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Executive Summary

Space nuclear power and propulsion—including radioisotope power systems (RPS) and fission power and propulsion systems (FPS)—enable the United States to conduct space missions in areas of the solar system where solar flux is too low or when sustained heating or high power generation is needed. However, in recent decades, the United States has flown fewer than two RPS missions every decade, and no fission reactor has been flown since 1965. High costs and schedule uncertainties associated with using RPS are potential deterrents for using such systems. Missions with RPS onboard are the only launches that require a complex launch certification and Presidential-level approval, typically given by the Director of the White House Office of Science and Technology Policy (OSTP). The launch approval process for RPS takes an average of 6.5 years. The cost is not well documented and varies from mission to mission. However, as is explained in the report, we estimate the launch approval process costs at least $32 million. Radiological contingency planning, which uses outputs from analyses conducted for the launch approval process, accounts for an additional $8.2 million, making the total launch approval process and related planning cost an estimated $40 million.

OSTP tasked the IDA Science and Technology Policy Institute (STPI) with reviewing the space nuclear launch approval process for RPS and proposing a potential process for fission power and propulsion systems (with a new fission reactor option on the horizon). The goals of this project were to examine the key statutory, regulatory, and policy basis for the current launch approval process, identify how the time and cost of the launch approval process breaks down, and analyze if and how the current system might be changed to allow for a safe, timely, and affordable launch approval process. We used a multi-modal data collection approach, including a literature review and interviews with nearly 60 subject matter experts. Additionally, STPI hosted a daylong workshop with government stakeholders to discuss strengths, challenges, and potential paths forward for the space nuclear launch process.

Current Launch Approval Process

Aspects of the launch approval process for space nuclear systems began as early as the 1950s. The review process as it exists today, however, was formalized in 1977 via the Presidential Directive/National Security Council Memorandum 25 (PD/NSC-25). Additionally, the 2010 National Space Policy (known as Presidential Policy Directive 4 or

PPD-4) formalized the role of the Department of Energy (DOE) in the safety review process.

Currently, the launch approval process for space nuclear systems is implemented in four components: 1) the National Aeronautics and Space Administration (NASA)-led National Environmental Policy Act (NEPA) process that results in an Environmental Impact Statement (EIS); 2) the DOE-led safety analysis that culminates in a final Safety Analysis Report (SAR); 3) the Interagency Nuclear Safety Review Panel (INSRP) review process that includes representatives from NASA, DOE, Department of Defense (DOD), Environmental Protection Agency (EPA), and Nuclear Regulatory Commission (NRC), which reviews the SAR and results in a Safety Evaluation Review (SER); and 4) OSTP's review of the SER and final decision for launch. Each of the four launch approval components vary in duration, though the NEPA review and the INSRP safety review tend to be the longest parts of the process. The NEPA review process is the only component of the launch approval process that is rooted in law, though NEPA does not explicitly reference space nuclear systems; all other directives are at the agency or interagency levels.

In principle, the same process that applies to RPS applies to FPS as well. However, no fission power systems have been launched in recent decades thus it is unclear how the system would be implemented to a future FPS.

Strengths and Weaknesses of the Current Launch Approval Process

One of the primary benefits of the current RPS launch approval process is its flexibility. This flexibility has allowed the reviewers to perform new analysis as lessons are learned with each launch. The current safety review process is thorough—it involves modeling many different launch failure and reentry scenarios. The risk analysis can lead to design changes in the launch vehicle, spacecraft, or mission architecture for improved safety of the current or future missions. INSRP is comprised of an interagency group of technically competent personnel who are not directly participating in the missions under review; they can therefore provide relevant expertise while still maintaining independence so as to accomplish an unbiased review. Lastly, involving OSTP in the process provides political top cover.

The core strength of the current process—namely its flexibility—is simultaneously a challenge. This flexibility can lead to uncertainty regarding whether sufficient analyses have been completed and what specifically is needed or required of each process. The threshold for triggering the launch approval process is low; all space nuclear systems used by the United States fall well above the threshold. A one-size-fits-all safety review process does not reflect the relative hazards of different space nuclear systems that have different quantities and different types of radioisotopes. There are no criteria for what needs to be included in the safety analyses; as a result, unbounded analyses are conducted until resources are exhausted and may not sufficiently leverage analyses produced for past missions. Analyses conducted during the safety approval process for a given mission are potentially duplicative. In particular, duplication between the EIS (NEPA review process) and SAR (DOE safety review) is the result of different data being available at different points in the review process; the EIS is conducted early in the mission design phase and uses preliminary data while the SAR is conducted later in the mission design and uses "updated" data. The most rigorous option for satisfying NEPA—the EIS—is pursued regardless of the type of nuclear system and regardless of how often that system has been flown in the past. There is little to no guidance for INSRP. Presidential approval is a functional formality, where OSTP has been given little time to review materials provided from safety analyses and has been expected to approve the launch without adding analytical value.

The result of this process is that launch approval is not only time-intensive—requiring years to approve previously-flown technologies—but also expensive, adding tens of millions of dollars to the cost of a mission. It is unclear if the time and expense necessarily lead to improved safety.

Options Moving Forward

We identified several options to address challenges identified in the current process (Table ES-1). Some of these options require updates to either PD/NSC-25 or National Space Policy 2010 or both. Others only require updates to agency-level policies and practices.

The physics and operation of fission reactors is fundamentally different from radioisotope systems. From the perspective of launch approval, these differences warrant a different launch approval process from RPS that adequately reflects the relative hazards of FPS. As a result, there are additional considerations for the safety approval process for fission systems. However, currently PD/NSC-25 and National Space Policy 2010 provide the same launch approval guidance for all space systems including those with the potential for criticality. Many of the changes recommended for RPS apply to fission systems; however, a clean-slate approach should be considered (Table ES-1).

Table ES-1. Options for Revising the RPS Launch Approval Process

Stage/Topic	Option	Challenge Addressed	RPS or FPS	EOP Documents Needing Revision	Agency Documents Needing Revision
Triggering Launch Review	Raise the threshold for triggering review through the following ways: increasing the quantity allowed; using a different metric for the threshold; basing threshold on risk rather than quantities of material	Systems that do not need a formal launch approval process go through a needlessly lengthy and expensive review	RPS	PD/NSC-25	NPR 8715.3D
	Redefine the threshold for fission material in PD/NSC-25	Currently all systems with potential for fission must go through approval process	FPS	PD/NSC-25	
NEPA Review	Change timing of NEPA review to later in process	EIS done too early so less useful	RPS	None	NASA NEPA Desk Guide
	Only conduct an EA for RHUs	EIS on a RHU is unnecessarily lengthy and expensive	RPS	None	14 CFR Part 1216.3 NPR 8580.1A
	Add radioactive and fission material to NASA routine payloads EA	New EIS for each mission is redundant	RPS and FPS	None	14 CFR Part 1216.3 NPR 8580.1A
DOE Review	Adopt a gap analysis when appropriate	An entirely new EIS, SAR, and SER for a mission that is identical to another is redundant	RPS	None	None
	Establish safety basis and risk threshold	An entirely new EIS, SAR, and SER for a mission that is identical to another is redundant	RPS and FPS	None	None
	Eliminate the SAR, move EIS to later in the process, and perform an EIS and SER	Reviews are duplicative	RPS and FPS	NSP 2010	NPR 8715.3D

Stage/Topic	Option	Challenge Addressed	RPS or FPS	EOP Documents Needing Revision	Agency Documents Needing Revision
INSRP Review (SER)	Eliminate the SER, only perform an EIS and SAR	Reviews are duplicative		NSP	NPR 8715.3D
	Increase communication between INSRP, mission owners, and analysis performers	Agencies do not know which comments to prioritize; no formal process for adjudicating disagreements between INSRP and stakeholder agencies	RPS and FPS	None	None
	Define roles and responsibilities of INSRP members, mission owners, and analysis performers	Confusion over roles and responsibilities	RPS and FPS	None	None
	Develop an adjudication process for INSRP comments	No process for adjudicating disagreements	RPS and FPS	None	None
	Constrain INSRP to a specified length of time and/or specified number of meetings	Staff time and resources expended on multiple meetings over several years	RPS and FPS	None	None
	Convert INSRP to a standing committee	Lack of continuity between missions	RPS and FPS	PD/NSC-25; NSP	NPR 8715.3D
	Dissolve INSRP entirely	INSRP review is duplicative	RPS and FPS	PD/NSC-25; NSP	NPR 8715.3D
	Discourage INSRP from requiring or performing additional analysis	INSRP analysis may be duplicative	RPS and FPS	None	None
	Eliminate the SER, only perform an EIS and SAR	Reviews are duplicative	RPS and FPS	NSP	NSP 8715.3D
OSTP Approval	Eliminate requirement for Presidential approval	Presidential approval inserts uncertainty in the process	RPS and FPS	PD/NSC-25; NSP	

Conclusion

Use of space nuclear power and propulsion systems is pivotal to U.S. leadership in space science and human exploration of space. It is important that the launch approval process uphold the safety of launch while maintaining the most efficient and streamlined process possible. Several options for change are presented to address challenges in the launch approval process. These options for change are neither mutually exclusive nor independent from one another. Additionally, different options have different levels of impact. While each is meant to address a challenge in the system, there will likely be varying levels of difficulty in implementing changes, depending on which option or options are selected (Table ES-2).

A core finding of our review is that the launch approval process for nuclear systems should reflect the different levels of relative hazards. For example, the review process for a mission that includes a RHU (which contains 2 g of Pu-238) should not be treated the same as a mission that contains a multi-mission radioisotope thermoelectric generator (MMRTG) that has over 3,000 g of Pu-238, as is currently done. Similarly, in the future, fission systems, which pose different relative hazards from radioisotope power systems, should undergo a different launch approval process. While safety is a priority, the current launch approval process involves analyses that are redundant and do not add value or increase safety. Additionally, analyses conducted for new missions using RPS are conducted with a zero-based approach. In other words, missions are analyzed as if previous RPS have never flown. Options identified in this report aim to address these challenges and inefficiencies while still prioritizing the safety of the mission.

Within the Executive Office of the President (EOP), PD/NSC-25 and National Space Policy 2010 could be modified to enact the higher impact options. Options to address our finding that the launch approval process should reflect relative hazards include: (1) raising the threshold for triggering the INSRP review process and Presidential approval; and (2) only conducting an environmental assessment (EA) for RHUs. A third option—establishing a safety basis and risk threshold—would allow for a more nuanced assessment to determine if there is a baseline acceptable level of risk from mission to mission.

The following options address the inherent duplication of the review processes: (1) adopt a gap analysis when appropriate; (2) perform only two of the reviews by either eliminating the SAR or the SER; and (3) discourage INSRP from requiring or performing additional analysis.

The last group of focus area options represent process improvements that would increase the efficiency of the current system. These options are to: (1) develop an adjudication process for INSRP comments; (2) define roles and responsibilities of INSRP members, mission owners, and analysis performers; (3) constrain INSRP to a specified length of time and/or specified number of meetings; and (4) perform the NEPA review later in the process.

Table ES-2. Effort-Impact Matrix

Level of Impact	**High**		• Adopt a gap analysis when appropriate • Eliminate the SAR, and perform an EIS and SER • Establish a safety basis and risk threshold • Raise the threshold for triggering INSRP review process and Presidential approval	• Conduct a one-time EA for radioactive material similar to NASA's routine payload EA • Dissolve INSRP • Eliminate requirement for Presidential approval
	Medium	• Develop an adjudication process for INSRP comments	• Change timing of NEPA review to later in approval process • Only conduct an EA for RHUs • Define roles and responsibilities of INSRP members, mission owners, and analysis performers • Discourage INSRP from requiring or performing additional analysis • Constrain INSRP to a specified length of time and/or specified number of meetings • Eliminate the SER, and perform an EIS and a SAR	• Convert INSRP to a standing committee Key: NEPA Review Process Safety Analysis Process Safety Review Process Presidential Approval Process
	Low	• Increase communication between INSRP, mission owners, and analysis performers		
		Low	**Medium**	**High**
	Level of Effort			

Several of the medium and high impact options involving low to medium effort would require EOP to modify PD/NSC-25 and National Space Policy 2010. Such options are updating and/or raising the threshold for triggering the INSRP review process and Presidential approval, and eliminating either the SAR or the SER.

The current operational framework for space nuclear systems applies to fission systems; however, functionally there is no launch approval process in place for fission systems because no such system has launched since 1965. The process for RPS launch approval is not appropriate to retrofit for space fission systems. A nuclear reactor at launch does not contain the levels of radioactivity a radioisotope system does, so fewer precautions are needed to contain the fuel. In rare configurations, the fission reactor can achieve criticality, though the potential for harmful radioisotope exposure to the general public is still less than that for RPS. Nonetheless, analyses and testing would be required for the first-time fission launch approval. Many of the options for consideration outlined for RPS apply for the fission launch approval as well: there still needs to be a well-defined trigger to initiate launch approval; precise risk thresholds that define when analyses are complete; and a scoped INSRP review process that does not exceed its evaluation authority.

Contents

1. Introduction

A. Motivation and Goals

Deep space missions require thermal and electric power to support in-space functions, such as onboard processing, remote data collection, propulsion, downlinking acquired data, and surface activities such as roving. To support these functions, most deep space or planetary science missions have used a combination of solar power, fuel cells, and radioisotope power systems (RPS). Future missions may involve more complex or long-term activities such as mining or in situ resource utilization (ISRU) on the Moon, or human exploration of Mars, and will require larger and more reliable sources of power than currently exist.

Recent pronouncements by the Executive Office of the President,[1] legislation such as the National Aeronautics and Space Administration (NASA) Authorization Act of 2017,[2] and hearings on Capitol Hill[3] have focused on the United States' continued leadership in the exploration of space. The availability of space nuclear systems may play an important role in sustaining this global leadership, as future lunar and deep space missions may benefit from having nuclear sources as a power or propulsion option.

In recent years, the demand for space nuclear systems has been relatively low—fewer than two RPS missions have flown every decade (and no fission reactor has been flown since 1965). There are some indications that mission architects are apprehensive to incorporate space nuclear power systems into their mission designs because of perceived costs and schedule risks. In particular, the launch approval process has been underscored as a potentially burdensome aspect of the process required to use a space nuclear system. According to some experts, mission planners would turn down a free RPS unit because of the high added program cost and schedule risks associated with the launch approval process, among other reasons.

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[1] Presidential Executive Order on Reviving the National Space Council, June 30, 2017.

[2] Public Law 115-10, National Aeronautics and Space Administration Transition Authorization Act of 2017.

[3] For example, "Planetary Flagship Missions: Mars Rover 2020 and Europa Clipper: Hearing before the Committee on Science, Space, and Technology, Subcommittee on Space," U.S. House of Representatives, 115th Congress, July 18, 2017.

