism to minimize the uncertainty in the process, and allow designers to know when their designs are "safe enough" and mission planners to predict the time and resources necessary for approval. Currently, there are no criteria that, if met, would ensure the approval of a given launch. By leveraging existing policy for safe use of nuclear technology on Earth, it is possible to develop criteria that could be applied for most space launches. There are many different types of safety criteria that can be developed and implemented. For example:

- Probabilistic public risk goals, such as used by the NRC
- Deterministic design criteria, used in many industries
- Assured safety criteria, used in the nuclear weapons program

- Enveloping criteria, i.e., determining that the risk is less than previously approved missions
- Criteria based on Maximum Credible Events
- Combinations of the above

In choosing a proposed set of safety criteria, three guidelines were used:

- The criteria should be simple to understand and implement.
- The criteria should provide a similar level of safety to other federal nuclear safety criteria.
- The criteria should be design independent.

The different types of safety criteria identified above are discussed in more detail in Reference 44. The NRC Safety Goals provide an example of a safety goal policy that is reasonably clear in its intent.[42] The policy states that people living near nuclear power plants should "bear no significant additional risk" as a result of living near the plant. The policy then clarifies that "significant" shall mean 0.1% of the risks to which people are normally exposed. This is not to say that there will not be controversy associated with the actual calculations, only that the intent is relatively clear.

Consistent with the guidelines noted above, safety criteria for space reactors are recommended in the form of risk criteria. Risk in generally presented as a combination of probability (or likelihood) and consequences. Thus, separate probability and consequence criteria are presented below.

When considering similar levels of safety to other nuclear operations, it is very important to distinguish between *operational* limits and *accident* limits. For example, nuclear reactors have operational dose limits for workers and the public that are far lower than the dose limits for design basis accidents. The risk criteria defined herein for space reactors are for accident conditions, and thus should be compared to the criteria for accidents at terrestrial nuclear facilities. A separate set of criteria will ultimately be needed for operational safety of space reactors, relative to crew members and scientific equipment.

Another consideration in developing risk criteria is the choice between individual or collective risks. Individual risk criteria are chosen here, because they are easier for individual members of the public to understand, and the collective risks tend to involve very low doses to very large populations. The latter are not well understood and can result in misleading results. The International Commission on Radiological Protection has stated:[45]

> *Collective effective dose . . . is inappropriate to use in risk projections. The aggregation of very low individual doses over extended time periods is inappropriate, and in particular, the calculation of the number of cancer deaths based on collective effective doses from trivial individual doses should be avoided.*

In crafting the specific risk criteria, it is important to reflect all that has been learned in the evolution of nuclear safety since the 1960s. Further, it is important to recognize that the risk criteria themselves are likely to influence future designs. The calculations in Appendix B have confirmed previous analyses that accidents involving dispersal of cold uranium fuel pose minimal risk to the public. Therefore, accidents involving such cold fuel should be treated as any other radioactive source, in most cases by an Environmental Assessment with a Finding of No Significant Impact. Thus, the safety approval process should be restricted to accidents involving criticality or previously operated reactors, since they involve the bulk of the risk. Note that accidents involving criticality will lead to costly cleanup activities and have public relations implications even if no members of the public are harmed. Therefore, consistent with the recommended GDCs, risk criteria are recommended that encourage designs that minimize the likelihood of criticality events as well as the consequences of such events.

6.3 Recommended Risk Criteria for Space Nuclear Reactors

The first part of the recommended risk criteria is a high-level criterion that is a statement of intent:

> ***The likelihood of a space reactor accident shall be very small, and even if it occurs, will pose little threat to the public.***

As noted previously, accidents involving cold uranium fuel pose little threat to the public. Therefore, this statement applies to criticality accidents and accidents involving previously operated reactors. This high-level criterion contains two parts, one associated with likelihood or probability and one associated with consequences. In the discussions below, separate likelihood criteria are recommended for different accident types, while a single consequence criterion is recommended for the spectrum of accidents.

The approach to setting these criteria includes consideration of past work in space reactors and nuclear facilities. Most of the operating nuclear reactors in the U.S. are regulated by the NRC or DOE. The risk criteria proposed here have philosophical similarities to criteria and levels of safety routinely used by those organizations. That is, probabilistic risk criteria are proposed, and the values are compared to those accepted by the NRC and DOE. This facilitates communication with existing regulatory bodies and members of the public.

6.3.1 Likelihood Criterion for Inadvertent Criticality Accidents

Inadvertent criticality can occur in any accident involving launch and ascent or reentry, including failure to reach orbit. The first part of the stated safety goal is that the likelihood of an accident, including the contribution from criticality accidents, shall be very small. First, consider the portion of criticality accidents that occur during ground operations, launch and ascent. Previous work is consistent with a value of 1E-4 for the conditional probability of a criticality given a launch accident.[46] With launch failure rates projected at less than 10%, the total probability per launch of an inadvertent criticality would be approximately 1E-6. However, this is significantly more conservative than the levels implied by other criteria, such as the NRC Safety Goals. The NRC suggests that latent cancer goals are met with accident frequencies below 1E-4 per year and prompt fatality goals are met with large early release frequencies below 1E-5 per year.[47] Note that interchanging "per launch" and "per year" is conservative unless nuclear launches become more frequent than one per year on average.

Commercial nuclear power plants have fission product inventories that will be many orders of magnitude larger than that produced by the inadvertent criticality of a space reactor. Therefore, a value of 1E-4 per launch for the probability of an inadvertent criticality is somewhat conservative with respect to the NRC goals and seems reasonable for launch accidents. Conservatively assuming a launch failure rate of 10%, then the conditional probability of an inadvertent criticality given an accident during launch and ascent should be less than 1E-3. The total probability will vary slightly, depending on the launch vehicle; however, using the conditional probability may simplify the process for reactor designers. If the launch vehicle cannot be readily determined to have a failure rate less than 10%, then the conditional probability could be reduced to 1E-4.

Now consider inadvertent criticality upon reentry. Without mission specific data, it is reasonable to assume that the probability of inadvertent reentry will be far less than 0.1, based on the experience of modern satellites and rockets. Therefore, consistent with the discussions above, a conditional probability of criticality during reentry and subsequent impact of 1E-3 is conservative.

An additional consideration that was discussed for inclusion in the criterion could take into account the magnitude of the criticality event. That is, only criticalities that could generate a threshold number of fissions, e.g., greater than 1E20 fissions would be counted. Events generating fewer fissions than this threshold are unlikely to result in significant public health effects away from the accident or crash site. However, it is important to note that even "small" criticalities may require extensive cleanup, cause hazards to adjacent personnel, and generate negative public perception. Therefore, even if the magnitude of the criticality event were to be included, the GDC should drive designs that are unlikely to become critical during an accident and include positive means to prevent inadvertent criticality.