B. Project Goals and Methodology

The goals of this study have been to examine the key statutory, regulatory, and policy basis for the current launch approval process, identify how the time and cost of the launch approval process breaks down, and analyze if and how the current system might be changed to allow for a safe, timely, and affordable launch approval process. Our research questions were:

1. What is the current launch approval process for space nuclear power and propulsion?
    a. What are the various steps of the launch approval process? How do they differ between RPS and fission systems?
    b. Who are the stakeholders in the process?
    c. How long does the process take?
    d. What is the cost of this process?
2. How has the launch approval process evolved over time?
    a. What was the origin of the process?
    b. What was the approval process for SNAP missions, including SNAP-10A?
    c. What was the approval process during the Apollo era?
    d. What was the cost of the process?
3. How does the launch approval process for space nuclear power and propulsion compare to other safety and certification processes? What is the certification process for terrestrial reactors, and naval nuclear reactors?
4. How does the launch approval process for space nuclear power and propulsion compare to launch approval for other systems and materials? How is risk for relative hazards assessed?
5. What, if any, challenges are there to the current launch approval process? What, if any, improvements can be made?
6. What can be changed and how?
    a. What types of documents dictate the process (e.g., policy, law)?
    b. What are the origins and original intent of the process?
    c. How can these types of policies, laws, etc. be changed?
    d. What are options for change? Who can make the changes and how? What are the implications for making these changes?

One goal of this study was to look at potential options for change. Importantly, it was taken as a given that any suggested change in the launch approval process would only be included if there were minimal effects on the overall safety of the space nuclear systems in question. Such considerations are weighed in the findings of the report.

Data collection included a literature review, and interviews with nearly 60 subject matter experts—8 from industry, 24 from government agencies, 20 from national laboratories and academia, and 4 from other arenas (see Appendix B for a list of interviewees). Additionally, STPI hosted a daylong workshop with a select number of government-only subject matter experts to collect information on areas of challenges and potential ways forward (STPI 2018).

As a part of the literature review, we reviewed the current statutory, regulatory, and policy basis for the launch approval process, including the Presidential Directive/National Security Council Memorandum 25 (PD/NSC-25), the National Space Policy 2010, agency-level regulations and directives, among others. We sought to understand the origins of current practices, their evolution, if any, and intent behind establishing each piece of the process.

Through the literature review, interviews, and the workshop, the STPI research team identified options for making the review process for nuclear power and propulsion systems more efficient, timely, and affordable while still maintaining confidence in safety. We looked at what laws, regulations, and practices would need to change in order to streamline the launch approval process. For RPS, we also looked at how the cost for the launch approval process breaks down and how long each step in the process has taken for the three past missions that have used RPS.

C. Organization of the Report

In Chapter 2, we begin with background on types of nuclear systems being used or in development for U.S. space missions. We provide context for the nuclear launch approval process and a discussion of its origins, followed by the key legislative and executive branch documents that guide it in Chapter 3. We also provide an overview of the current RPS launch approval process in Chapter 4. A discussion of the current timeline and costs associated with launch approval for RPS is included. On the use of fission, in Chapter 5, we outline the established procedure for launching the SNAP-10A reactor, along with inputs from studies conducted on what the processes could look like for launching future fission reactors.

We discuss our findings in Chapter 6, and outline a set of options to consider. To contextualize these considerations, we provide comparisons to and lessons learned from other review processes involving nuclear material. Case studies include NASA’s safety review process for launching other hazardous materials (e.g., hydrazine), and the safety review and licensing process for defense nuclear facilities, terrestrial civil nuclear power, and naval reactors (Appendix C).

Additionally, information on radiological contingency planning, key terms, and summaries of review processes for other sectors can be found in the appendix sections.

2. Background

In this chapter, we briefly describe nuclear power systems that are currently used or proposed to be used in space, as well as the need for launch safety approval.

A. Space Nuclear Power and Propulsion Systems

Nuclear systems can provide spacecraft with power (i.e., electrical power and heat generation) or in-space propulsion. This section provides an overview of the various types and uses for nuclear power and propulsion technologies, as well as a brief history of the use and development of nuclear systems for U.S. missions.

There are generally two nuclear power approaches that have been used in space: isotopic decay, and fission. Isotopic decay systems capture some fraction of the heat energy released from the natural breakdown of radioactive isotopes of certain elements. In the United States, plutonium-238 is the radioisotope of choice for this application. Fission systems capture the nuclear binding energy released by the fission of a large isotope, contained in a controlled reactor core. In the United States, highly enriched (uranium with greater than 20% U-235) or low enriched uranium (less than 20% U-235) have been the fuels examined for space fission systems. Different hazards and safety considerations are relevant to each power or propulsion system.

1. Radioisotope Power Systems

An RPS uses thermal energy generated from the natural decay of radioactive elements. There are two main variants of RPS: radioisotope thermoelectric generators (RTGs) that convert the heat energy from isotopic decay into electricity, and radioisotope heater units (RHUs) that provide heat directly to keep instruments and systems on a space mission working effectively in the extreme cold of the space environment.

Only certain radioactive fuel sources have the characteristics necessary for use in an RPS. These sources must be able to produce sufficient amounts of heat from their decay, have a relatively long half-life to ensure continuous energy production, and possess a large heat power-to-mass ratio (Jiang 2013). In the United States, plutonium-238 (Pu-238) is the radioisotope of choice for RPS. Pu-238 is generally considered an ideal isotope for RPS because of its relatively long half-life of 88 years, meaning that electricity produced by these systems decreases slowly and predictably, and provides several decades of functionality. Additionally, Pu-238's high heat density allows the heat sources to be quite compact. Finally, it decays primarily by alpha emission, so only a thin shielding is required for radiation protection (NASA and DOE n.d.). Maintaining an adequate U.S. supply of Pu-238, however, remains a perennial concern (GAO 2017). There is also neutron emission from Pu-238 for which shielding is needed.

Pu-238 and HS-PuO_2

Pu-238 is a radioactive isotope of plutonium that releases ionizing energy through alpha decay and neutrons via spontaneous fission. This type of plutonium is different from material used in weapons and cannot explode like a bomb, and can only present a significant health hazard if it breaks into very fine pieces or is vaporized and then inhaled or swallowed (NASA, "Safety of RPS").

To limit exposure to natural and manmade sources of ionizing energy, released by radioactive material, NRC regulations request that exposure is limited to a committed effective dose equivalent (CEDE) of 5 rems for workers in industries where exposure may occur. Based on NRC's annual limit on intake (ALI), inhalation of a small amount of the Pu-238 isotope, approximately 1 nanogram, would exceed the exposure limit of 5 rems.

A number of different RTG designs have been used in missions over the years (e.g., general purpose heat source RTG, multi-hundred Watt RTG) (Cataldo and Bennett 2011). Currently, the United States uses a variant of RTG known as a multi-mission radioisotope thermoelectric generator (MMRTG) that uses static thermoelectric conversion technology. Mars Science Lab (MSL) uses an MMRTG; another is slated to be used on the Mars 2020 rover. The MMRTG and its predecessors are best used in situations where continuous power is needed—on the order of hundreds of watts of electricity, or less in harsh conditions or conditions where solar power is otherwise infeasible to use. The MMRTG is referred to as "multi-mission" because it can be used both in vacuum (for in-space missions) and in atmosphere (for surface missions). An MMRTG contains 4.8 kg of heat-source plutonium dioxide (HS-PuO_2) and generates approximately 120 W_e at the beginning of life. RHUs use a smaller amount of Pu-238 than their RTG counterparts because the direct application of heat is far more efficient than conversion to electricity; each RHU contains 2 g of HS-PuO2 and produces about 1 W_{th}. RHUs provide a highly reliable and continuous source of heat, and like the MMRTG, have no moving parts.

RPS are built with numerous engineered safety mechanisms. For an MMRTG, the fuel itself—Pu-238—is pressed into ceramic pellets of its dioxide form that are mechanically and chemically stable and fire-resistant, which reduces the possibility of Pu-238 dispersion in the event of a launch or reentry accident (NASA n.d.-a). The ceramic form resists being dissolved in water and is otherwise relatively unreactive (NASA n.d.-a). Each pellet is encased in iridium, a strong, ductile metal, which is then encased in multiple layers of graphite and a graphite aeroshell for additional protection. These physical layers of protection are meant to contain the Pu-238 material if a launch or reentry accident occurs. In the event that the HS-PuO_2 were compromised and exposed, the pellet is designed to break into non-inhalable chunks. Furthermore, having each clad individually encapsulated decreases the chance of multiple pellets being affected in the event of an accident. The overall design is meant to survive a wide range of potential accidents including solid propellant liquid fuel fires, blasts (e.g., launch vehicle explosions), intense thermal effects (e.g., atmospheric reentry), water submersion, and impacts (NASA n.d.-b; McNutt and Ostdiek 2015).

RHUs also have engineered safety features. For example, RHUs are packaged as HS-PuO2 and encased in a clad of platinum-rhodium as a containment mechanism in the event of an accident. The RHU is also encapsulated by a graphite aeroshell and a graphite insulator for additional protection. Each pellet is individually encapsulated for the same reasons as they are for MMRTGs.

2. Fission Power Systems

A fission reactor produces heat through the neutron-induced splitting of a fissile nucleus—such as uranium-235 (U-235)—which causes a chain reaction through the splitting of additional nuclei. The kinetic energy of the fission fragments can then be converted to thermal energy that can be converted into electricity, either through thermocouples or by heating a fluid that drives a turbine that can produce electricity.

The United States has only launched one fission reactor to space, the SNAP-10A (although others, such as the SNAP-50, were designed and developed; a total of six prototype space nuclear reactors were tested between 1951 and 1973) (Voss 1984). Launched in April 1965, the SNAP-10A reactor weighed about 435 kg and used approximately 5.2 kg of uranium, enriched to 93 percent U-235 (Wahnschaffe et al. 1995). The reactor was placed in a 500 mile high orbit around Earth and once in orbit, the reactor began operating and produced more than 600We (DOE n.d.; Bennett 2006). After 43 days, however, due to a high voltage failure in the electrical system of the spacecraft, the reactor shut down (DOE n.d.).

While no reactor has been launched by the United States since SNAP-10A, NASA has led several power reactor development efforts. For example, in 1982, the SP-100 program was created to develop a 100 kWe reactor. Although hardware and electronics components were tested, the program was terminated by Congress in 1994 (Mason 2010).

After SNAP-10A, other space reactor programs have been funded, however no reactor technologies have since reached a flight test. Long technology development timelines, costs, and complications with new materials or processes have been cited as rationales for the limited success to date (NASA 2018).

Today, NASA Glenn Research Center and the Department of Energy’s (DOE) National Nuclear Security Administration (NNSA) are investing in a nuclear fission technology demonstration project, Kilopower (Figure 1). The fission reactor concept would use approximately 30 kg of highly enriched U-235 as fuel for a 1 kW$_e$ (4 kW$_{th}$) system; the reactor concept would incorporate passive sodium heat pipes and Stirling converters for heat conversion. Designs currently in development could be capable of providing 500 W$_e$ to 10 kW$_e$ of energy; as a set of modular units, multiple Kilopower reactors could be used to meet the 40 kW$_e$ estimated necessary to support a human outpost on Mars or the Moon (NASA 2018a).

Testing is currently underway at NASA for early designs of the Kilopower reactor. Building upon previous work, such as proof-of-concept tests completed in 2012, the Kilopower Reactor Using Stirling Technology test completed an on-ground full power test over a 2-day period in March 2018. The test included steady state and transient operations of the reactor and Stirling engines, meeting all test objectives with results that are consistent with pre-test predictions. The test sought to validate models; operate the reactor in flight-like conditions; and demonstrate start-up and steady state performance during a full-power run of the reactor core (NASA 2018).

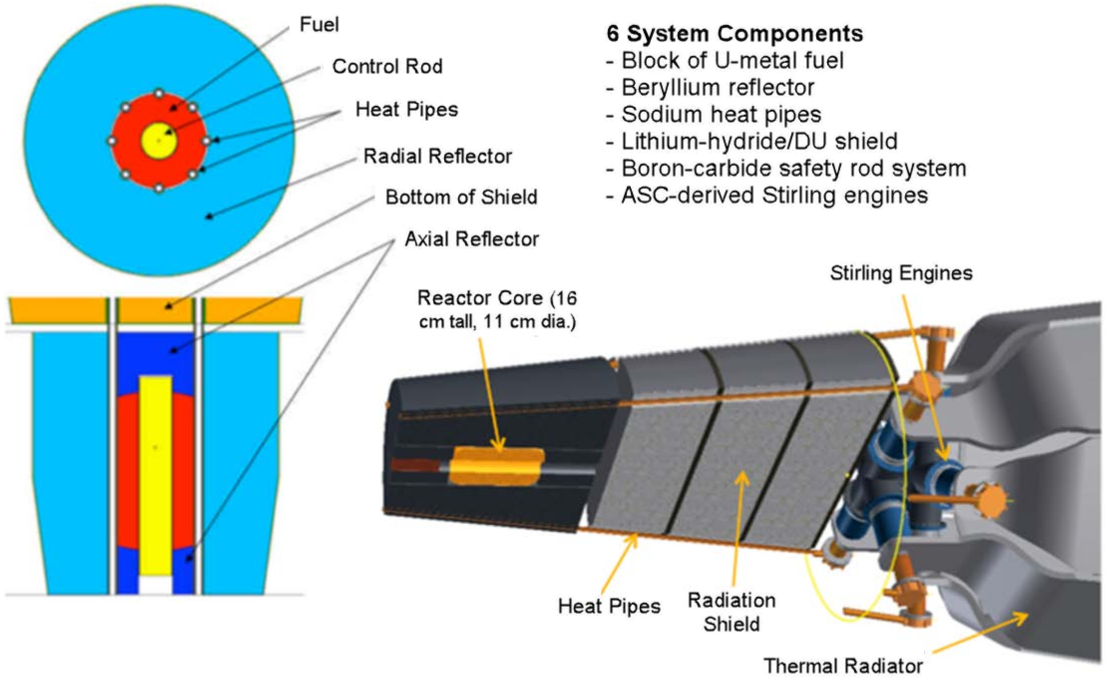
Uranium-235 and plutonium-238 are radioactive materials that release energy either through fission of nuclei or alpha decay. The amount of energy released by these materials varies by nearly seven orders of magnitude. Therefore the amount of energy, released from radioactive decay, contained in one MMRTG (3.3 kg of Pu-238 isotope in the 4.8 kg of HS-PuO$_2$)[a] is roughly equivalent to the energy contained in approximately 26 million kg of U-235.[b]

The average amount of radiation individuals in U.S. receive from natural and human sources (e.g., medical X-rays) is approximately 0.36 rem per year.[c]

[a] NASA, “Final Environmental Impact Statement for the Mars Science Laboratory Mission,” November 2006, table 2-4.

[b] NRC, 10 CFR Part 71 Appendix A, August 29, 2017, https://www.nrc.gov/reading-rm/doc-collections/cfr/part071/part071-appa.html.

[c] NASA, “Final Environmental Impact Statement for the Mars Science Laboratory Mission,” November 2006, table 3-5.



Source: P. McClure, D. Poston, D. Dixon, M. Gibson, L. Mason, "The Kilopower Reactor as a Starting Point for Moving Space Nuclear Power Forward" White Paper, Undated.

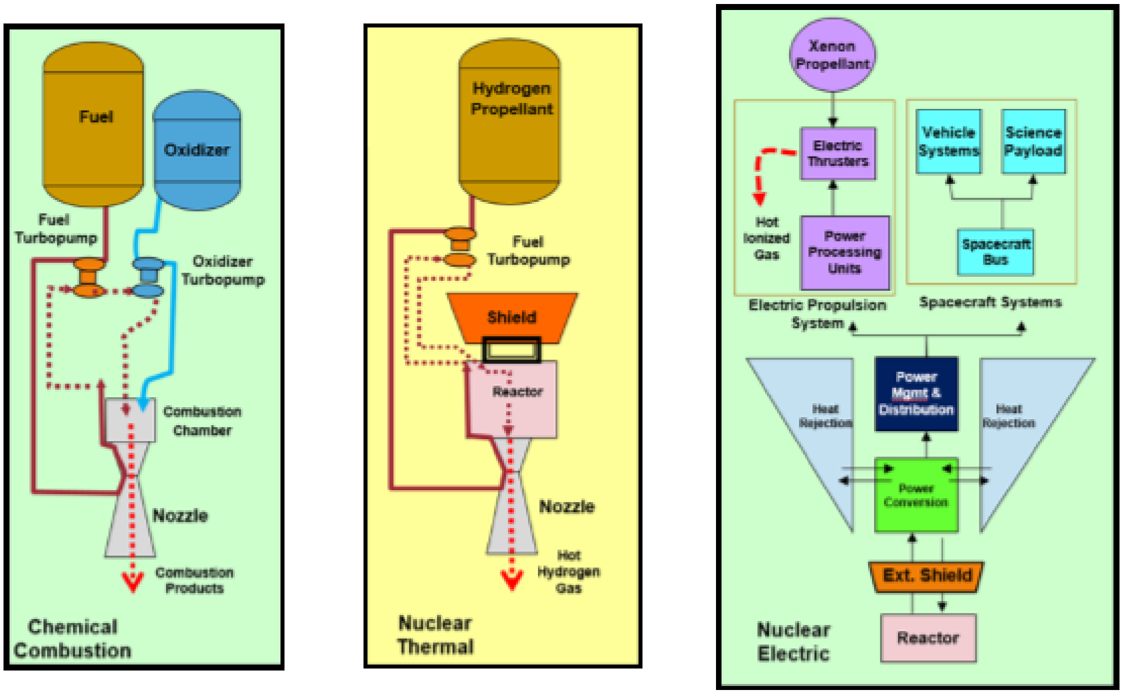
Figure 1. Kilopower Reactor Concept Overview

3. Fission Propulsion

Fission systems capable of generating power at the megawatt (MW) levels enable nuclear propulsion. There are two primary types of nuclear power propulsion systems: nuclear thermal propulsion (NTP) systems, and nuclear electric propulsion (NEP) systems. Figure 2 provides a high-level comparison between typical chemical (combustion) propulsion, NTP, and NEP systems.

In NTP systems, the nuclear reactor is used to directly heat propellant, typically hydrogen, to high temperatures before it is expelled through a conventional nozzle. The specific impulse of these rocket engines, calculated as the thrust divided by the rate at which fuel weight is consumed, can be more than twice that achievable with the best chemical rockets.

Alternatively in NEP systems, the thermal energy from the reactor is converted to electrical energy, which in turn powers an electric engine. There are a variety of technologies the reactor could be coupled to, including arcjets, magnetoplasmadynamic thrusters, ion thrusters, Hall thrusters, and microwave thrusters.



Source: Roger Myers and Russell Joyner, "Space Nuclear Systems: Opportunities and Challenges" (Aerojet Rocketdyne, November 12 2015).

Figure 2. Comparing Standard Chemical, NTP, and NEP Systems

Reactors capable of producing the amount of power necessary for propulsion must be engineered so that the energy conversion and thermal management systems ensure successful operation throughout the long mission durations. NEP systems provide much higher specific impulse but lower thrust than NTP systems, and are especially promising for in-space propulsion.[4] Additionally, NEP systems could use their reactors to provide power for the various other spacecraft needs besides propulsion (e.g., payload power, thermal management, data relay, guidance, navigation, and control).

DOE and NASA have supported research to develop nuclear propulsion technologies. As part of the Rover/NERVA program that ran through 1972, the United States designed, built, and tested 20 NTP engines on the ground; however, no such systems have ever flown, and nuclear engine testing stopped in 1972 (Houts 2015). There have been more recent plans for NEP; for example, in 2003, the Jupiter Icy Moons Orbiter program was created (and terminated shortly thereafter in 2005) to research and develop technologies for a 200 kW_e power NEP system.

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[4] Initial designs for an NTP system would have a specific impulse of 83–100 sec at 2300–3100 K. Though no specific NEP system is actively being developed, proposed designs could reach a specific impulse of 5000 sec. More at: Melissa L. McGuire, Michael C. Martini, Thomas W. Packard, John E. Weglian, and James H. Gilland, "Use of High-Power Brayton Nuclear Electric Propulsion (NEP) for a 2033 Mars Round-Trip Mission," *AIP Conference Proceedings*, vol. 813, no. 1, pp. 222–229, 2006.

In the 2018 budget, $75 million was appropriated for NASA to work on its NTP activities (Smith 2018). In 2017, NASA’s Marshall Space Flight Center contracted with Aerojet Rocketdyne and BWXT Nuclear Energy Inc. to develop a high-assay low-enriched uranium nuclear thermal reactor that could be used for a nuclear thermal rocket (NASA 2017). Initial designs estimate an NTP system would require approximately 500 kg of ~19.75 percent low enriched uranium (LEU); the fuel would be sourced, initially, from either DOE or international sources. Significant amounts of research and development are still necessary to develop the fuel forms and associated thermal controls and shielding that would remain reliable at high temperatures to ensure safe operations.

B. Need for Launch Safety Analysis and Approval

Despite rigorous work to integrate safety features into nuclear systems and to conduct the extensive safety review, there is always a risk of a launch or reentry failure, as discussed in Mission Failures with Space Nuclear Systems. A launch approval process assesses this risk to ensure that it is as low as reasonably achievable.

During the launch approval process for nuclear systems, the risk of launch or reentry failure, among other accident scenarios, is typically analyzed and modeled through computer simulations complemented by ground testing. Potential exposure to radioactive material as a result of such accident scenarios is estimated through multiple risk analyses methodologies. Because of the potential adverse effects of radioisotope exposure, understanding the risk of radiological dispersion over populated areas is important for decision makers to understand in order to approve the launch. The process by which missions with nuclear systems are approved for launch is unique to nuclear material; in other words, other hazardous materials on payloads do not undergo the same rigorous process, and there is no relative hazards assessment in the nuclear launch approval process. The remainder of this report documents the launch approval process, examines its strengths and weaknesses, and provides options for improving the current system.

3. Origin and Evolution of the Nuclear Launch Approval Process

This chapter presents a review of the origin and evolution of the launch approval process for space nuclear systems. It also provides an overview of the key documents that guide launch approval. Such documents include legislation from the U.S. Congress, documentation from the Executive Office of the President (EOP), and agency-level regulations and directives, among others.

A. Origin of the Nuclear Launch Approval Process

With the development of the SNAP program, starting in 1955, the need for a safety review process led to the formation of the Aerospace Nuclear Safety Program. Based on interactions among the Atomic Energy Commission (AEC), the Air Force, NASA, Sandia National Laboratory, Atomics International (AEC contractor), and other Federal agencies, a safety plan was developed in the early 1960s and implemented through the Aerospace Nuclear Safety Program. Risk analyses were conducted, under contract with AEC, by Atomics International, and experiments were conducted at Sandia and Phillips Petroleum (Voss 1984).

In 1961, due to the international policy implications of launching nuclear material into space (Bennett 1995) and ahead of the first RTG launch, McGeorge Bundy, President Kennedy's National Security Advisor, issued National Security Action Memorandum No. 50 (NSAM 50), which informed NASA that the "President desires to reserve to himself all first official announcements covering the launching into space of systems involving nuclear power in any form" (Bundy 1961). The White House thus became directly involved in the nuclear launch approval process, though only as the formal announcer of the launch. NSAM 50 was revised April 10, 1965 (Appendix E).

After the first NSAM 50 was issued, the respective heads of NASA, the Department of Defense (DOD), and the AEC (now DOE) discussed what the launch approval process for space nuclear systems should be. This correspondence indicates that an interagency review process was desired for space nuclear systems in the early 1960s. The Deputy Secretary of Defense, Roswell Gilpatric, indicated in a memo to the NASA Administrator, James Webb, that "…such an interagency group [should] be purely advisory and without limiting the operational and management responsibilities of the respective agencies."[5] In

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[5] Correspondence of Mr. Gilpatric to Mr. Webb, June 18, 1963.

1970, the National Aeronautics and Space Council (NASC), a precursor of today's National Space Council, required that they be able to review the safety analysis report (SAR) of a space nuclear system after its preparation. NASC made this request for any nuclear system above a certain amount of radioactive material per regulations from the International Atomic Energy Agency (IAEA) (IAEA 2018). At the time, such regulations were defined by amount of radioactivity in the material, as measured in Curies (Ci).

In 1963, NSAM-235, also issued by President Kennedy's administration, outlined policy guidelines for "large-scale scientific or technological experiments that might have significant or protracted effects on the physical or biological environment" (The White House 1963). All experiments, likely inclusive of space science missions, were required to provide an evaluation to the Special Assistant for Science and Technology outlining the importance of the experiment and potential effects associated with it. Public information on these experiments was to be disseminated, and if "significant or protracted adverse effects" were expected, Presidential approval would be required.

During the Carter Administration, NSAM 50 and 235 were both rescinded and supplanted by PD/NSC-25 in 1977. PD/NSC-25 laid out a more detailed procedure for the required review process prior to nuclear space launches (Appendix F). Key elements of the process were the requirement for an environmental impact statement or a nuclear safety evaluation report for missions containing nuclear material, and a threshold above which Presidential approval and review by an ad hoc interagency nuclear safety review panel would be required.

Additional guiding documents include the National Space Policy from the Executive Office, and agency-level policies and regulations, though PD/NSC-25 is still the governing policy document for the launch approval process. More detail on the various laws, regulations, and policy dictating the review process is presented in section B.

B. Key Documents Guiding the Nuclear Launch Approval Process

Documents guiding the nuclear launch approval process come from multiple sources including EOP, legislation, agency-level policies and interagency agreements, and international agreements to which the United States is a signatory. Table 1 summarizes the guidance from all key documents.

Table 1. Summary of Documents Relating to the Launch Approval Process

Document	Source	Guidance Relevant to the Nuclear Launch Approval Process
National Environmental Policy Act (NEPA)	Congress	Requires Federal agencies to conduct an evaluation of potential environmental impact for major actions. NEPA regulations encourage Federal agencies to consolidate environmental impact assessments for similar activities.
National Response Framework (NRF), National Incident Management System (NIMS)	FEMA	Pertains to radiological contingency planning and requires that a plan is in place in the event of an accident
Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space (Outer Space Treaty)	International Treaty	Establishes that the launching nation is liable for missions launched by its government or other non-government actors (e.g., repercussions of launch accidents)
PD/NSC-25	White House	Requires an environmental impact assessment or nuclear safety evaluation report (EIA or SER) for missions containing nuclear material. For missions with nuclear material above an identified threshold, an ad hoc INSRP is required to evaluate mission risks and final launch approval must come from OSTP or the President.
EO-12114	White House	Extends environment impact analyses conducted for NEPA to the “global commons” and other nations
National Space Policy	White House Office of Science and Technology Policy (OSTP)	Concurs with the Presidential approval and INSRP review requirements in the PD/NSC-25 (1996) for missions above the identified threshold. Requires DOE to conduct a nuclear safety analysis and assist DOT with licensing space transportation.

1. Executive Office of the President

a. Presidential Directive National Security Council 25 (PD/NSC-25)

PD/NSC-25 replaced both NSAM 235 (1963) and NSAM 50 (1965) to establish a process for scientific or technology experiments funded or licensed by the Federal Government that could have potential large-scale adverse effects. For these types of experiments, the sponsoring Federal agency has to develop a report for the Director of OSTP that evaluates the importance and potential environmental effects of the experiment. The Director then makes a recommendation to the President for approval in consultation with other relevant Federal stakeholders.

Though PD/NSC-25 pertains to all scientific and technology experiments with potential adverse effects, it establishes a separate and unique review process for spacecraft containing radioactive material that present a higher level of risk (e.g., material in quantities above a defined threshold). For such nuclear systems, the directive mandates an assessment of environmental effects or a nuclear safety evaluation, as appropriate. Since the terms are not defined, agencies have interpreted the environmental requirements as a formal Environmental Impact Statement (EIS).[6]

The directive also requires Presidential approval via OSTP for certain missions, such as those that contain a large amount of radioactive material. Presidential approval is routed through the Director of OSTP, who can approve the flight unless he considers it advisable to forward the matter to the President.

PD/NSC-25 also instructs an ad hoc Interagency Nuclear Safety Review Panel (INSRP) consisting of members from the DOD, DOE, NASA, and the Environmental Protection Agency "to evaluate the risks associated with the mission and prepare the Safety Evaluation Report" (SER) for missions requiring Presidential Approval. The Nuclear Regulatory Commission (NRC) participates as a technical advisor "as appropriate." Historically, since the establishment of PD/NSC-25, every radioisotope mission has empaneled an INSRP; future missions containing fission power or propulsion systems would also likely require an INSRP if they were to follow the current version of the PD/NSC-25. Note that INSRP, through the SER document, provides advice only to the White House; the directive does not give INSRP the authority to approve or certify any missions.

For missions above the specified threshold, the directive provides the President with final authority for launch approval. The directive specifies that "the head of the sponsoring agency will request the President's approval for the flight through the OSTP. The Director is authorized to render approval for such launches, unless he considers it advisable to forward the matter to the President for decision."

b. Presidential Policy Directive 4 (National Space Policy 2010)

In 2010, the White House released Presidential Policy Directive 4: National Space Policy (NSP) of the United States of America (referred to in this document henceforth as NSP) (The White House 2010). In the section "Space Nuclear Power," NSP asserts the President or a designee must approve any launches with nuclear power systems onboard that have "a potential for criticality or above a minimum threshold of radioactivity, in accordance with existing interagency review process," and that such systems much be

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[6] In one instance, for the Mars Pathfinder mission, an Environmental Assessment (EA) was conducted instead of an EIS. The distinction between an EIS and EA can be found in the National Environmental Policy Act of 1970 section of this report.

launched on a United States Government spacecraft (The White House 2010). Additionally, NSP requires a nuclear safety analysis provided through the Secretary of Energy and an evaluation of the analysis by the *ad hoc* Interagency Nuclear Safety Review Panel that is called to "evaluate the risk associated with launch and in-space operations" (The White House 2010). Furthermore, the NSP calls on the Secretary of Energy to:

1. (Assist the Secretary of Transportation in the licensing of space transportation activities involving spacecraft with nuclear power systems;
2. (Provide nuclear safety monitoring to ensure that operations in space are consistent with any safety evaluations performed; and
3. Maintain the capability and infrastructure to develop and furnish nuclear power systems for use in United States Government space systems (The White House 2010).