Thus, the recommendation for a single probability criterion for all mission phases is:

> ***The conditional probability of an inadvertent criticality, given the occurrence of an accident, shall be no more than 1E-3.***

There are various approaches for meeting the criterion. The simplest approach is to develop robust engineering designs that preclude criticality. Examples of this approach that may apply to one or more mission phases are:

- Launch the reactor in a disassembled form
- Provide redundant assured shutdown mechanisms sufficient to withstand bounding environments, such as approaches that have been incorporated into previous designs including
    - Varying core dimensions (length to diameter ratio) to prevent criticality from water moderation
    - Including burnable poisons in the core to prevent criticality from water moderation
    - Inserting poison wires in the hydrogen flow channels of an NTP to prevent criticality from water moderation
    - Adding diverse and redundant control mechanisms (for example control drums and a central control rod) to prevent criticality due to rod ejection
    - Making material choices to minimize the effects of ground surface impact (for example ceramic versus metals) to aid in prevention of criticality from impact
    - Including a range destruct mechanism which would break up the core or reflector integrity thereby preventing criticality
- Demonstrate through test and analysis that the reactor cannot achieve criticality under all credible accident conditions

The design of any system would need to include choices of methods, materials, and configuration that would meet their specific mission application. The burden of proof would be on the designer to show that they met the criterion for preventing criticality. Additionally, a designer could choose to include redundant options. The burden of proof then falls on the design team to make the argument for meeting the criteria. If one, or more, of the examples above is chosen, then the safety review could be limited to ensuring the validity of the engineering solutions proposed, accounting for possible failure mechanisms.

The second approach is to actually calculate the probability of a criticality, given an accident. In this approach, the range of accident scenarios must be considered, along with the response of the reactor to those scenarios. Submersion, crushing, and loss of control systems are among the responses that must be evaluated. It is expected that conservative or bounding calculations can be used in most cases.

6.3.2 Likelihood Criterion for Hot Reentry

Reentry involves a number of scenarios that are different from those that occur during ground operations, launch, or ascent. Reentry can occur from failure to achieve orbit, after achieving the intended orbit, during a gravity-assist flyby, or during a return-to-Earth scenario. The latter would include, for example, a nuclear propulsion system that transports cargo back and forth to the moon or Mars. The actual reentry could involve a critical or subcritical reactor, and either hot or cold fuel. When the reentry occurs, the reactor might completely burn up, land intact, or some combination of the two.

Risks to individuals are extremely low for reentry scenarios. If the reactor burns up and disperses the fission products globally, the doses to any particular person are vanishingly small. Further, if the reactor lands intact or in pieces, the likelihood of it landing near any particular person is also extremely low. However, if the reactor does not burn up, locally high doses may be present near the landing site. In some cases, a criticality might occur as a result of the crash. However, the overall doses from previously operated reactors may be dominated by fission products from previous operation, as opposed to fission products from a transient criticality. The criticality may provide the driving force for dispersing the fission products. The likelihood criterion for an inadvertent criticality is covered by the criteria in the previous section, i.e., the conditional probability of an inadvertent criticality given an unplanned reentry shall be no more than 1E-3. This criterion applies to all reentries, whether hot or cold. The remainder of this section will discuss the likelihood criteria for an unplanned reentry of a hot reactor.

It is difficult to ensure complete burnup, because reactors by their nature include high-temperature materials. As a result, some previously planned missions included measures to ensure intact reentry.[17] Even those designs are difficult and expensive to validate, due to the complexities of calculating high-speed reentry behavior, and the difficulty in performing validation tests. Some historical references were discussed in Section 2. For these reasons, the proposed likelihood criterion focuses on minimizing the likelihood of an unintended reentry.

Therefore, the recommended likelihood criterion for hot reentry is:

> ***The probability of an unintended hot reentry after reactor operation shall be less than 1E-4 over the life of the mission.***

There are a few things to note about this criterion. By definition, the risk to individual members of the public will be very low, comparable to the probability of spacecraft parts landing on them. Next, the criterion does not explicitly address orbit altitude during the mission. The altitude may affect the probability of unintended reentry, but lower orbits are not necessarily excluded. The approach is to consider that unintended reentry is undesirable, and the probability of such an event must be kept very low.

For the purpose of the above criterion, mission life is defined as the time from first departure from the Earth’s atmosphere through the final shutdown and disposal of the reactor in space. Fission products build up rapidly towards an equilibrium value in operating reactors, so there is little to be gained by parsing the mission life, although the approach taken is conservative. It is recognized that this criterion is also very conservative for an orbiting reactor when viewed from a per year basis. In fact, that is the intent, given the difficulties associated with calculating reentry behavior and the possible political implications of a hot reactor reentry.

As with the criteria for criticality, a modified criterion can be proposed for unintended hot reentry that considers the hazard level of the reactor. A curie limit could be used to exclude certain reactors that are extremely low power or have been inoperative long enough for the fission product inventory to decay to safe levels. In this case, there is still the probability criterion for the likelihood that the reentering cold reactor goes critical upon impact. In the same manner that the criticality criterion is intended to drive reactor design to avoid criticality, the hot reentry criterion is intended to influence mission profiles to reduce the likelihood of inadvertent reentry. No mission profiles are a priori precluded, but more work may be needed for approval of some mission profiles versus others.

6.3.3 Public Health Criterion

In setting a public health criterion, it is useful to review radiation effects and existing dose limits. The average person in the U.S. is exposed to about 300 millirem/year due to naturally occurring background radiation.[48] According to the EPA, doses above about 75 rem can produce acute effects, while lower doses can potentially cause cancers or other latent health effects.[49] It is very difficult to determine individual health effects below about 10 rem.

The NRC and the EPA have specified radiation dose limits for members of the public under certain conditions. Typically, these limits apply to nuclear reactors or other operating nuclear facilities. Consider the following:

- NRC limit for persons living next to nuclear power plants due to normal emissions – 100 millirem/year[50]
- EPA limit for members of the public near nuclear facilities due to operations – 25 millirem/year[51]
- NRC limit for person at the site boundary due to a design-basis accident – 25 rem[52]
- DOE guidance for consequence levels for DOE facilities – Low < 5 rem, Medium $\geq$ 5 rem, High $\geq$ 25 rem[53]

Higher limits are typically allowed for plant workers or emergency responders. There is not a specific dose limit for RPS system launches but missions such as Cassini, New Horizons, Mars Science Laboratory and Mars 2020 were shown to have accident doses below 5 rem, except for some very low probability accidents (in the range or less than 1E-6).[34]

Typically, operating dose limits are much lower than accident dose limits. For space reactors, the public doses from a normal launch are expected to be essentially zero, and these limits are not of concern. Given that the likelihood of a criticality or hot reentry has been set to be extremely small, higher dose limits still result in very low individual risk. The 25-rem limits that have been implemented by the NRC and DOE preclude acute health effects and are recommended in the criterion presented below.

Before setting the actual criterion, it is important to consider the distance at which the dose is to be calculated. If a reactor criticality occurs at the launch site, the nearest members of the public are expected to be several kilometers away, depending on the launch site and the controls implemented for a particular launch. If a reactor lands adjacent to a person and becomes critical, the dose to the adjacent person will far exceed any reasonable dose limit. However, this risk is not dissimilar to the accepted risk of a rocket or rocket parts falling near an individual. Due to planned launch trajectories and range safety, the probability of such events is extremely low. However, a large rocket explosion can impact a significant area, and the approach taken here is to keep the impact of a critical or reentering hot reactor localized. This can be achieved by setting a reasonable distance from the reactor for the 25-rem limit. Setting the distance to 1 km is conservative with respect to accidents at the launch site and reasonable with respect to localizing the effects of accidents occurring in unexpected locations. Note that using 1 km for hot reentry implies that either full burnup or intact reentry is desired and not an accident that distributes hot pieces of fuel over a wide area. The actual recommended number of 1 km is somewhat arbitrary and could be modified following further review but is the right order of magnitude. The recommended consequence criterion is then:

> ***For any credible space reactor accident, doses to members of the public shall remain less than 25 rem at 1 km from the reactor.***

For this criterion, *credible* is defined as having a probability that is greater than or equal to 1E-6. For launch and ascent, this means 1E-6 per launch, while for hot reentry this means 1E-6 over the mission life. This criterion is expected to be met with conservative calculations. Consider two types of criticality events:

- Prompt critical disassembly
- Sustained or pulsing criticality

For a prompt critical disassembly, the doses to the public will be driven by the total number of fissions that occur during the event. Experience shows that it is very difficult to get above 1E20 fissions, which would probably be necessary to achieve significant doses at 1 km.[54] Between 1E17 and 1E18 fissions, depending on the size of the reactor and reactor fuel type, enough energy is generated to completely melt the core.[55] Once a significant part of the fuel begins to move, the reaction shuts down. Therefore, the reactor must stay together for several neutron generations after reaching its melt temperature in order to reach 1E20 fissions or more.

For a sustained or pulsing criticality, such as might occur in a submerged reactor, a large number of fissions may be possible before the reactor is ultimately shut down. Thus, a potentially large source term is present. However, if the reactor is critical and intact, there is no driving force to disperse the fission products. Except for the gases and a fraction of the volatiles, they are contained in the fuel. The reactor may be very hot with locally high radiation fields, but doses will be extremely low at any distance from the reactor.

If a member of the public comes close to a critical or hot reactor, including one that may have disassembled, they may receive a large dose due to direct shine. However, as discussed previously, this risk is not dissimilar to that of a rocket impact nearby. Thus, the public health criterion above assumes that the dose will be calculated based on a 1-km distance from the reactor. The most likely area for a critical reactor to occur will be at the launch site or down range over the ocean if launched from Kennedy Space Center (KSC). Given that the probability of a criticality has already been set to be less than 1E-4, the probability that the criticality occurs in a public area is even lower. Therefore, these scenarios can probably be addressed by showing that they are incredible (<1E-6/launch). Such scenarios may be more important at a launch site other than KSC. For hot reentry, there are no credible scenarios for reactors that are not operated near the Earth and do not involve return to Earth or flyby scenarios. For credible scenarios, the consequence criterion should be addressed.

Safety review against the public health criterion should ensure that credible accident scenarios have been addressed or bounded. The probabilities of similar scenarios should be grouped together for the purpose of determining credibility. Most likely, conservative fission product release and transport models can be used, and the review should verify the validity of those models and their application.

6.3.4 Consistency with Other Federal Regulatory Approaches

The NRC has proposed a dose-frequency relationship for new reactors.[47] This relationship is shown in Figure 6-1. This figure simply proposes that events involving higher doses should have lower frequencies. The upper right portion of the figure is "unacceptable," and the lower left portion of the figure is "acceptable." The shaded area represents the likelihood and dose criteria recommended for space reactors. As shown, these criteria are consistent with the NRC criteria.

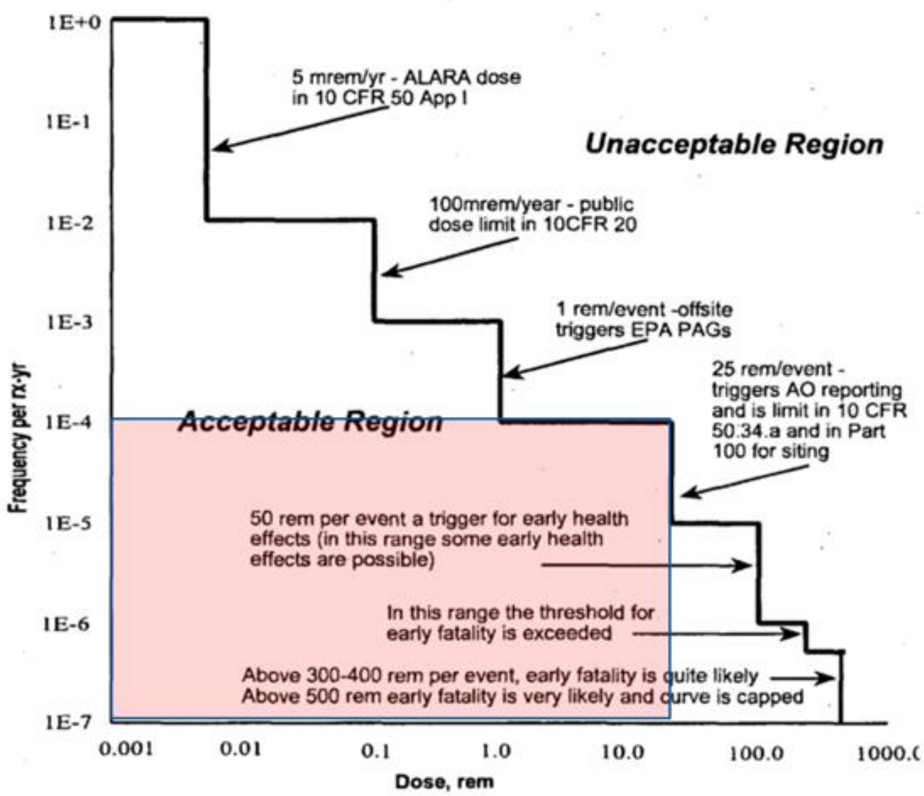

Figure 6-1. NRC frequency - dose criteria compared to proposed space reactor criteria.

Similarly, DOE has dose-frequency criteria that are used in managing nuclear facilities. DOE considers risks to be of "major concern" where the probabilities are above 1E-4 and the doses are above 25 rem.[53] Neither the NRC nor the DOE criteria are recommended for direct adoption for space reactors; however, it is reasonable to adopt criteria that indicate similar low levels of public risk. In summary, the recommended criteria provide a high level of public safety, are transparent regarding their intent, are consistent with the levels of safety provided for other nuclear operations, and are practical to implement.

7.0 Graded Approach to Safety Criteria

The concept of a "graded approach" to nuclear safety has a long precedence in the nuclear community going back decades. The basic concept is that the level of analysis and actions to comply with a requirement be commensurate with the magnitude of the hazard. This is articulated more fully in several DOE,[56] NRC and International Atomic Energy Agency (IAEA)[57] documents. As an example, the definition from 10CFR830 states:

Graded approach. The process of ensuring that the level of analysis, documentation, and actions used to comply with a requirement in this part are commensurate with:

- *The relative importance to safety, safeguards, and security;*
- *The magnitude of any hazards involved;*
- *The life cycle stage of a facility;*
- *The programmatic mission of a facility;*
- *The particular characteristics of a facility;*
- *The relative importance of radiological and non-radiological hazards; and*
- *Any other relevant factor.*

The goal of the graded approach is to ensure that adequate safety is assured in a cost-effective manner. Performing a conservative hand calculation in lieu of a detailed computer analysis to show compliance to a criterion is an example of the graded approach.