While NSP endorses the current process, it differs from PD/NSC-25 in the following ways. First, NSP explicitly calls for the Secretary of Energy to conduct a nuclear safety analysis (the SAR), whereas PD/NSC-25 makes no reference to this. Second, NSP requires INSRP to evaluate the risks but not does specify it must prepare a report (the SER), whereas PD/NSC-25 calls for one to be prepared.

2. Legislation

a. DOE and NASA Authorizing Statutes

The Atomic Energy Act of 1954 established the AEC to oversee nuclear weapons and civilian uses of nuclear materials. In the Energy Reorganization Act of 1974, these functions were divided into two: the precursor to the DOE, the Energy Research and Development Administration (ERDA), which oversees nuclear weapons, nuclear power promotion, and other energy-related work, and the NRC, which handles the regulatory aspects. The Department of Energy Organization Act of 1977 replaced ERDA with DOE and established it as a cabinet-level department. DOE retains the authority originally granted to the AEC to transfer, deliver, acquire, own, or process special nuclear materials, which include plutonium and enriched uranium.[7]

Signed by President Eisenhower, the National Aeronautics and Space Act of 1958 established NASA as the U.S. Government agency responsible for leading the Nation's exploration of space. Congress directed NASA to develop, construct, test, and operate aeronautical and space vehicles for research purposes.[8]

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[7] Atomic Energy Act of 1954 (PL 83-703), as amended.

[8] National Aeronautics and Space Act of 1958, as amended, Sec. 103 (Pub. L. No. 85-568)

b. The National Environmental Policy Act of 1970

The National Environmental Policy Act (NEPA) 42 U.S.C. §§ 4321-70, enacted in 1970, mandates that all Federal agencies, including NASA, must consider environmental impacts in all proposed Federal actions (NASA n.d.-c). All actions that are not considered an emergency or an exempt action per NEPA requirements go through a preliminary environmental evaluation to determine the action's level of potential environmental impact (NASA n.d.-c). Depending on the magnitude of potential environmental impact, there are three levels of process and documentation compliance:

> **Level 1: Categorical Exclusion (CatEx)** are activities that the agency considers "having no significant impacts on the human environment." A Record of Environmental consideration (REC) may be used.
>
> **Level 2: Environmental Assessment (EA)** is required when the agency proposes actions that could possibly lead to significant environmental impact or when the agency is unsure if the actions could lead to such impacts. If at the conclusion of the EA, significant impacts are determined, the agency provides a Notice of Intent in the Federal Register and an EIS is prepared. If no significant impacts are found, the agency provides a Finding of No Significant Impact (FONSI).
>
> **Level 3: Environmental Impact Statement (EIS)** documents actions the agency expects to have a significant environmental impact. An EIS fully describes the environmental impacts and array of alternatives considered and the public is given several opportunities to comment (NASA n.d.-c).

NASA has established agency-level implementation guidelines for NEPA. For additional information, see 3(a) of this chapter.

3. Agency Regulations and Policy

a. NASA NEPA Regulations and Policy

To facilitate compliance with NEPA, NASA has promulgated agency-level regulations and developed internal policy to meet NEPA requirements (NASA n.d.). Under Code of Federal Regulations (CFR) Part 1216, Subpart 1216.3 Procedures for Implementing the NEPA, actions normally requiring an EIS include:

(c) Development and operation of a space flight project/program which would launch and operate a nuclear reactor or radioisotope power systems and devices using a total quantity of radioactive material greater than the quantity for which the NASA Nuclear Flight Safety Assurance Manager may grant nuclear safety launch approval (i.e., a total quantity of radioactive material for which the A2 Mission Multiple is greater than 10.)[9]

The NASA CFR Part 1216 Subpart 1216.3 refers to the mission's A_2 value, which is the value listed in Table I of the International Atomic Energy Agency's Safety Series No. 6, *Regulations for the Safe Transport of Radioactive Materials*, 1985 Edition (as amended 1990). The sidebar explains the terms A_1 and A_2.

A_2 Values

The IAEA, as an international body, establishes safety and handling standards and regulations for nuclear material. In these standards and regulations, the A_2 value is defined as the activity value of radioactive material that is not in a special form—meaning radioactive material in an indispersible solid form or in a sealed capsule. Non-special form material has the potential to become airborne and inhaled in the event of an accident. A_1 values are the activity values for such special form radioactive material. Note that A_1 and A_2 values do not pertain to U-235 or other fissile material unless otherwise indicated.

For reference, the amount of Pu-238 in an MMRTG is 1.3×10^7 times the A_2 value and the amount of Pu-238 in a RHU is 6840 times the A_2 value.

Further, NASA Procedural Requirements (NPR) 8580.1A lays out NASA NEPA implementation procedures including definitions, roles and responsibilities, and timing. NPR 8580.1A indicates that responsibility for NEPA compliance for missions using RTGs or RHUs belongs to NASA Headquarters. Additionally, NPR 8580.1A instructs missions using RTGs or RHUs where the NEPA process cannot be completed during the formulation phase to prepare a request for the NEPA process schedule to be extended. The NASA NEPA Manager and Office of General Counsel are responsible for reviewing and approving extensions.[10] To date, this extension has not been exercised for missions with RTGs and RHUs.

b. Nuclear Safety for Launch

NPR 8715.3D NASA General Safety Program Requirements details NASA policy regarding safety.[11] Chapter 6, Nuclear Safety for Launching Radioactive Materials, describes the procedural requirements for "characterizing and reporting potential risks associated with a planned launch of radioactive materials into space."[12] It does not cover

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[9] 14 CFR § 1216.306 Actions normally requiring an EIS,

[10] NPR 8580.1A 2.1.3 (a) and (b)

[11] NPR 7120.5E "NASA Space Flight Program and Project Management Requirements" also applies to all NASA space flight programs and projects, but nuclear-specific policies and procedures are found in NPRS 8715.3D.

[12] NPR 8715.3D Chapter 6.1

ground processing or preparation of radioactive materials for space uses or radioactive exposure to workers at DOE sites that are covered by various DOE policy documents.

NPR 8715.3D outlines the different levels of review required depending on the amount of radioactive material associated with the mission. A summary of actions per NPR 8715.3D is provided in Table 2.

Table 2. Levels of Action by Amounts of Radioactive Material per NPR 8715.3D

Level of Radioactive Material (A_2) Multiple	Action
A_2 multiplier < 0.001	Letter of concurrence from the Nuclear Flight Safety Assurance Manager (NFSAM)
A_2 multiplier ≤ 0.001 < 10	Letter of concurrence from the NFSAM and notification of intent to launch to OSTP
10 ≤ A_2 multiplier < 500	Nuclear safety review; notification of intent to launch to OSTP; and Chief and Mission Assurance approval
500 ≤ A_2 multiplier < 1,000	Safety analysis summary (SAS); notification of intent to launch to OSTP; and Administrator approval
1,000 ≤ multiplier A_2	INSRP empanelment; safety analysis review (SAR) preparation; safety evaluation report (SER) facilitation; and EOP approval

For lower levels of radioactive material, NPR 8715.3D provides detail on required analysis. For example, for launches with A_2 mission multiples equal to or greater than 10 but less than 500, the nuclear safety review must include "an analysis of probabilities of launch and in-flight accidents which could result in the terrestrial release of radioactive materials (surface and air)," and "an estimate of the upper bound of health and environmental effects due to a radioactive material release." When Presidential approval is required, however (as is the case when an RTG is present), NPR 8715.3D simply outlines a general process and is silent regarding the scope and content of the necessary analysis. The policy states that the NASA Administrator shall empanel an INSRP, in accordance with PD/NSC-25, and appoint a NASA INSRP coordinator. NASA program executives, in consultation with the Nuclear Flight Safety Assurance Manager (NFSAM), the empaneled INSRP, the program, and the appropriate DOE offices, are responsible for developing the schedule for delivery of the nuclear safety analysis (e.g., SAR) and preparing or having a SAR prepared. Historically the NSFAM serves as the NASA INSRP Coordinator, and the program executive is the mission manager. The policy requires that the NASA INSRP Coordinator facilitate the preparation of an INSRP-developed SER of the radiological risk for the proposed nuclear mission as required by PD/NSC-25. Additional direction indicates:

> In cases where the DOE provides the radioactive material, the DOE programmatic SAR may be adopted to satisfy this requirement, in

> accordance with the interagency agreement(s) for specific missions. In cases where launch vehicles, configuration, and radioactive materials are similar, the program executive, in consultation with the NFSAM and the INSRP, is encouraged to use a comparative analysis based upon previous mission(s) safety analyses that bound the anticipated risk for the new mission.[13]

This direction is in contrast with the previous NPR 8715.3C (2008, updated in 2013) which indicated:

> The level of detail and content of the SAR will be commensurate with the mission radiological risk. In cases where the DOE provides the radioactive material, the DOE programmatic SAR may be adopted to satisfy this requirement, in accordance with the interagency agreement(s) for specific missions.[14]

c. DOE-NASA Memorandum of Understanding

The Memorandum of Understanding (MOU) between DOE and NASA concerning RPS for space missions details each agency's role and funding responsibility during "the research, technology development, design, production, delivery, space vehicle integration, and launch phases with respect to certain radioisotope power systems, including Radioisotope Thermoelectric Generators (RTGs) and Radioisotope Heater Units (RHUs)."[15] The memorandum was signed in 1991 and updated on October 31, 2016.

The MOU states that DOE shall provide a documented analysis of potential accidents and their associated risks with the help of NASA and any other agencies, if needed. The agreement requires DOE to specify, "in consultation with NASA, the minimum radiological, occupational/public health, safety procedures/criteria, and provid[e] guidance with respect to safeguards and security requirements related to NASA facilities and services associated with the radioisotope power systems."

Per the MOU, DOE and NASA must also share information pertaining to the safety analysis process. For example, DOE must share information required for NASA to complete documents required as a part of the mission definition and the environmental analysis. Additionally, NASA must provide DOE with technical data and technical support for safety tests and analyses needed for the nuclear launch safety approval process.

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[13] NPR 8715.3D 6.7.3.1 (d)

[14] NPR 8715.3C 6.3.7.1 (d)

[15] The NASA-DOE MOU is available at: https://www.energy.gov/sites/prod/files/2015/08/f25/MOU%20between%20DOE%20and%20NASA%20concerning%20RPSs%20for%20Space%20Missions.pdf

4. International Documents

a. The Outer Space Treaty

The 1967 United Nations (UN) Treaty on Principles Governing the Activities of States in the Space Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, popularly referred to as the "Outer Space Treaty" is considered the foundation of international space law. Articles 1–4 of the Outer Space Treaty call for peaceful uses of space that benefit and are in the interest of all nation states. The treaty encourages international cooperation, and indicates that no nation state may claim sovereignty over any part of space. With respect to nuclear payloads, Article 4 states that space missions orbiting the Earth may not contain any nuclear weapons.

Article 6 indicates that any nation state conducting a mission to outer space is responsible for the mission or responsible for any mission being conducted by a non-governmental entity in that nation state. Additionally, Article 7 indicates that any launching nation is internationally liable for that launch. The nation state conducting a mission in outer space remains responsible for any objects launched into space, landed objects, and all of the associated components. None of the articles in the Treaty has any specific guidance on how the launch of a nuclear system is to be approved.

b. UN General Assembly Resolution 47/68

UN Resolution 47/68, the Principles Relevant to the Use of Nuclear Power Sources in Outer Space,[16] a non-binding resolution adopted in December of 1992, provides high-level principles for the use of space nuclear power systems.[17] The resolution only applies to space nuclear electric power sources and does not specifically reference nuclear propulsion systems (Hertzfield 2008).

To ensure safe use of nuclear power systems, Resolution 47/68 outlines criteria for use in safety and risk assessments. The Resolution calls upon nations to perform safety assessments to reduce risks, specifically recommending the inclusion of a probabilistic risk assessment (PRA).[18] Additional recommendations include the use of design and construction to ensure sub-criticality during all possible launch events, use of highly

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[16] United Nations General Assembly Resolution 47/68 is available at: http://www.unoosa.org/oosa/en/ourwork/spacelaw/principles/nps-principles.html

[17] UN General Assembly resolutions are not listed as a source of international law by Article 38 of the Statute of the International Court of Justice, but can play a formative role in the development of international law. Straubel, Michael S. "Space Borne Nuclear Power Sources—The Status of Their Regulation." 20 Valparaiso University Law Review 2, 1986.

[18] See definition in Appendix A.

reliable systems to ensure disposal, and the use of system designs to ensure low probabilities of catastrophic events.

Furthermore, Resolution 47/68 contains recommendations on the types of nuclear activities permitted in space. First, fission reactors should only be allowed to reach criticality after reaching orbit or beyond. Further, reactors should operate on either interplanetary missions—at sufficiently high orbits, to ensure radioactive decay prior to reentry—or in low orbits if stored in sufficiently high orbits after operation. Finally, the Resolution indicates that reactors should only use highly enriched uranium (HEU) fuels. The rationale behind this stipulation is unclear. This exclusion of LEU from use in outer space potentially limits options for using different fuel forms and may limit reactor designs.

4. Current Launch Approval Process Implementation: RPS

The launch approval process as completed for past RPS missions involves four distinct review points: (1) the NEPA environmental review process, which results in an EIS; (2) the DOE safety process, which results in a SAR; (3) the interagency safety review process, which results in a SER; and (4) the White House launch approval decision (Figure 3). This chapter will examine how these four processes have been implemented by recent RPS missions. In addition to these four review points, radiological contingency planning (RCP) is completed to prepare response plans in the event of radioactive material release. RCP is discussed in Appendix D.

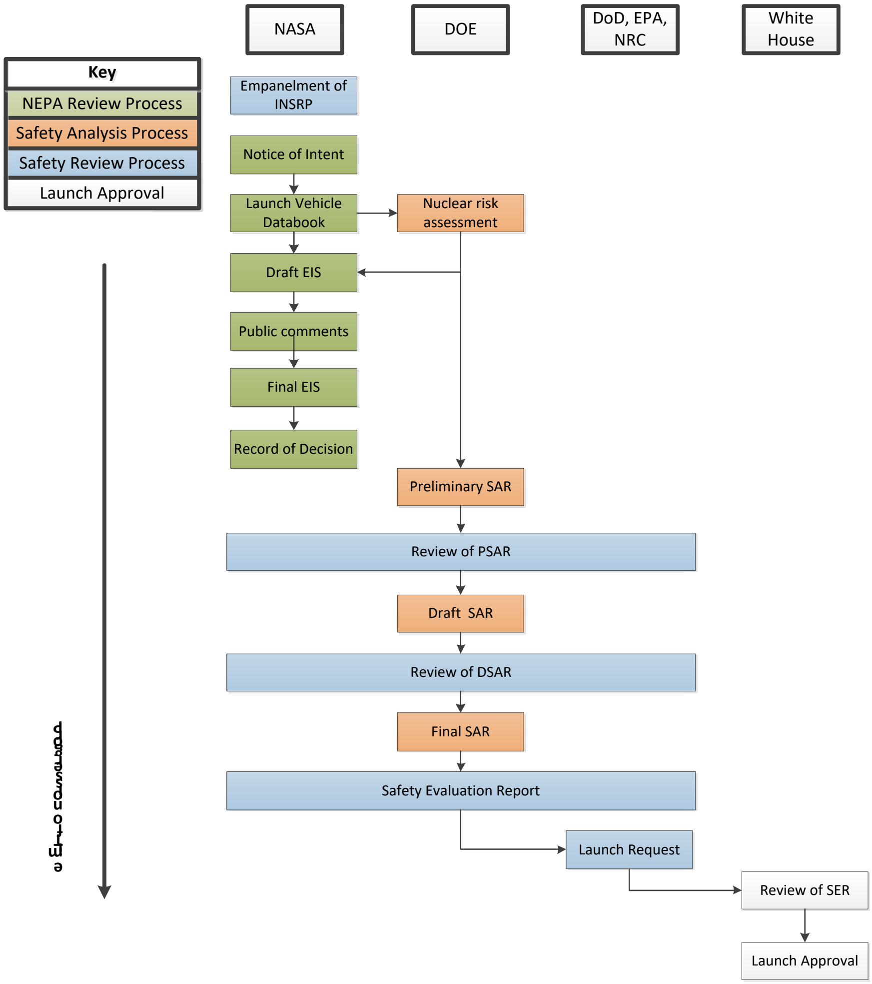

Figure 3. Overview of Nuclear Launch Safety Review

The nuclear launch approval process is initiated for all missions containing radioactive material that meet or exceed the threshold as defined in PD/NSC-25. Per this definition, all current RPS (e.g., MMRTGs, containing 4.8 kg of HS-PuO_2 and RHUs containing about 2 g of HS-PuO_2) must go through the same launch approval process.

The duration for the entire nuclear launch approval process varies mission to mission, but on average takes 6.5 years. The duration of each component of launch approval varies, but for the past five missions, the DOE safety review process has taken the longest (Figure 4).[19]

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[19] The length of the launch approval process varies based on considerations unique to each mission. For example, the Mars Exploration Rovers (Spirit and Opportunity) launched in 2003 did not have an RTG, but rather RHUs; all other missions shown had at least one RTG.

Source: Draft and Final EIS documents from each mission, NASA mission announcements, and Federal Register Notices

Note: The length of each process is defined by key mission milestones; for Mars 2020, dates are estimated based on interviews with subject matter experts. The time required for all pre-launch (inclusive of both approval and non-approval related activities), are represented by the green bar.

Figure 4. Review Process Duration for Past Four RTG Missions

A. The NEPA Process

In accordance with NEPA, the agency that is the mission agency (e.g., NASA) conducts a review of the environmental impacts of all missions, proposing to launch payloads containing nuclear material, prior to launch (NASA n.d.). The NEPA process begins with a review of the proposed mission, and a determination of the level of analyses required. NASA conducts a preliminary environmental evaluation (typically done by completing an environmental checklist) to determine the mission’s level of potential environmental impact (NASA n.d.-c). If a mission is not expected to have the potential for significant environmental impact, an EA is developed.[20] Otherwise, a more in-depth analysis is conducted and published in an EIS. Historically, every mission with an RTG and most missions with one or more RHUs have released an EIS (Norwood 2018). The 1994 launch of the Mars Pathfinder, where an EA was conducted, is the only exception (NASA 1994).

In earlier missions, environmental impacts associated with the nuclear material were cited from the SAR. However, after citizen-initiated lawsuits were filed against the EIS Record of Decision (ROD), modifications were made to the NEPA process.[21] Following these lawsuits, the NEPA process is completed early in an effort to avoid disturbances to the mission's development timeline that could result from similar litigation.[22] This has resulted in DOE conducting a Nuclear Risk Assessment (NRA) ahead of the SAR, which is considered by some to be a more notional risk assessment. To support an NRA, a Launch Vehicle Databook is first developed by the mission agency and the launch vehicle provider (e.g., United Launch Alliance). The Launch Vehicle Databook provides technical characteristics of the launch vehicle and launch site, configuration of the spacecraft, potential accident scenarios and their accident environments (e.g., explosion, fire, reentry, and impact), and the probability of various accident categories (Bechtel 2011). Based on the mission-specific information contained in the Databook, DOE develops an NRA in advance of a SAR. The NRA is used to provide risk analysis for the EIS before the launch vehicle is selected. Thus, analysis is completed for all the launch vehicles that may be selected for the mission, and is presented as an average. The NRA, sometimes referred as the NEPA Databook, is used as a foundation for the risk analyses contained in the EIS. Similar to DOE's SAR, the NRA assesses the probabilities of each accident scenario, the potential for a release of nuclear material (e.g., Pu-238) for each scenario, and the radiological consequences and risks in the case of a release (NASA n.d.-f). In addition to these analyses, the EIS document contains the following information:

1. Purpose and need for the mission: an overview of the mission, hazardous materials required, and rationale for the mission (e.g., science goals).

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[20] The guidance from CEQ requires agencies to review "reasonably foreseeable significant adverse impacts," which includes potential accidents, even if there is incomplete or unavailable information (Hill 2010). In other words, documents prepared under NEPA should inform the decision maker and the public about the chances that reasonably foreseeable accidents associated with proposed actions and alternatives could occur, and about their potential adverse consequences. The term "reasonably foreseeable" extends to events that may have catastrophic consequences, even if their probability of occurrence is low, provided that the analysis of the impacts is supported by credible scientific evidence, is not based on pure conjecture, and is within the rule of reason. [Council on Environmental Quality (CEQ) NEPA Regulations, 40 CFR 1502.22] (DOE 2002).

[21] Three NASA missions using RPS have been sued to date: Cassini, Ulysses, and Galileo.

[22] The information on the EIS is open for public comment prior to completion.

2. Description and comparison of alternative missions: an overview of alternative mission options (e.g., a mission with no nuclear material, or no mission at all), and an analysis and comparison of the risks associated with each option, such as differences in scientific goals that can be achieved by alternative options, if any.
3. Description of potential impact on the environment: an overview of the impacts on human health and the environment (e.g., launch site and global environment, cultural impacts of an accident and impact on human health) that are either possible or inevitable.

After a draft EIS is complete—often by a NASA contractor—the document undergoes a public comment period and revisions are incorporated into a final EIS document (NASA n.d.-f). Finally, a Record of Decision (ROD) is published by the mission agency (e.g., NASA), containing the decision on whether to proceed with the proposed mission.

The NEPA process takes 1 to 4 years and costs roughly $3–4 million, depending on the mission.[23] This cost is more than twice the cost for NASA to prepare an EIS for a mission not involving nuclear material and twice the cost of SMD's NEPA process.

B. The DOE Safety Analysis Process

In accordance with the NSP, DOE conducts a nuclear safety analysis that is reviewed by INSRP in accordance with PD/NSC-25, prior to launch. Historically, the safety review process conducted by DOE has coalesced into an iterative process where a preliminary draft and a final SAR document are developed and reviewed by the INSRP. Throughout the development of the safety analysis and review process, depending on mission and administration, OSTP has conducted regular meetings with INSRP coordinators (e.g., quarterly meetings held during the Ulysses mission between INSRP coordinators and OSTP). Historically, the SAR document had been developed by G.E. Aerospace (acquired in 1993 by Martin Marietta, later Lockheed Martin) under DOE contract for missions prior to and including the New Horizons mission, and by Sandia National Laboratories thereafter, starting with the Mars Science Laboratory (MSL) mission. The shift occurred in part to allow Lockheed Martin to propose missions and avoid a conflict of interest, as the former assessor of a mission's risk.

A Launch Vehicle Databook, similar to the one developed for the NEPA process, is used as an input into the SAR analyses. The two Databooks differ in that the SAR Databook may be revised as updates are made to the mission or launch vehicle. The content contained in the Launch Databook is used to develop simulations of scenarios where nuclear material would be released; several million trials are conducted to develop a probability distribution

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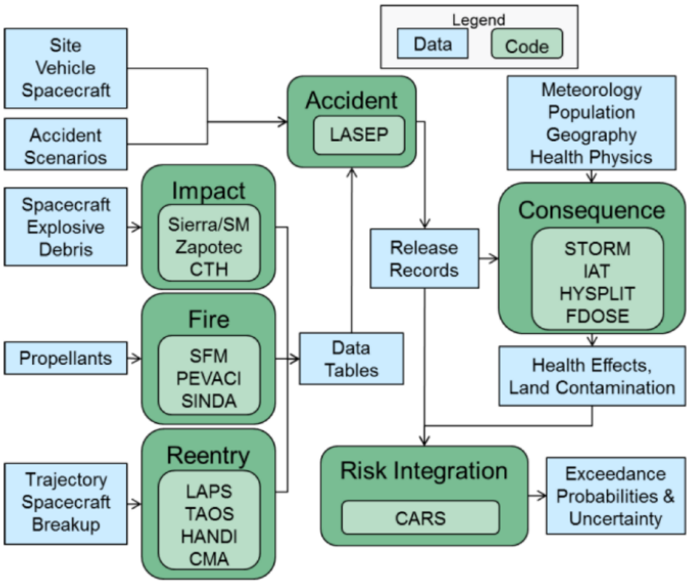
[23] Length estimated based on Federal Register notices published by NASA for past five missions. Cost estimated from conversations with NASA's RPS program office.

for possible scenarios. An overview of the codes used by Sandia for the MSL SAR is shown in Figure 5.

Codes used to understand potential pathways for material release and dispersion (i.e., impact, fire, and reentry) are fed into models to determine potential accident scenarios, their consequence (e.g., impact on human health and environment), and their likelihood. The results of these calculations provide the basis for the risk assessment contained in the SAR document.



Source: Clayton, James, Lipinski, and Bechtel 2015

Figure 5. Codes Used to Support Calculations Reported in the SAR

For missions through MSL, DOE has delivered three separate versions of the SAR to the INSRP for their review. The first document, the Preliminary SAR (PSAR), is released early in the development of a mission and contains an initial risk analysis based on a preliminary spacecraft design, launch vehicle, and prior missions. The document is completed early to ensure that recommendations for design changes can be addressed. The Draft SAR (DSAR) is released shortly after the design of the spacecraft is finalized; additional analyses are completed based on the newly available data for the mission (Lee 1994). Based on feedback incorporated from the INSRP and a final mission design and trajectory, the Final SAR (FSAR) is sent to the INSRP outlining DOE’s final risk assessment. The SAR process takes 1 to 6 years and costs roughly \$20 million, depending on the mission.[24]

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[24] Length estimated based on the publication date of the launch vehicle data book and the Final SAR for the past five missions. Cost estimated from conversations with NASA’s RPS program office.

C. Safety Review Process (INSRP)

The three SAR documents are reviewed by the ad hoc INSRP that is empaneled for each mission. The INSRP is composed of four coordinators from NASA, DOE, DOD, and EPA, and a technical adviser from NRC. Different agencies serve on INSRP to provide expertise and to add a level of independence to the safety review process. Additionally, each member of INSRP has a different role in the launch of space nuclear systems: DOE is in control of the radioactive material, NASA is in charge of the mission, DOD has control of the launch range, EPA would be involved in hazardous cleanup, and NRC has nuclear expertise. Some of the staff are from agencies represented by INSRP membership while others are contractors. The inclusion of each agency is intended to accomplish two goals: first to ensure that at least one INSRP coordinator has no vested interest in the outcome of the analyses, and second, to harness the unique technical expertise found at each agency. The coordinators historically have been supported by 5–6 working groups composed of 1–10 members; the working groups include both Federal employees and contractors. The INSRP reviews the Launch Vehicle Databook, PSAR, DSAR, and FSAR to conduct an independent assessment of safety and risks associated with the mission. The independent analyses and evaluation completed by INSRP are reported in the SER that is reviewed by the leadership of each of the four coordinating agencies.

The length and cost of the INSRP safety and review processes vary from mission to mission. The process can take 2 to 7 years to complete. We estimate the cost of INSRP to be at least $7 million. Of this, $1 million is from NASA and $6 million is from DOD. NRC and EPA appear to be reimbursed in full by NASA for any agency resources they use.[25]

D. The OSTP Role in the Launch Approval Process

The final step in the approval process for launching nuclear material is OSTP's launch approval decision, as required by PD/NSC-25. After the completion of the SER, the head of the agency sponsoring the mission requests approval to launch from the President, through OSTP. The request coincides with the delivery of the SER to OSTP. In the most recent four RPS missions, a launch decision was made shortly after the delivery of the SER (less than 1 year). Only the Director of OSTP or the President is authorized to render approval for a launch; the INSRP only provides recommendations, through the SER, and not a formal certification for any mission.

According to a Sandia report, the Director of OSTP signed off on the launch of the New Horizons mission with the following words:

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[25] Length estimated based on interagency correspondence empaneling INSRP and the publication date of the SER for past five missions. Cost estimated from conversations with NASA's RPS program office and expert interviews.

> Based on the information and analysis contained in the Department of Energy's final Safety Analysis Report and the Safety Evaluation Report completed by the Interagency Nuclear Safety Review Panel, as well as the contingency plans that you have in place, I concur with your recommendation and hereby approve your request for nuclear safety launch approval for New Horizons, consistent with Presidential Directive/National Security Council 25, as amended May 8, 1996 (Lipinski 2008).

To date there has never been a denial of approval to launch. The OSTP launch approval decision takes place up to 3 months in advance of the launch, though in some cases has taken place the same month as launch.

E. Updates to the Process

In the past year, there have been two proposed updates related to the upcoming Mars 2020 mission and future launches. In 2017, DOE issued a memo notifying stakeholder agencies that instead of a full analysis, a gap analysis for the SAR would be conducted for Mars 2020. There have also been discussions at NASA to change the radioactivity level (Ci) that triggers an EIS.