For space reactors two examples are presented for the launch and ascent phase. The first example involves fire and explosions not involving criticality. The second example is for accidents involving accidental criticality. These examples are shown in the flowchart contained within Figure 7-1. A similar figure could be constructed for hot reentry.

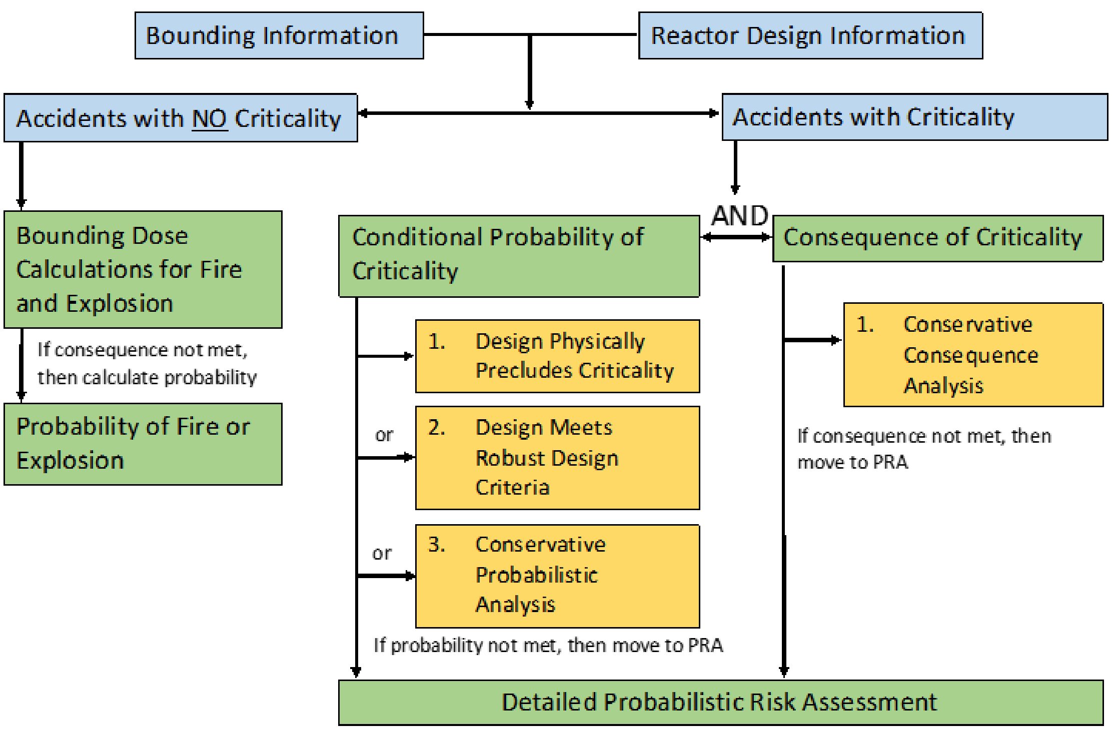

Figure 7-1. Flow chart showing graded approach for space reactor launch safety.

Since most space reactors have only a few curies of radioactivity in core during launch, a simple bounding calculation can be performed for a launch pad explosion to show that the result is orders of magnitude below the criteria being proposed in this document (see Appendix B on cold reactor launch showing this type of calculation). This would be an example of using the graded approach to show adequate safety.

A similar type of analysis can be done using a graded approach to calculate the probability and consequence of criticality. Given a conditional probability of criticality set to the value of 1E-3 AND a dose below 25 rem (as recommended in this document), there are several approaches possible for achieving compliance. Any of the approaches are considered acceptable and are listed in order of complexity from the flow chart for both probability and consequence.

<u>Probability Option 1 – Physically Preclude Criticality</u>

In this option, criticality is physically precluded, most likely by launching a disassembled reactor. The disassembly must be sufficient to preclude criticality if the partial reactor were damaged or submerged in water or sand. Such an approach should lead to simple approval but has the disadvantage of requiring a potentially complex, and probably impractical reactor assembly in space.

<u>Option 2 – Robust Engineering Design Criteria</u>

In this approach, if specified conservative design criteria are met, then the goal of 1E-3 is assumed to be met. An example set of criteria could be:

- Provide two independent means of maintaining shutdown, including cases involving submersion or other credible reactivity insertion, and
- Ensure that at least one shutdown system will remain functional during conservative impact and explosion scenarios, at least until the reactor itself is destroyed.

An example of a design that might satisfy Option 2 is one with a control rod system and an independent reflector control system, provided that both are capable of ensuring that shutdown is maintained upon submergence and that at least one is more robust than the reactor itself. In this approach, the safety approval process can be limited to validation of the engineering design. This would include such things as reviewing the reactivity parameters or the definition of the conservative scenarios and the material behavior of the relevant components.

<u>Probability Option 3 – Conservative Probabilistic Analysis</u>

Option 3 is similar in some respects to option 2. The design may have robust design features that make the probability of criticality for a given accident type very low. However, in this case there are not a priori engineering design criteria, rather, accident sequences are examined to determine the most conservative sequences with combined conditional probabilities greater than 1E-3. An event tree model or similar logical construct is used to determine the potential sequences that have the greatest impact, worst fire, etc. Then, the design is assessed against those particular sequences, and the probability of criticality is determined for each of those sequences. If the conditional probability of criticality is shown to be less than 1E-3 for these conservative cases, then the probability criterion is met. The review and approval process can focus on the worst-case sequences and the assessment of reactor response to this limited set of events. As an example, consider a highly reflected fast spectrum reactor where an intact reflector is necessary to achieve criticality. A ceramic reflector may be much less robust than the reactor fuel and may break prior to events that could lead to criticality. Thus, whole classes of scenarios may be shown to have low probabilities without having to analyze all possible impact orientations and magnitudes.

<u>Consequence Option 1 – Conservative Consequence Analysis</u>

For the consequences of a criticality event, it may be that a simple bounding analysis can be done for potential consequences. This may involve estimating the number of fissions that is credible based upon the design of the reactor. If the number of fissions can be bounded, then a simple, conservative estimate of the consequences can be determined. If this value is below 25 rem, then the criteria are assumed to be met.

<u>Option 4 – Detailed Risk Analysis</u>

In this option 4, detailed calculations thoroughly explore the parameter space and determine the likelihood of criticality and the consequences for each set of scenarios. The disadvantage of this approach is that it is much more time consuming and expensive. Conceptually, the approach is similar to that currently used for RPSs. The advantage of the approach is that designers can take credit for many more things, for example, favorable impact orientations or packaging benefits. The typical steps in the approach would be:

1. Develop a detailed logic model, i.e., probabilistic risk assessment (PRA) model, to describe the possible accident progressions
2. Implement detailed physical models of the accident and spacecraft/reactor response.
3. Develop detailed accident calculations to estimate the number of fissions and the associated consequences for “representative” types of accidents. An example of a “representative” calculation might be an accident where the reactor goes critical in water, while another type might be the reactor going critical due to land impact causing core geometry changes. Use the detailed consequence calculations to assign each end state in the PRA to a consequence bin.
4. Use sampling techniques to determine the probability of criticality for each end state and the associated uncertainty. Express the results in a form that effectively presents the cumulative risk of criticality.