1. DOE's Gap Analysis for the Mars 2020 Safety Analysis Report

Given that the spacecraft and mission were similar to the 2011 MSL mission launched in 2011, DOE revised its nuclear safety analysis approach for the Mars 2020 mission to a gap analysis. That meant that rather than prepare a new SAR for the Mars 2020 mission, as in prior missions with RTG systems, DOE's nuclear energy office notified its laboratories to assess the differences (or gaps) between the MSL and the Mars 2020 missions. Specifically, "these differences, or gaps, will be analyzed for their safety significance and impacts consistent with existing Departmental processes and evaluated for inclusion in an appendix to the MSL Final SAR" (Bishop 2017).

DOE's nuclear energy office specifically called upon laboratory contractors to support the gap analysis in the following ways (Bishop 2017):

1. Identify experts to support the gap analysis, sourced from multiple laboratories.
2. Freeze computational code and model alterations, until a determination is made on what adjustments are necessary relative to the MSL Final SAR.
3. Identify the gaps that either were resolved or need to be resolved, as recognized previously by NASA and INSRP (to be completed by SNL).
4. Review NASA's expressed concerns on the safety of the iridium cladding used on the RTG systems (to be completed by INL).
5. Suspend ongoing experiments and tests, conducted for launch safety, pending review of their relevance and importance to the Mars 2020 mission.

As of this writing, the gap analysis for the Mars 2020 SAR is being conducted in accordance with existing DOE processes. The gap analysis, used to assess the risk of the Mars 2020 mission, is consistent with DOE's 3009 standard, which outlines a DOE method used to review the safety and risk of nonreactor nuclear facilities (DOE 2014). Consistent with the Department's policy, the gap analysis approach is technology dependent. In other words, if future missions have a mission design or use a different RPS, it would likely undergo a full SAR and not a gap analysis. While the similarities between MSL and Mars 2020 missions afford the latter the ability to do a gap analysis, it is unlikely that any planned or proposed missions in the near future would meet similar criteria unless they use the same RPS, the same launch vehicle, and the same launch trajectory.

In February of 2018, members of INSRP wrote a memo to DOE in response to the gap analysis announcement signed by all five INSRP coordinators (including NASA). The content of this memo and any possible resulting action is deliberative at the time of this writing.

F. Summary

The launch approval process can be broken down into five parts. Each is driven by congressional, Presidential, or agency level guidance. It is important to note that there is no congressional guidance except for NEPA that applies to all activities by all agencies. This has implications that will be discussed in Chapter 6. Table 3 provides a summary of the launch approval process and illustrates the length of the cost of the process and related activities (over $40 million).

Table 3. Launch approval process outputs, agency leads, guiding documents, duration, and cost

Process Name	Output	Lead Agency	Guiding Document(s)	Average Length (years) [a]	Estimated Cost (million USD)[b]
NEPA Review Process	EIS or EA	NASA	42 U.S.C. § 4321; 14 C.F.R. 1216; NPR 8580.1	1.92	$3.4
Safety Analysis Process	SAR	DOE	PD-NSC/25; NSP 2010; DOE/NASA MOU; NPR 8715.3D	2.75	$21.7
Safety Review Process	SER	NASA/ INSRP	PD-NSC/25; NSP 2010; NPR 8715.3D	3.92	$7[d]
EOP Review and Approval	Launch decision	OSTP	PD-NSC/25; NSP 2010	0.5	-

Process Name	Output	Lead Agency	Guiding Document(s)	Average Length (years) [a]	Estimated Cost (million USD)[b]
Launch Services [c]	Radiological contingency plan	NASA, DOD	NRF NIMS	3	$8.2
Entire Approval Process	**-**	**-**	**-**	**6.17[e]**	**$40.3**

[a] Average length of process is estimated for the last five missions launched.

[b] Costs are estimated for a mission similar to Mars Science Laboratory.

[c] Radiological contingency planning (RCP) constitutes one part of launch services planning requirements. RCP is separate from the EIS, SAR, and SER because RCP does not attempt to assess the level of risk associated with a launch. RCP is intertwined with the launch approval process though, as some RCP activities depend on results from the SAR, and RCP is often part of the final presentation to OSTP that informs the decision to launch.

[d] The $7 million estimation is a conservative estimate that does not include fees that DOE may be providing for INSRP to produce the SER. It also may not include any costs incurred to complete field testing recommended by INSRP.

[e] The total time for launch approval is less than the sum of its sub-processes, as some of those processes overlap and are conducted concurrently.

5. Current Launch Approval Process: Fission Systems

The last fission reactor approved for launch was the U.S. Navy SNAP-10A reactor—in 1965—prior to the enactment of PD/NSC-25 in 1977. Research programs such as the SP-100 program in the 1980s and interagency groups such as the Nuclear Safety Policy Working Group in the 1990s have developed recommendations for reactor designs and content to be included in launch safety analyses.

A. Safety Review Process for the SNAP-10A

The SNAP-10A reactor was the first and only U.S. fission reactor launched into space. The mission was reviewed and approved for launch through an interagency safety review process that predated both the PD/NSC-25 process and the environmental assessment approach developed to meet NEPA legislation. This process included what has been described as a "comprehensive" Aerospace Nuclear Safety Program, which evaluated nuclear hazards and developed safety designs (Voss 1984; Harty et al. 1984).[26] The safety program was developed with input from various agencies including the AEC and the Air Force, government laboratories such as Sandia National Laboratories, and contractors such as Atomic International. The following is a high-level overview of the safety review process undertaken for the launch of a SNAP device.

> Before a launch was permitted, AI had to provide proof that under all circumstances the launch of the reactor would not pose a serious threat. First they had to go before an AEC licensing board, which was the advisory committee on safeguards used for civilian nuclear plants. The safety committee had planned to adopt the same stringent safety review used for civilian purposes with the exception of the public review. All review was done in a closed meeting. Upon receiving approval of the safeguards board, they had to receive final approval by a joint committee of AF and AEC (Voss 1984).

For the SNAP program, a series of experimental data and theoretical models were used to evaluate the radiological safety of the SNAP reactors. Analyses were conducted to determine the following:

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[26] The Aerospace Nuclear Safety Program applied to the SNAP program, which included both radioisotope and fission systems.

> (1) the disintegration of reactors reentering the atmosphere; (2) the burnup of fuel elements reentering the atmosphere, including ablation and dispersal of particles; (3) reactor criticality conditions and the assurance of subcriticality in water; (4) the behavior of reactors in transient power operation; (5) the nuclear behavior of reactors on impact with the earth and in handling accidents; (6) the assurance of shutdown at the end of the power production lifetime; (7) risks by various exposure modes from different methods of reactor disposal; and (8) thermophysical properties of SNAP fuel materials (Otter et al. 1973).

B. Considerations for Fission Power and Propulsion Systems

As discussed in Chapter 2, the operation of fission reactors is fundamentally different from radioisotope systems. From the perspective of launch approval, these differences simultaneously obviate the need for some safety measures and introduce the need for others. Both are discussed in turn in the proceeding subsections.

1. Release of Radiological Material

Fission reactors (such as Kilopower or the SNAP-10A) are designed to be launched in a so-called “cold” state and only started when they have reached their desired orbit or location in space. In other words, radioactive fission products are created only after the reactor is started. Therefore, in the event of an accident, if all the uranium fuel in a cold reactor were released to the environment during launch or reentry, there would be minimal harm to human health. This is because U-235 has relatively low radioactive levels. Initial analyses indicate that the dose to humans, from dispersion of the HEU fuel and neutron source of a cold 10 kW reactor with 46 kg of HEU, would be at least an order of magnitude lower than the normal background radiation from other natural and human sources (Voss et al. 2017).

In contrast to U-235, Pu-238 immediately and continuously releases alpha particles the moment it is produced. As reference, at the time of launch, 3.5 kg of Pu-238 (the amount of Pu-238 in an MMRTG) releases about 60,000 Curies (Ci) of radioactivity; whereas 30 kg of HEU (the amount of fuel likely to be in a 1 kW level Kilopower) at the time of launch emits only about 3–4 Ci of activity, orders of magnitude less radioactive than Pu-238 (Voss et al. 2017). On a per kilogram basis, Pu-238 contains 300,000 times more radioactivity relative to U-235 as measured in Ci. Pu-238 is also 25 million times more toxic than U-235. As a result, an accident involving the release of uranium from a fission reactor holds less radiation risk to the public as compared with an accident involving the release of plutonium fuel from an RPS.

2. Potential for Criticality

A fission reactor could pose a higher radiation risk if the reactor is critical during launch or accident.[27] Criticality is not possible in radioisotope systems and is an issue only for fission systems. Potential scenarios where a reactor could go critical include accidental reentry in a particular configuration once a reactor has been turned on in orbit, or a launch accident that accidentally triggers the reactor to reach criticality. Once a reactor reaches criticality, various radioisotopes are produced. These products, with varying levels of radioactivity and lifetimes, affect time-dependent calculations for the transport and health impacts of an accident scenario for a critical fission reactor. Note that the daughter products of uranium in a critical fission system are different from those created in the decomposition of Pu-238 in RPS systems.

All criticality events do not necessarily yield a high risk of exposure to the public, since several factors may limit the radius and intensity of radiation exposure. For instance, if a reactor is submerged in water and goes critical, anyone more than a few feet away is likely safe from radiation due to the shielding effects of the surrounding water.[28] The timing of a reactor core's disassembly can also affect the rate at which a reactor goes critical and the level of criticality that it reaches. For instance, a more violent disassembly of the reactor core gives the fuel less time to produce fission products, which can limit public exposure.

3. Proliferation Risk of HEU Fuel

HEU poses a potential proliferation risk if material intended for use in a space mission were to be somehow redirected for weapon use. For reference, the nuclear bomb in Hiroshima had about 64 kg of 80 percent enriched uranium; the core of a 1 kW a Kilopower reactor would have approximately 30 kg of 93 percent enriched HEU.

Given the potential for proliferation, security associated with transporting and using HEU fuel requires higher cost and procedural burdens (by some estimates, $70 million just to guard it at the launch site). DOE is currently in charge of securing HEU fuel systems for terrestrial use, and more procedures may need to be developed to involve DOE in the use of fission reactors in space. In this report, our focus is on safety analyses and reviews, not the costs associated with the physical handling and security associated with nuclear fuels.

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[27] Criticality in a nuclear system is a state in which a self-sustaining chain reaction of uranium fissions can be achieved. This happens when the number of neutrons produced from fissions equals their loss through absorption or leakage, and can result in very high localized doses (which can also challenge recovery and clean-up processes).

[28] This case would likely pose a greater cleanup and recovery challenge than a radiation risk to the public. Costs for cleanup and radiation are usually prepared for in the radiological contingency planning process, which is discussed in Appendix D of this paper.

C. Recommendations of the Nuclear Safety Policy Working Group for Future Missions

The Space Exploration Initiative (SEI), announced in 1989, called for a return to the Moon and manned missions to Mars, and both nuclear thermal and nuclear electric propulsion were identified as potentially enabling technologies to support the objectives of the program (Bennett et al. 1991). In response to SEI, NASA hosted joint agency workshops with DOD and DOE in 1990, leading to the development of a joint agency Nuclear Safety Policy Working Group (NSPWG). The NSPWG was chartered to develop recommendations for high-level nuclear safety policy and safety requirements and guidelines for nuclear propulsion technologies (Marshall et al. 1991).

In 1993, the NSPWG published recommendations that are more generally applicable for future missions utilizing nuclear propulsion technologies. The NSPWG recommended the following safety policy:

> The fundamental program safety philosophy shall be to reduce risk to levels as low as reasonably achievable. In conjunction with this philosophy, stringent design and operational safety requirements shall be established and met for all program activities to ensure the protection of individuals and the environment. These requirements shall be based on applicable regulations, standards, and research (Marshall et al. 1993).

Specifically, the working group laid out a series of recommendations for guidelines to ensure the safe operations of nuclear propulsion systems. The safety guidelines covered the following topics related to launch safety (Marshall et al. 1993).

- Reactor Start-Up: reactors should not be operated prior to space deployment and should remain subcritical (not active) until planned orbit is achieved.
- Inadvertent Criticality: criticality should not be accidently achieved during either normal operations or under various credible accident environments.
- Radiological Release and Exposure for Routine Operations: in space, radiological releases shall have an insignificant impact on Earth, not impair the spacecraft, not contribute to significantly to the local space environment, and follow 29 CFR 1910.96 for on-board dose limits.[29]
- Radiological Release and Exposure in an Accident: The probability of a significant release of radiological material should either be insignificant to Earth relative to values defined for terrestrial nuclear activities, or be extremely low—defined as not expected to occur over the lifetime of the spacecraft.

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[29] 29 C.F.R. 1910.96 outlines the U.S. Occupational Safety and Health Administration’s (OSHA) standards for the total dose, per year, that workers can be exposed to from ionizing radiation.

- Disposal: safe disposal of spent nuclear fuels should be built into mission design and adequate cooling systems shall prevent disruption or degradation of a reactor during either normal or accident conditions.
- Reentry to Earth: a reactor should remain subcritical in an advertent entry and impact and should be designed to either remain intact or achieve full dispersal at a high altitude. The probability and consequences of an inadvertent entry should be as low as reasonably possible.

Recommendations from the NSPWG were incorporated into future missions that sought to develop and launch fission technologies. Programs include the Nuclear Electric Propulsion Space Test Program, which sought to demonstrate the Russian-built TOPAZ II reactor, and the Space Nuclear Thermal Propulsion program at NASA (Gray 1993). A full launch approval process, however, was not completed as neither program successfully launched a reactor to space.

D. Developing a Launch Approval Process for Future Fission Missions

Unlike recent RPS missions, where mission-specific safety analyses build upon those conducted for prior missions, future fission power and propulsion missions will require data, analyses, and testing specific to the fission technology used and the mission application—each of which has yet to be defined. Recommendations from the NSPWG, that build upon the SNAP-10A mission and other proposed missions, provide high level recommendations that can be used to influence the design of future fission systems. An early establishment of operational and safety guidelines or requirements will help ensure their early incorporation into the design and testing programs for fission reactors (Voss 2017).

Based on the current version of the PD/NSC-25 (1996) and National Space Policy (2010), a fission reactor would be required to undergo the same review process discussed for RPS systems. Analysis codes, currently used for RPS missions, could be adapted to incorporate the unique considerations of fission reactors (e.g., low radiation levels). Further, to support the SAR analyses, reactor designers could consider potential probabilistic risk targets to demonstrate the safety of their designs, such as: (1) the risk is less than recently approved RPS launches, (2) the risk is lower than published NRC safety goals for terrestrial commercial power reactors, or (3) potential doses are below limits set by the EPA for people living near terrestrial reactors (Voss 2017). The level of analyses could then be commensurate with the risk of the mission; thus if a mission owner could prove the risk of their mission is below these targets, additional analyses would not be required.

Furthermore, similar to the RPS launch approval process, there currently are no criteria that have been outlined that, if met, would ensure a launch approval would be granted. High-level criteria could be developed to help mission owners determine the level of analyses necessary to receive approval for future missions. A summary of a few safety criteria that could be developed is provided; a combination of multiple criteria could be used for future missions (Voss 2017).