Using option 4 results in a very complex analysis process and a complex review process, requiring the reviewers to understand many more details about the designs and the models. This approach can be expected to take much longer than other options.

8.0 Potential Organizational and Process Changes

A number of potential organizational and process changes were considered during the course of this study. Various organizations have recently completed or are in the process of studying the complexities of the launch approval process for power and/or propulsion concepts, which utilize nuclear materials. These include the NPAS[21] and OSTP/ Science and Technology Policy Institute (STPI) RPS[28] studies which extensively discussed many of the organizational complexities related to the current nuclear launch approval processes. The NPAS and STPI studies specifically illustrated the multiple overlapping analyses that are currently required to achieve launch approval, and they generally reach the same conclusions. The STPI study has noted that the estimated risk for each of the most recent nuclear launches were generally the same and any differences from one mission to the next were generally less than their study approximate uncertainties. This is demonstrated in Figure 4-1.

The previous studies also observed a number of other organizational misconceptions including that INSRP is not required to perform completely independent analyses, though it often does. It is also noted that in other areas of nuclear oversight and regulation that during the conduct of their review of license applications, the NRC formally reviews all submittals by licensees, but it does not necessarily repeat the analyses. Furthermore, it is also noted that the DOE currently has the expertise and capabilities to fully complete the complex analyses needed to populate the SAR for both radioisotope and reactor systems.

Because of the importance placed upon managing fissile materials DOE will likely continue to own the security and protection of any mission that calls for the usage of HEU. The current study also finds that the White House should retain full authority over all national security missions requiring the use of nuclear systems and, based upon the language of PD/NSC-25, it needs to be notified and fully informed of other missions well in advance of their launch; however, the White House does not need to be the final decision maker for all other missions, especially civilian and commercial missions.

The STPI study identified a number of important challenges that exist with the current launch approval process. These include an observation that there are currently no criteria for the conduct of nuclear mission safety analyses that the mission planners or system developers can reference. They identified that the analyses to be conducted to demonstrate mission safety are currently unbounded leading to the potential for duplication of efforts and results. Their study concluded that there is a lack of guidance for INSRP and that this allows the INSRP to perform excessive work and request analysis that may lead to unnecessary conservatism in the risk results. Finally, they concluded that there is no special guidance for fission systems.

These observations led this Study Group to consider a clean slate approach to the launch approval of fission-based power and propulsion systems with a few guiding principles. These include the objective of designing an outcome that includes a single review/decision process with a well-defined, clear, and documented pathway for both government and commercial agencies/organizations. Such a simple and straightforward process would be desirable, but not necessary or required. The Study Group also agrees that the final process could be streamlined to reduce overlap among the EIS, SAR, SER, and associated databook, thereby reducing the complexity of the current reports. Further, it may be possible to combine all of the crucial aspects of these reports into a single, or at most two reports instead of the three or more separate reports that are a central part of the current process. A simplified report structure benefits both decision makers and the public. Because of the lack of guidance given to all parties of the current process, reviewers are encouraged to act like a regulator instead of truly acting solely as reviewers.

It is clear that the current process for fission nuclear power and propulsion sources needs to be revised to consider the utilization of modern analytical tools and organizational structures. The Study Group makes the following recommendations:

1. OSTP should take a lead role in the reconsideration of the entire launch approval process for fission power and propulsion activities including the development of clear and specific safety standards and criteria. This reconsideration should be driven by a single operating principal: “What are you doing to improve safety?” It would establish specific criteria for expected safety levels and probabilities in the review process for applications. Furthermore, it would aim to institute specifically established technical safety standards to be met by mission developers instead of using ad hoc or internally derived criteria

safety criteria for each separate mission. If these safety criteria can be developed and recognized, then they would become accepted as the global standard for nuclear launch process risk.

2. OSTP should utilize the regular technical and engineering standards development process for these "Standards," and the Study Group recommends the utilization of already established mechanisms for their development, such as the nuclear standards already developed through the American Nuclear Society (ANS). This could evolve to an ANS Standard on Space Nuclear Launch Risk.
3. It would be desirable if OSTP could reduce the number of agencies and organizations involved in the process into three general categories of participants in the launch approval process. These three general categories would be known as the "Applicant," "Reviewer," and "Decision Maker/Regulator." It is possible that these last two could be embodied within the same agency or organization. These three separate roles would be independent of whether the launch is purely governmental, purely commercial or a combination of the two. It would be advantageous to designate a single government agency to own all of the independent review and approval processes and clearly act as the "Decision Maker/Regulator" in the process. Then the organization or agency designing the reactor would be considered as the "Applicant" and would be fully responsible for the safety case, own the SAR, and perform the safety analysis. If OSTP is to be the decision maker/regulator, it would be beneficial if they could provide direct oversight and direction to INSRP and institutionalize their current functions through changes to PD/NSC-25 while specifically identifying their role as a "Reviewer" in the process. This would eliminate the ad hoc/mission specific aspects of the review process and would establish clear boundaries for INSRP to focus on their "Reviewer" role. Additionally, OSTP should develop a "Standard Review Plan" for the launch approval process, similar to the plans developed years ago by the NRC to regulate other nuclear activities in the U.S.

It is clearly recognized that all organizational or launch approval process changes may require modification to the mechanisms established long ago to approve the launch of nuclear materials and systems into space. These include:

- PD/NSC-25
- National Space Policy
- Existing MOUs between Federal Agencies
- Internal Agency Procedures

The aim of these changes would be to take a holistic approach to the complete safety review process, with a goal for a straightforward decision to launch or not. The revised approach would include consideration of possible nuclear material reentry issues for both hot and cold systems, as well as inadvertent exposures and criticality.

9.0 Implications for RPS

RPSs and RHUs are currently required to be evaluated through the PD/NSC-25 launch approval process, as well as comply with the National Environmental Policy Act, NASA and Air Force safety standards, and radiological contingency planning with federal, state and local agencies. The RPSs and RHUs supplied by the DOE are highly engineered, extremely rugged devices that are designed to contain all radioactive material in the event of a launch accident. Despite the safety features built into RPSs and RHUs, the current PD/NSC-25 and National Space Policy require extensive, time consuming and resource intensive reviews prior to launch. The proposed changes discussed in this report hold the potential to reduce the amount of analyses required, while continuing to maintain safety and environmental protection.

DOE has considered several options for nuclear launches subsequent to Mars 2020. One option is to prepare a documented safety analysis (DSA), centered around the RPS or RHUs, using DOE published standards as guidelines or references. Once such a DSA is in place, it can be used to bound the conditions for launch in a technology and mission independent fashion. For example, the DSA could show that the RPS or RHU has a very low probability of releasing Pu^{238} under a given set of pressures, temperatures, and shock limits. If future missions do not result in conditions that exceed these established limits, then further analysis of the accident scenario, or any modification to the DSA, would be unnecessary. This approach would be consistent with the methodology outlined in this report.

A documented safety analysis for a nuclear-enabled mission is the primary means to demonstrate that this criterion is met, specifically with regards to showing the effectiveness of controls that reduce consequence and likelihood of an accident leading to a dose received by the maximally exposed individual (MEI). It must, as appropriate, account for the complexities and hazards associated with the nuclear technology employed in the mission and how they couple with accident conditions associated with launch vehicle and space vehicle mishaps through all phases of mission operations leading to effects on public health and safety. Missions utilizing nuclear technology similar to that in a previously approved documented safety analysis will undergo an evaluation to ensure that the safety basis (i.e., the documented safety analysis and implemented hazard controls) for previous similar missions remains applicable. For comparable nuclear-enabled missions, modifications to documented safety analyses should be limited to situations where:

- The probability of the occurrence or the consequences of an accident increase or the effectiveness of design features important to safety decrease in comparison to what was previously evaluated in the documented safety analysis;
- The possibility of an accident or malfunction of a different type than any evaluated previously in the documented safety analysis could be created;
- A margin of safety could be reduced; or
- The documented safety analysis may not be bounding or may be otherwise inadequate.

While the criterion above is independent of nuclear technology, it is worthy to note the differences between radioisotope and fission-based power/heat sources with regard to how the source term leading to a dose to the MEI is analyzed. For radioisotope systems, the amount of releasable radioactive material is determined by its material characteristics, how it interacts in an energetic accident environment, and how any respirable radioactive material is transported from the accident site to the MEI location. Thus, the primary mechanism for the MEI to receive harmful doses of significance is by exposure to a passing cloud of radioactive material and ingesting the material via respiration. Safety analysis would, therefore, consider the release fraction of material in an energetic accident, the transport of the respirable component of the released material to the MEI, and the radiobiological effect of material deposited in the lungs of the MEI.

Applying this criterion will lead to identifying design features that serve as controls to prevent and mitigate radiation exposure of the public and environment. For radioisotope systems, the controls evolve from the protective materials surrounding the heat source plutonium and the ability of these materials to limit the damage and release of plutonium under accident conditions.

Employing this type of analysis for the future could enable new classes of missions that are not considered feasible under the current review procedures. For example, small spacecraft and cubesats (very small spacecraft) have been proposed that would use RHUs for thermal management and potentially for small amounts of power generation. The current review regime, and the resources it requires, provides a strong disincentive for such missions. In fact, mission planners have often ruled out the use of RHUs in their concept developments because of these hurdles. Streamlining the review and approval process could reveal new, novel missions and enable the science they would produce, while maintaining the appropriate safety controls.

10.0 Summary of Conclusions and Recommendations

The conclusions and recommendations presented here are extensions of those presented previously in other studies. This report attempts to add specificity to the actions that need to be taken in order to move forward with successful space fission reactor programs. Without action to address the perceived and real problems in the launch approval process, designers and mission managers will be reluctant to commit the resources necessary to make space fission reactors a reality.

Conclusion 1: Progress has been made in the launch approval process for RPS; however, more work is needed especially for fission reactors.

Recommendation 1: Continue to improve the launch approval process in a manner that complements activities in the RPS program.

Conclusion 2: Accidents involving cold reactors pose little risk without criticality.

Recommendation 2: Implement a graded approach that requires minimal effort for non-critical accidents.

Recommendation 3: Explicitly address criticality in design and safety criteria.

Conclusion 3: Reactor designers need clear design guidance and acceptance criteria.

Recommendation 4: Adopt a set of GDC for space fission reactors, such as presented in Section 5. These criteria should be reviewed by both the power and propulsion teams at NASA and examined relative to anticipated designs and missions. These GDCs provide a high-level framework for safety, while numerical risk criteria per recommendations 5 and 6 help determine when the implemented safety strategy is adequate.

Suggested GDCs might include:

- The reactor shall not be operated prior to space deployment, except for low-power testing on the ground, for which negligible radioactivity is produced.
- Inadvertent criticality shall be avoided for both normal conditions and credible accident conditions.
- The radiological risk and consequences on Earth's surface of a release from an accident shall be insignificant.
- The reactor shall not be operated below a "sufficiently high orbit" per UN Resolution 47/68.

- In-space disposal shall be limited to sufficiently high orbits or extra-terrestrial planetary surfaces where not precluded by planetary protection requirements.

Recommendation 5: Adopt a set of Safety Criteria for space fission reactors, such as presented in Section 6. These criteria should provide levels of safety commensurate with other U.S. government nuclear activities. Begin sample studies to develop the safety case for near-term designs.

Recommendation 6: It is recommended that a high-level, readily understandable safety criterion be adopted such that:

> ***The likelihood of a space reactor accident shall be very small, and even if it occurs, will pose little threat to the public.***

This criterion includes two parts, one associated with likelihood (or probability) of an inadvertent criticality, and one associated with health effects. The recommended likelihood criteria contain two parts considering both inadvertent criticality and unintended hot reentry following reactor operation:

> ***The conditional probability of an inadvertent criticality, given the occurrence of an accident, shall be no more than 1E-3.***
>
> ***The probability of an unintended hot reentry after reactor operation shall be less than 1E-4 over the life of the mission.***

The recommended health effects criterion is:

> ***For any credible space reactor accident, doses to members of the public shall remain less than 25 rem at 1 km from the reactor.***

For this criterion, *credible* is defined as having a probability that is greater than or equal to 1E-6. For launch and ascent, this means 1E-6 per launch, while for hot reentry this means 1E-6 over the mission life.

The Study Group considered the possibility that the criterion could take into account the magnitude of the criticality event. That is, only criticalities that could generate a threshold number of fissions, e.g., greater than 1E20 fissions would be counted. It can be argued that events generating fewer fissions than this threshold value are unlikely to result in significant public health effects away from the accident or crash site. However, it is important to note that even "small" criticalities may require extensive cleanup, cause hazards to adjacent personnel, and generate negative public perception. Therefore, even if the magnitude of the criticality event were to be included, any GDC should drive designers to aim for designs that are unlikely to become critical during an accident and include positive means to prevent inadvertent criticality.

Recommendation 7: Develop standards for acceptable methods and analyses to determine compliance with the adopted safety criteria.

Conclusion 4: Roles and Responsibilities are unclear and have evolved over time, leading to redundancy of efforts and uncertainty in achieving approval.

Recommendation 8: Continue to support efforts at OSTP to clarify and improve the launch approval process.

Recommendation 9: Develop clear roles for applicants, reviewers, and regulators.

Recommendation 10: Include independent technical review in the process, with clear guidance for the review process.

Recommendation 11: Develop a process that is consistent for government and commercial launches.

Recommendation 12: Utilize the regular technical and engineering standards development process for the development of safety and launch approval criteria.

Conclusion 5: Significant work will be required to implement a new launch approval process.

Recommendation 13: Begin now to identify and update the procedures and processes inside and outside of NASA that may require modification. This should include developing implementation guidance with examples for the GDCs and safety criteria.