1. Probabilistic Risk Goals: quantitative goals, similar to those set out by the NRC for terrestrial power reactors, are used to determine if something is a tolerable risk (e.g., annual risk to nearby public is below a certain threshold).
2. Deterministic Design Criteria: specific design standards (e.g., number of fissions in a reactor to remain subcritical) are developed; if a reactor achieves the standards then it would be considered safe.
3. Assured Safety Criteria: common in nuclear weapon safety reviews, the designer is required to prove a technology will behave in a predictable and safe manner during normal and abnormal operations.
4. Envelope Criteria: when a system is demonstrated to have no additional risk relative to a similar system that has been approved previously, then approval is granted. This is especially applicable for true “heritage” software.
5. Maximum Credible Events Criteria: worst case scenarios can be examined for their radiological threat to human health; if the risk is found to be demonstratively low, additional analyses are not required for lower risk scenarios.

6. Assessment of the Launch Approval Process and Options for the Future

This chapter provides our assessment of the strengths and challenges of the current space nuclear launch approval process. Based on this assessment, we provide options for modifying the RPS launch approval process, and creating and implementing a future fission launch approval process.

A. Strengths of the Current Process

One of the primary benefits of the current RPS launch approval process is its inherent flexibility. None of the documents that guide the approval process for launching space nuclear sources provides details regarding the scope or content of required analysis. This in turn has provided a measure of flexibility to allow the review process to evolve over time as capabilities have progressed and more test data have been collected. This flexibility has allowed the reviewers to perform new analysis as lessons are learned with each launch. For example, in 1997 after a Delta II 241 (that was not carrying a RPS) exploded just after launch and rained burning solid propellant on the launch complex, the launch approval participants, including INSRP, realized they had no test data to evaluate the possible consequences if a RPS was near burning solid propellant. New solid propellant fire tests were performed and solid propellant fire specifications were included in the Databooks of Mars Exploration Rovers (2003), New Horizons (2006), and Mars Science Laboratory (2011).

The current safety review process is thorough—it involves modeling blast and impacts, launch vehicle propellant fires, spacecraft and RPS or RHU atmospheric reentry from space, accident sequence paths, atmospheric transport and food pathways, and health effects. All of this leads to calculations of the:

- Probability of a release of HS-Pu-238 fuel.
- Probability distribution of the potential amount and particle size of fuel of plutonium dioxide fuel released.
- Probability distribution of potential health effects produced (incremental latent cancer fatalities over 50 years).
- Probability distribution of potential land contamination above specified levels.

- Risk (mean number of health effects times the total probability of fuel release) (Clayton et al. 2015).

The risk analysis can lead to design changes in the launch vehicle, spacecraft, or mission architecture for improved safety of the current or future missions (Clayton et al. 2015). INSRP has led to modifications that have arguably improved safety. For example, after input from INSRP on Cassini, DOE committed to improving the thermostructural response of the general purpose heat source (GPHS) module. New Horizons and MSL both used an enhanced GPHS module. Launch contingency planning can also be enhanced—after the New Horizons FSAR predicted possible accidental near-pad RTG releases, environmental continuous air monitors (ECAMs) were deployed around the launch pad for the New Horizons and MSL missions (Chang 2018).

INSRP is made up of an interagency group of technically competent personnel, who are not directly participating in the missions under review. This is intended to utilize the expertise resident in each agency while still maintaining independence so as to accomplish an unbiased review. Additionally, each member of INSRP is meant to have a valuable perspective on launch: DOE is in control of the radioactive material; NASA is in charge of the mission; DOD has control of the launch range; EPA would be involved in hazardous cleanup; and NRC has nuclear expertise. Agency reviews are therefore consolidated into one entity, the INSRP, eliminating independent parallel reviews.

Lastly, involving OSTP in the process provides political top cover. While launches will directly help NASA, DOE, and DOD meet their scientific missions, the missions of EPA and NRC are primarily focused on environmental protection and nuclear safety, respectively. Having the higher authority of OSTP/EOP could help adjudicate any inherent incompatibility between the stakeholder agencies that might be associated with their respective missions.

B. Challenges Associated with the Current Process

The core strength of the current process—namely its flexibility—is simultaneously a challenge as well. This flexibility can also lead to uncertainty regarding when sufficient analyses have been completed and what specifically is needed or required of each process. This flexibility affects which analyses are performed, how reviews are performed, and how the INSRP operates.

1. Threshold for Triggering Launch Approval Process

One challenge in the launch approval process is that the threshold that triggers the full process is low. Several attempts have been made to understand why the threshold was set; however, no insights were uncovered. Launch of a RHU (that contains about 2 g of HS-PuO_2) necessitates the production of a SAR, the empanelment of INSRP, its preparation of a SER, and approval by the Director of OSTP or the President. In other words, the similar burdens are placed on a mission flying one RHU as a mission flying multiple RTGs.

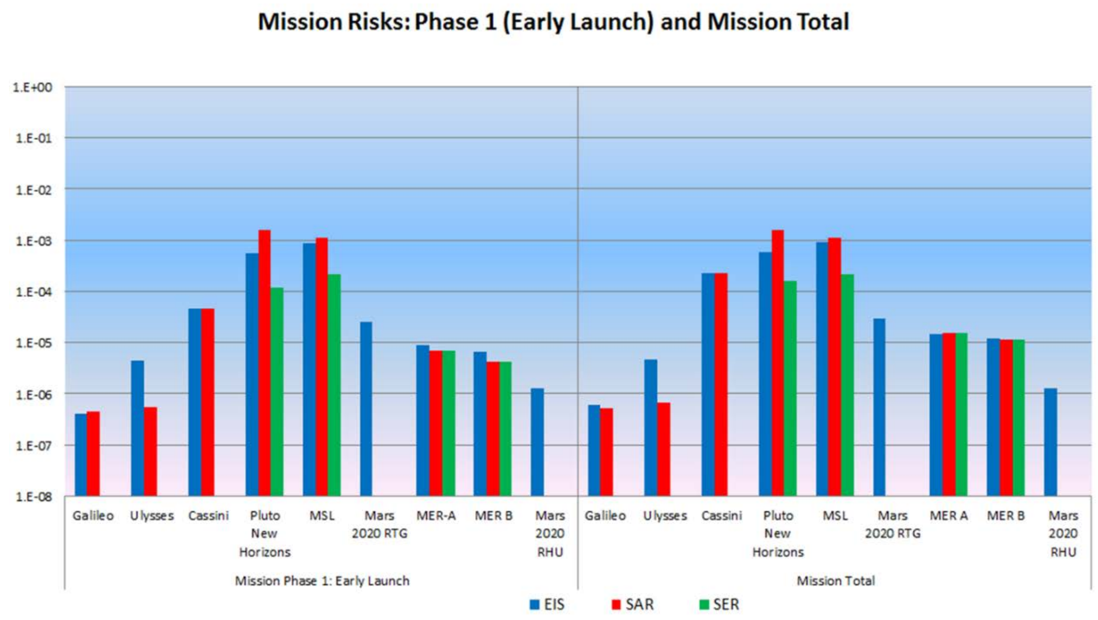
2. Criteria Related to Safety Analyses

Few criteria or guidance, beyond precedent set by prior missions, exist to govern the level of safety analyses and reviews necessary to support a launch approval decision. The types of analyses conducted for each step of the approval process are based on what various stakeholders in the process deem as appropriate; these analyses are not bounded. On the one hand, this allows for the flexibility to conduct additional or different analyses as needed based on the mission at hand. However, this flexibility has also led to a system in which the level of analysis performed is primarily limited by resources.

Furthermore, in the absence of guidance from OSTP or the President, a culture has developed in which those conducting analyses and reviews are forced to assume what OSTP wants to understand about the associated safety and risk of the mission. This is a challenge because it makes the evaluation of risks an open-ended process, which in turn directly impacts the cost and duration of the process.

3. Duplicative Analyses

The DOE review resulting in the SAR has substantial components that are duplicative with analyses that are conducted in the EIS. Figure 6 illustrates the overlap. It shows the estimated mean health effects risks associated with early launch and the overall mission, separated by mission and documented analysis (i.e., EIS, SAR, and SER). This graphic illustrates that in the most recent missions, the estimated risk did not vary widely between the EIS, SAR, and SER.



Source: Daniel Gallagher, Douglas Outlaw, “A Review of NASA NEPA and Safety Requirements with Lessons Learned from Previous Safety Analyses,” *Leidos Incorporated*, July 2017.

Note: The Mars 2020 Mission EIS evaluated a configuration with only an RTG and one that included RHUs. Therefore the Mars 2020 RHU data on this chart is from the mission configuration alternative evaluated but not chosen.

Figure 6. Risk to Public Health Estimates by Mission and Documented Analysis

One argument for duplication is that the inputs change between the EIS and SAR because the design of and information about the mission progresses over time. Additionally, the EIS is designed to take a programmatic point of view to help decide whether the mission should be completed using nuclear material, to consider the possible alternatives, and to make conceptual-level decisions. It happens before the selection of a launch vehicle. Once the launch vehicle is selected, DOE conducts the SAR based on specific scenarios that are launch vehicle specific.

The duplication is not just within a mission, but also across missions. The NEPA process and the DOE safety analysis are conducted completely anew regardless of similarity between the missions.[30] In other words, analyses are conducted in a manner that treats the present mission as if it were the first RPS mission to fly; lessons learned from past missions are not used to reduce the number of new analyses required.

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[30] With the exception of the SAR gap analysis conducted for Mars 2020 which is still being contested by INSRP

4. Practices for Satisfying NEPA Requirements

There are three ways for agencies to satisfy NEPA requirements: (1) determine that the proposed action falls within a categorical exclusion because it has “no potential for substantial effects on the quality of the human environment;” (2) conduct an EA that leads to a FONSI or recognition that an EIS is needed; and/or (3) prepare an EIS that fully describes the environmental impacts and array of alternatives considered.[31] Depending on the type of mission, an EA or an EIS might be appropriate for a nuclear launch. RPS missions almost always undergo the most rigorous option to fulfill NEPA requirements, regardless of whether the mission contains one RHU (that only has a few grams of Pu-238) or several RTGs (that could have tens of kilograms of Pu-238). NASA NEPA regulations say that an EIS is “normally required,” for “a nuclear reactor or radioisotope power systems and devices…for which the A_2 Mission Multiple…is greater than 10.”[32] Despite the regulations, there are instances in the past when an EA—the less intensive option—has been conducted instead of an EIS. For example, in 1994 NASA prepared an EA for the Mars Pathfinder mission, which had three lightweight radioisotope heater units on board and concluded with a FONSI by NASA that was not challenged. However, since that time, NASA has prepared an EIS for every RHU and RTG mission (Table 4).

Table 4. NEPA Review for RPS Missions

Mission	Nuclear System(s)	NEPA Document		Record of Decision Date	Launch Date
		EIS	EA		
Mars 2020	RTG	x		Jan 2015	2020
MSL	RTG	x		Aug 2010	Nov 2011
New Horizons	RTG	x		Sep 2005	Jan 2006
Mars Exploration Rovers	RHU	x		Jan 2003	Jun, Jul 2003
Cassini	RTG, RHU	x		Aug 1997	Oct 1997
Mars Pathfinder	RHU		x	Oct 1994	Dec 1996
Ulysses	RTG	x		Jun 1990	Oct 1990
Galileo	RTG, RHU	x		Jun 1989	Oct 1989

Source: Norwood, Hayes, and Steiner 2018

Second, the timing of the EIS is problematic. The NEPA review used to be performed at the same time as SAR and SER, but is now performed much earlier due to the threat of launch delays from NEPA-related litigation. Since it is performed so early, the design is

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[31] NPR 8580.1A NASA National Environmental Policy Act Management Requirements.

[32] 14 CFR § 1216.306(c)

still in flux, so the EIS is based off of what is considered preliminary data—specifically the NRA prepared before the launch vehicle is selected. To some, the description of risks in the EIS is perceived as less accurate. However, a recent comparison by NASA of the NRA and SAR data developed over the past 30 missions has shown them to be similar.

5. Lack of Guidance for INSRP

No documents related to the space nuclear launch approval process provide any guidance as to the scope and role of INSRP. Consequently, there is disagreement among stakeholders over the roles and responsibilities of INSRP, and what is in INSRP's purview. Similarly, a lack of high-level guidance leaves what should be included in the SER ambiguous. In practice, INSRP works iteratively with stakeholders involved in the process while preparing the SER. Some of these iterations involve INSRP asking for additional analyses, tests, or information to be collected or executed. Because the SER prepared by INSRP is what is ultimately delivered to OSTP, there is a sense within the community that whatever INSRP asks for must be done. For example, some INSRP members indicated that comments sent to NASA and DOE were simply questions the panel had, and that the agencies could choose to address them or ignore them. However, DOE and NASA have regarded these INSRP questions as commands, and felt obligated to perform additional analysis to respond to them. It is clear that there is no prioritization of INSRP comments to DOE and NASA, and the agencies have no process for determining how to prioritize.

There is no formal line of communication between INSRP and other stakeholders, and there appears to be a lack of communication among members of INSRP and DOE and NASA. In the event that there is a disagreement between INSRP, mission owners, NASA, or DOE, there is no formal adjudication process. As a result, any potential conflict could pose a significant schedule risk on the mission and mission launch date. For example, in 2017, DOE proposed using a gap analysis instead of performing all risk analysis anew (as is typically done for a SAR) for its review of Mars 2020. INSRP objected and warned that it may not be able to complete its analysis in time for the scheduled launch if DOE changed its analytic outputs. There is no formal process to resolve this dispute.

6. Requirement for Presidential Approval

Launch approval from EOP is unique to nuclear systems in that other launches with hazardous or precious (such as humans) payloads do not require such high-level approval. During the course of this study, we attempted to understand how decisions to approve nuclear launches were previously made. However, there is no available documentation of the decision-making process for past launches, such as who at OSTP was involved, when and how often the decision makers met, and if additional questions were asked of NASA, DOE, and/or INSRP. After conversations with extant OSTP officials who were involved in the approvals of MSL and New Horizons, we learned the review was done quickly (in less than a week), and with little opportunity for meaningful engagement. It was described as a pro forma, scripted exercise where everyone knew the outcome ahead of time.

Additionally, RTGs and RHUs are flown infrequently, meaning that there is no continuity of review given the turnover rate of political appointees and detailees at OSTP across administrations. In this regard, institutional memory regarding the nuclear launch approval process and associated decision-making is limited.

7. Impact of Challenges on RPS Missions

Having an unnecessarily burdensome launch approval process discourages mission planners from using RPS. As noted in Chapter 3, costs for launch approval and related services total over $40 million. Security for the launch site and other launch services can cost at least another $5 million.

Schedule risk is also a potential deterrent for using space nuclear systems. Table 3 illustrates that the launch approval process could take up to 7 years. For example, if disputes among agencies regarding the gap analysis are not resolved, the launch for Mars 2020 may not meet its launch window. A delay in launch can lead to increased mission costs, including costs associated with storing the payload, maintaining workforce, and re-testing as needed, until the next available launch window opens. For missions with narrow launch windows, a launch delay could potentially mean a stand-down for the entire mission.