Appendix A Study Group Members

Co-Chair – Allen Camp – Retired in 2013, following 35 years at Sandia and Los Alamos National Laboratories. Previous assignments included Manager of Nuclear Risk Management Programs and Chief of Staff for National Security Programs at Sandia, and Program Director for Space Systems at Los Alamos, including both NASA and national security space programs. For the American Nuclear Society, positions included Chair of the Risk-informed Standards Committee, Chair of the Nuclear Installation Safety Division, and member of the Standards Board. He has Bachelor's and Master's Degrees in Nuclear Engineering from Missouri University of Science & Technology, and a PhD in Engineering from the University of New Mexico.

Co-Chair – Andrew Klein – Is Professor Emeritus in the School of Nuclear Science and Engineering at Oregon State University (OSU). He has been a member of the faculty at Oregon State University since 1985. He is a Past President (2016-17) of the American Nuclear Society and serves as the Editor for the peer-reviewed archival journal *Nuclear Technology*. He has held positions as Department Head, Radiation Center Director, and Space Grant Director at OSU and Director of Educational Partnerships at Idaho National Laboratory. He currently is a member of the National Nuclear Accrediting Board for the Institute for Nuclear Power Operations and the Board of Directors for the Foundation for Nuclear Studies. Dr. Klein is registered as a Professional Engineer (Nuclear) in the State of Oregon.

Pete McCallum – Pete McCallum is the Program Control and Nuclear Launch Approval Manager for NASA's Radioisotope Power Systems (RPS) Program, located at the Glenn Research Center in Cleveland, OH, managing all business aspects of the RPS Program, as well as providing coordination of the various elements supporting nuclear launch approval. His past experience includes 8 years as the Chief of Glenn Research Center's Office of Environmental Programs, developing programs and oversight to ensure compliance with regulatory requirements of the Nuclear Regulatory Commission, the Occupational Safety and Health Administration, and the Environmental Protection Agency. Prior to that, he was the environmental compliance manager for BP Chemicals in Lima, OH and for Kennecott Utah Copper in Salt Lake City. He has a Bachelor's Degree in Chemical Engineering (University of Minnesota) and a Juris Doctorate (Cleveland State University, Cleveland Marshall College of Law).

Patrick McClure – Is the project lead for the Kilopower project at Los Alamos. He helped define the groundbreaking approach to reactor development for Kilopower and he was the regulatory lead for the project. Mr. McClure is a former line manager for the Nuclear System Design and Analysis Group. He has been at LANL for 24 years performing nuclear design for very small reactor systems and safety analysis for a variety of reactor concepts with an emphasis on severe nuclear accidents like Three Mile Island and Fukushima. Mr. McClure has a B.S. from the University of Oklahoma and a M.S. from the University of New Mexico.

Susan Voss – Nuclear engineer with over 36 years working in the field of space nuclear power, small modular reactors, and international safeguards and security. She began working on space nuclear power systems in 1981 when she completed a comprehensive review of the Systems for Nuclear Auxiliary Power Program and design reviews of the Rover/ Nuclear Engine for Rocket Vehicle Application Program. She worked as the nuclear subsystems systems engineering on the SP-100 at Los Alamos National Laboratory (LANL) and spent two years at Department of Energy Nuclear Energy supporting program management of the SP-100. She was the nuclear design and system engineering on the U.S./Russian Topaz flight team and a technical reviewer for DOE on the Timberwind nuclear rocket project. During her 24 years at LANL she received 5 Distinguished Performance Awards including individual and small and large team. Susan is the President of a nuclear consulting company, Global Nuclear Network Analysis, LLC.

Appendix B Exclusion of Cold Uranium Fuel from Approval Process

LAUNCHING A COLD REACTOR

A cold reactor is defined as a reactor that has not undergone fission. The notable exception would be zero power critical testing of a reactor prior to launch which produces a negligible amount of fission products and therefore is still considered a cold reactor. This example analysis is only for non-critical launch explosion and fire accidents. Reactor criticality accidents would require additional analysis.

A space reactor that has not undergone fission will have on the order of single curies to tens of curies in radioactive inventory depending on fuel loading and the potential presence of a neutron source. Almost all of this radioactivity will be from the U^{234} isotope that is carried along with U^{235} during enrichment. The U^{235} isotope provides most of the remaining radioactivity. Uranium is an alpha emitter and almost exclusively provides a dose to humans by inhalation. The amount of radioactivity in a space reactor is far below that of current radioisotope thermoelectric generators (RTGs) already being flow in space, which typically have about 60,000 curies of Pu^{238} in radioactive inventory.

Given the low inventories of radioactivity, a cold space reactor will not present a significant risk to the public if a launch accident were to occur. This is true even if the reactor is considered to completely dispersed during an accident. For RTGs, safety is assured by having a robust packaging to prevent or greatly mitigate release. For a space reactor, safety during launch is obtained by minimizing the hazard, in this case by using uranium instead of Pu^{238}.

To illustrate the point of low risk (or in this case very low dose), an example is presented for the Kilopower space reactor concept. In order to even have an offsite dose from an accident involving the Kilopower reactor, a portion of the fuel must be “aerosolized” during an accident and be transported offsite by atmospheric wind conditions. The two leading accidents capable of creating a large amount of aerosol would be a fire or an explosion. Other accidents, such as impact from a drop, may create an aerosol but the amount created would be trivial.

For the fire and explosion accidents there are competing factors. First, the size of the fire and size of the explosion are important in how they impact the nuclear material and how much becomes aerosolized. However, this effect is offset by the fact the that the explosion and fire both loft the plume and cause increased dispersion of the aerosol. For this example, the amount that becomes an aerosol was set to the maximum value while plume lofting varied.

The radioactive inventory for Kilopower was set to that for a 10-kWe reactor. The uranium content of U^{234} was set to the maximum allowable amount of 1% U^{234}, although actual material to date is about 0.7%.[58] Using the largest core and maximum of U^{234} the curie content of the reactor then is:

2.7 Ci of U^{234}

8.4E-2 Ci of U^{235}

8.5E-4 Ci of U^{238}

The uranium core may be accompanied by a neutron source that ensures that neutrons are available for the start-up of the reactor. The use of a neutron source has not been decided given the abundance of neutrons in space. The curie content of the source could vary from sub-curies to as much as 0.5 curies. For this example, the maximum curie content of 0.5 curies will be used.

Release fractions for the postulated accidents are based on the maximum values provided in DOE-HDBK-3010-94.[59] DOE-HDBK-3010 is the Department of Energy (DOE) standard for accidental releases for nuclear material at DOE sites. The values used are the maximum values for both explosion and fire involving uranium metal. Explosions on a launch pad would involve a large amount of fuel exploding and producing a large explosive force that could vary from 1000s of kgs TNT equivalent up to kiloton TNT equivalent (estimate of the Russian N1 rocket accident).[60] This force would cause a shock wave that would impact the reactor core in a violent manner with the most extreme case being the complete aerosolization of the reactor core. For this example, the experimental work performed for accidental implosions of nuclear material during weapons testing is used a surrogate. The data are for an implosion device imparting a shock wave into the nuclear material and causing all the material to be aerosolized. The material in the air forms an aerosol distribution that has approximately a 20% fraction that is less than 10 microns Aerodynamic Equivalent Diameter and can be inhaled. The remaining material is an aerosol but cannot be inhaled.

A large fire on the launch pad will most likely melt the reactor metal core and cause the metal to both oxidize and relocate simultaneously. The closest phenomena in DOE-HDNB-3010 is the spill and free fall of molten uranium which has an airborne release fraction times respirable fraction (Atmospheric Release Fraction (ARF) x Respirable Fraction (RF)) of 6E-3. To be conservative this value will be rounded up to 1.E-2.

The Nuclear Regulatory Commission and DOE both use the 95% percentile worst-case weather conditions when examining the potential dose from accidental releases of nuclear material. Based upon experience with these types of calculations, the 95% percentile weather conditions occur under very stable weather conditions with very low winds speeds. These are conditions that tend to not disperse the aerosols and therefore produce the maximum offsite dose. These weather conditions are best represented by an F weather stability and a wind speed of 1 m/s in the direction of the nearest population center or the closest distance to public access. A simple Gaussian plume dispersion model was used for this example.

The dose for a range of rocket explosions, a range of distances, with and without a neutron source are shown in Table B-1.

Table B-1. Dose at distance for rocket explosion accidents, entire core aerosolized.

Distance in km	Dose in Rem (Total Dose Effective Equivalent)					
	Core Only – No Neutron Source			Core plus Neutron Source		
	1000 lbs TNT	10,000 lbs TNT	50,000 lbs TNT	1000 lbs TNT	10,000 lbs TNT	50,000 lbs TNT
1	1.3E-3	4.3E-4	5.7E-5	4.0E-2	1.3E-2	5.8E-3
2	8.3E-4	2.9E-4	4.3E-5	2.5E-2	9.0E-3	4.2E-3
4	5.0E-4	1.9E-4	3.1E-5	1.5E-2	5.7E-3	2.8E-3
6	3.6E-4	1.4E-4	2.5E-5	1.1E-2	4.3E-3	2.1E-3
8	2.9E-4	1.1E-4	2.1E-5	8.8E-3	3.5E-3	1.8E-3
10	2.4E-4	9.8E-5	1.9E-5	7.5E-3	3.0E-3	1.5E-3
20	1.4E-4	5.9E-5	1.2E-5	4.4E-3	1.8E-3	9.5E-4
40	8.6E-5	3.8E-5	8.1E-6	2.6E-3	1.2E-3	6.3E-4
60	6.4E-5	3.0E-5	6.5E-6	2.0E-3	9.2E-4	5.0E-4
80	5.2E-5	2.6E-5	5.6E-6	1.6E-3	7.8E-4	4.3E-4

The results show that all of the doses are in the low 1 to 10s millirem range for a 50-year dose from inhalation along the plume centerline. 1 millirem is about the maximum for the reactor core with no source. Approximately 40 millirem is the maximum with the neutron source included. The neutron source could be packaged to survive most explosions, or it may not even be required.

As would be expected larger explosions loft the material higher, thereby lowering the dose. Given that all explosions are set to the maximum release this is not unexpected. In reality, small explosions would impact the material less.

The results from the fire and point source release are shown in Table B-2. The results show the typical pattern where the plume touches down at a distance one to several kilometers beyond the release point. The doses are largely in the low millirem range to sub-millirem range. Given that explosions did not produce high doses it is no surprise that fires, which have a much lower amount of release, did not produce doses any greater than a few millirem with the source included.

Table B-2. Dose at distance for rocket fire accidents and point source at 200 ft.

Distance in km	Dose in Rem (Total Dose Effective Equivalent)					
	Core Only – No Neutron Source			Core plus Neutron Source		
	Point Source @200 ft	1 MW fire	10 MW Fire	Point Source @200 ft	1 MW fire	10 MW Fire
1	3.4E-8	2.6E-5	2.5E-12	1.0E-6	7.9E-4	7.5E-11
2	2.0E-5	2.6E-4	3.7E-7	6.0E-4	7.9E-3	1.1E-5
4	8.2E-5	3.0E-4	1.1E-5	2.5E-3	9.2E-3	3.4E-4
6	9.0E-5	2.4E-4	2.0E-5	2.8E-3	7.2E-3	6.2E-4
8	8.5E-5	1.9E-4	2.4E-5	2.6E-3	5.9E-3	7.3E-4
10	7.8E-5	1.6E-4	2.5E-5	2.4E-3	4.9E-3	7.7E-4
20	4.9E-5	8.2E-5	2.1E-5	1.5E-3	2.5E-3	6.5E-4
40	2.7E-5	3.7E-5	1.5E-5	8.4E-4	1.1E-3	4.5E-4
60	1.8E-5	2.0E-5	1.1E-5	5.5E-4	6.3E-4	3.4E-4
80	1.3E-5	1.4E-5	8.9E-6	4.1E-4	4.2E-4	2.7E-4

The risk to the public from the dispersal of the reactor core either from explosion of fire would be very low. The probability of a fire or explosion given any launch is probably on the order of 3 to 4% per launch and bounded by something like 10%. This would be combined with the inherently low dose to the public. What this example shows is that for these types of accidents (explosions or fires), doses on the order of a few microrem to 10's of millirem would be the largest anticipated dose at a point location. The doses also include the dose contribution from the neutron source. If the neutron source were not included (say because it is packaged robustly), then the largest dose is on the order of a single millirem. This dose would be a 50-year dose that a person at this point would receive over a lifetime assuming no medical procedures (such as chelation). This means that the yearly dose to an individual would be in the tens of microrem per year.

In addition, this is the maximum dose at this point (i.e., the Maximally Exposed Individual). Other locations not on the centerline of the aerosol plume (down-wind dead center) will have doses that are one to several of orders of magnitude smaller. All these factors mean that actual public doses would be minimal, and the calculations are extremely conservative.

To put these doses in perspective, the dose for a typical New York City-to-Los Angeles trip in a commercial airplane exposes a person to about 2 to 5 millirem (mrem) less than half the dose received from a chest X-ray (10 mrem). The Environmental Protection Agency allows nuclear operations to provide 100 millirem to the public as a matter of routine operation. The background dose to the public is on the average about 200 to 300 millirem per year.[61] So, a Kilopower launch accident dose without criticality would be orders of magnitude below background radiation.

In summary, the dose to the public from an extremely conservative estimate of launch accidents involving Kilopower is minimal and below a level of concern. Even given the probability of a fire or explosion as being in the few percent range, the risk presented by reactor for material release is very low.

Based on this simple analysis for launching a cold reactor it is recommend that either: 1) these accidents be screened from further analysis based on low curie content of the fuel or 2) analyzed using simple analysis such as for this Kilopower example, with no other actions required for safety approval. Larger reactors, such as a 100-kW nuclear reactor for nuclear electric propulsion or a nuclear thermal rocket, will still have less than 100 Curies of radioactivity, so this type of analysis will still be valid.

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14. ABSTRACT
This study was chartered by NASA's Nuclear Power & Propulsion Technical Discipline Team to examine potential improvements to the nuclear safety and launch approval process. The study concurs with previous efforts that have identified excess duplication, complexity and uncertainty in the current approval process. With a focus on fission reactors, general design criteria and safety criteria are proposed that ensure public and environmental safety, while reducing the uncertainty and complexity in the review and approval process. Also, recommendations are made for changes in organizational responsibilities to clarify roles and reduce duplication.

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