8. No Guidance for Fission Launches or Commercial Nuclear Launches

No space fission system has flown since the issuance of PD/NSC-25. While the Presidential directive and National Space Policy 2010 apply to space fission systems as well as to RPS, agency-level guidance, procedures, and best practices need to be agreed upon and established. The radiological risks posted by a sub-critical U-235 fission reactor are less than that of a Pu-238-based RPS, and it may not be appropriate to retrofit the radioisotope process onto fission system launches.

C. Options for Changes to the RPS Launch Approval Process

In this section, we discuss options that could address the challenges previously discussed. The options are neither mutually exclusive nor independent, and the intention is that their implementation will not impact the safety of the mission. These options are not a reduction in meaningful standards; rather, they offer a way to streamline parts of the current process that seemingly add no safety advantages.

Options for modifying the RPS launch approval process are organized by each of the parts of the approval process. Table 5 lists all options, and the specific challenges these address. In the following section, we also discuss the pros and cons of each option, how much effort each will take to implement, and what its impact on the process could be. We begin below with a discussion of the options.

1. Thresholds for Launch Approval Process

As discussed in the preceding section, there are situations for which the full-scale launch approval might be unnecessarily burdensome.

Currently, this threshold for the launch approval process includes amounts as low as what is contained in a single RHU. Changing the trigger threshold would better reflect the risks and impacts of different types of space nuclear systems. All of these options would require updating PD/NSC-25 and associated agency documents.

Options for modifying the threshold that triggers the launch approval process include:

- **Changing the threshold quantity**. It is unclear why the current quantity is used as the trigger threshold. The quantity could be changed to reflect a more meaningful trigger threshold.
- **Base threshold on other metrics.** Instead of basing the trigger threshold on a seemingly arbitrary quantity of radioactive material, definitions could be based on intended use of RPS. For example, the threshold could be changed to distinguish processes for a RHU versus an RTG.

2. Practices for Satisfying NEPA Requirements

Challenges associated with the NEPA process include the timing of the EIS, and that an EIS—the greatest level of analysis—is conducted for every RPS mission. Options to address these challenges include:

- **Move the NEPA review to later in the process**. Conducting the NEPA review later would allow the analysis of a more complete mission design, so that it could be used to a greater extent when preparing the SAR and the SER or replace the SAR altogether. Additionally, completing the NEPA review later in the launch approval process could obviate the need for conducting an NRA, which is currently completed prior to vehicle selection and thus has to use a composite risk that averages the risk analyses for all potential vehicles. However, this will likely also lead to even more duplication between the EIS and the SAR because inputs would be more similar. If one were to choose to forgo the SAR, it would be critical that the EIS be performed using a final or close-to-final design. This could violate the intent of the law if not the letter of the law since the NEPA review is supposed to be conducted *before* the Federal action. The closer the mission is to launch, the more likely one could argue that the review is pro forma.

- **Prepare a Programmatic EA (PEA) for RHUs.** Typically an EIS is performed regardless of whether the power or heat source is an RTG or an RHU. An EA takes less time (approximately 1 year instead of 2 years) and costs less ($400K instead of $3.4M) than an EIS for the NEPA contractor due to the fees and additional savings of not having to do an NRA. There is precedence for the use of EAs for RHUs. The Mars Pathfinder mission, for example, contained three RHUs, and an EA was successfully completed and the launch approved on that basis. Additionally, NASA has prepared a PEA for routine payloads that includes assessments based on launch location, launch vehicle and envelop payload characteristics. These are presented in a checklist used for evaluate each mission (Appendix C). The RHU PEA would provide a similar checklist to be used as a criterion to determine if the RHU mission falls within the PEA or additional NEPA analysis would be required.
- **Conduct a one-time EA for radioactive material similar to NASA's Routine Payloads EA of 2011**. NASA has an EA for routine payloads, which includes assessments for hazardous materials (Appendix C). Similarly, a one-time EA could be done to assess nuclear material. A hazard scale similar to other hazardous materials could be used to determine the appropriate criteria that would ensure the spacecraft, launch, and operation would not present any new or substantial environmental or safety concerns. This would significantly reduce the time and resources devoted to NEPA review. Given the public perception (and reality) of the hazards involved with nuclear launch, it is not certain that this would survive public review or any legal challenges if it were issued.

3. DOE Safety Analyses

Analyses and outcomes conducted in the DOE safety analysis process may be unnecessarily duplicative of content from the EIS. The analyses are unbounded and by some indications the computational analyses continue *ad infinitum* until funds or time are exhausted, and sometimes further analyses are done at the request of INSRP. Additionally, the DOE safety analyses are conducted such that results from previous missions are not sufficiently leveraged. Options for changes include:

- **Conduct gap analysis:** DOE could modify the way they perform their review by conducting a gap analysis that uses previous missions as a baseline for future safety and risk instead of redoing an analysis each time a SAR is to be prepared. No EOP documents would need to be revised, and DOE is currently using this approach for the Mars 2020 mission.
- **Establish basic criteria and expectations for the SAR:** Increased communication between OSTP, NASA, and DOE could result in clearer goals

for conducting the SAR and potentially bound analysis efforts to what is useful for decision makers.

- **Establish safety basis and risk threshold:** DOE could modify the way they perform their review by developing upper and lower bounds for safety and risk, and use these to bound future mission analyses. DOE already has approaches to do this to approve their facilities. This would preclude endless analysis and establish clear thresholds beyond which no further analyses are required. Using tools from that toolkit, SAR would only address Unreviewed Safety Questions (USQ)[33] or Potential Inadequacies in the Existing Safety Analyses (PISA),[34] rather than an entirely new review each time. No EOP documents would need to be revised.
- **Eliminate the SAR and perform only an EIS and SER**: INSRP could use the EIS instead of the SAR to conduct its review. This would require the EIS to be performed later so it is reviewing the final design. The 2010 National Space Policy will need to be revised because it refers to the Secretary of Energy conducting a nuclear safety analysis for evaluation by INSRP.

4. INSRP Process

INSRP has no formal direction or guidance other than to conduct a safety review of the SAR produced by DOE. Communication between INSRP and other relevant stakeholders (such as DOE and NASA) appears to be weak, and no adjudication process exists for instances when there is disagreement between INSRP and other stakeholders. Options for consideration include:

- **Increased communication.** Increased communication between INSRP, mission owners (NASA), and analysis performers (DOE and NASA) might help agencies determine which comments to prioritize and whether there is any confusion over meaning of comments. This could be accomplished without any changes to or release of new documents.
- **Define roles and responsibilities of INSRP**. This could involve establishing or reiterating reporting structures and responsibilities, including that INSRP reports to the mission owner, not OSTP, and INSRP’s comments are not mandates, but either questions or input. This option could be accomplished by creating an INSRP charter document that defines their role and scope; no existing EOP

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[33] The USQ process is used to determine if a change falls within the safety basis. See Appendix C for additional information.

[34] A PISA document is developed to review safety issues that were not otherwise adequately addressed in the safety basis. See Appendix C for additional information.

documents would need to be changed. Agency documents would likely need to be updated to reference the charter.

- **Develop an adjudication process for INSRP comments**. When there is disagreement between INSRP and NASA and/or DOE, there is currently no formalized way to resolve or adjudicate the disagreement. Further guidance on how to handle such cases may help speed decision-making. This option could be accomplished through the INSRP charter document.
- **Constrain the length of time of INSRP is empaneled.** INSRP could be directed to meet during a limited amount of time or be constrained to a maximum number of meetings. This change could reduce the amount of staff time and resources that are currently expended over multiple years. No policy documents would need to change to implement this approach.
- **Convert INSRP to a standing committee**. Discontinuity of personnel between analyses can make it difficult to retain insights gained across missions. A standing INSRP committee that would be available to answer questions from the agencies might provide a better avenue for post-mission discussion and the ability to capitalize on lessons learned. This approach may not be useful if the gap between missions is as large as it currently is—less than two RPS missions per decade (given personnel turnover in agencies). However, if the flight rate increases, this option could be productive. PD/NSC-25 and the 2010 National Space Policy would need to be revised to change INSRP from an “ad hoc” committee to a standing committee. Agency policy documents would need to be updated accordingly as well.
- **Dissolve INSRP**. All challenges associated with INSRP would be overcome by eliminating INSRP, and the process would automatically be more efficient and streamlined. The significant drawback is an entire safety review would also be eliminated. Assuming no safety features are dependent on INSRP review, then safety would not be compromised, though no new lessons learned would be developed from the INSRP review. PD/NSC-25 and the 2010 National Space Policy would need to be revised to remove the requirement for INSRP in the case of a space nuclear launch. Agency policy documents would need to be updated accordingly as well.

The following set of changes is related to the creation of the output of the INSRP process: the SER.

- **Discourage INSRP from requiring or performing additional analysis**. INSRP has performed analysis in the past to validate the SAR findings, and to determine whether there are gaps in the analysis. In order to streamline the INSRP review process, INSRP could be constrained to only reviewing and providing feedback on analysis performed by mission owners and their partners, and would not perform its own analysis. The potential drawbacks are that the overall safety analysis may be less thorough and there may be gaps, though these could be identified by INSRP and filled by the mission owners and their parts via an update to the EIS and SAR. This option could be accomplished in the INSRP charter document mentioned earlier.

- **Eliminate the SER and perform only an EIS and SAR.** Instead of completing three separate safety reviews and preparing three reports, NASA could prepare an EIS, and DOE could prepare the SAR. INSRP could still make recommendations regarding launch approval based on its review of the EIS and SAR, but would not need to produce its own standalone document.

5. Presidential/OSTP Approval

The rationale for having OSTP approve past launches is poorly documented. OSTP review and approval may be a formality in the process, but it arguably provides top-cover for mission owners. It also reinforces a message to the international community that the United States takes its treaty obligations seriously.

- **Eliminate the need for Presidential/OSTP approval**. Instead of INSRP submitting the SER to OSTP, the SER could be delivered to the NASA administrator. The NASA administrator could then make a final decision on launch based on the SER and recommendations from each agency serving on INSRP. EOP could still have the opportunity to announce the launch and notify the international community. This would require changes to PD/NSC-25, the National Space Policy 2010, and a revision to NASA’s 8715.3D NPR.
- **Involve OSTP in earlier stages of INSRP.** Currently, OSTP is only included once the SER is completed. Instead, OSTP could be included in earlier stages of INSRP, possibly by chairing the panel.

D. Options for Changes to the Fission System Launch Approval Process

Under PD/NSC-25 and National Space Policy 2010, a fission reactor would be required to undergo the same launch approval process as RPS. However, given the relatively low radiological risk of U-235, a simplified safety analysis could be conducted for accident scenarios associated with cold reactors. A graded approach for nuclear safety, currently outlined in NASA Procedural Requirement (NPR) 8715.3C Chapter 3, could be leveraged.[35]

In part based on lessons learned from other sectors, including lessons learned from the RPS launch approval process, the following options could be considered for the development and refinement of a launch approval process for space fission reactors. Specific implementation of each pathway might be unique to the technology under development (e.g., fission power versus propulsion, both electric and thermal); therefore, the pathways examined would require additional analyses to refine. Further details on sectors referenced in the following sections can be found in Appendix D.

1. Development of Safety Analysis Criteria

Similar to the RPS launch approval process, there currently are no criteria outlined that specify what needs to be included in the safety analyses for a fission reactor launch. Such criteria should be developed to bound risk and safety analyses as fission reactor technologies emerge. Although safety criteria would likely need to come from the decision maker, such as OSTP, such criteria can be developed with input from experts within the community. The guidance could then be used to help the mission owner and DOE determine the level of analysis necessary to support a launch decision.

Alternatively, quantitative safety goals could be communicated to the community, similar to NRC's published safety goals for civilian power reactors (see Appendix C).[36] The challenge with this is that stakeholders in the process look to OSTP as the decision maker and thus the entity that should set such goals. However, at any given point OSTP may or may not have the in-house expertise to set such standards. Regardless, such goals provide guidance to individuals conducting safety and risk analyses; if a mission is unable to achieve the safety goals, then approval would be unlikely. However, similar to the goals of terrestrial fission reactors, the space safety goals would be meant as guidance. The ultimate decision to launch incorporates a variety of factors including level of risk, technical, political, or economic considerations. Examples of criteria include probabilistic and deterministic design goals.

2. Graded Approach to Safety Analyses

The risk and safety considerations, as discussed in chapter 3 for missions containing fission power and propulsion systems, vary widely based on characteristics such as

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[35] See Chapter 6 for further discussion of how a graded approach could be used for the launch approval of a fission reactor.

[36] One example is the NRC's published goal that a reactor core has less than a 1 in 10,000 chance of being compromised within a year. Given the unique considerations of launch activities (e.g., short time periods, and potential for global rather than localized consequences) alternative safety goals may need to be considered.

technology (power versus propulsion reactors), fuel (HEU versus LEU) and mission trajectories (Earth orbiting versus deep space operations). To ensure the level of safety analyses conducted are benchmarked against the expected risk posed by the mission, a graded process could be developed.

A graded approach, similar to that used by DOE for defense nuclear facilities, separates potential hazards into various risk classes. If a specific action is considered to pose a relatively low risk, fewer analyses are conducted than for a riskier action. For example, to support the SAR analyses for fission reactors, system designers could consider potential probabilistic risk targets to demonstrate the safety of their designs, such as: (1) the risk is less than recently approved RPS launches, (2) the risk is less than published NRC safety goals for commercial power plants, or (3) potential doses are below limits set by the EPA for people living near power plants (Voss 2017). The level of analyses would then be commensurate with the risk of the mission; thus if a mission owner could prove the risk of the mission is below these targets, additional analyses would not be required.

An approval process could grade the environmental analyses (EA or EIS) or safety analyses based on the risk posed. For example, the NASA Routine Payload Environmental Assessment of 2011 identified safety studies and published governmental standards for acceptable risk to the public in order to determine the amount of the hazardous material that would not pose a significant threat to the environment (e.g., less than 3,200 kg of hydrazine fuel) in the case of a launch accident (NASA 2011). Therefore, if a future mission contains less than the threshold reported, additional environmental analyses are not necessary.[37] A similar concept could be applied to the approval of fission reactors; safety analyses and governmental health standards for radiological risk could be adapted to determine what fission reactors designs necessitate more detailed safety analyses.

3. Development of a Reactor-Specific Safety Basis

To reduce the duplication of safety and risk analyses from mission to mission, especially if heritage fission reactor technology is used (as will likely be the case for any power systems based on Kilopower), the safety basis approach used by DOE for defense nuclear facilities could be adapted for space missions. For this option, a safety basis would be developed, a process similar to the USQ and PISA processes (discussed in Appendix C), used by NRC and DOE for civilian power reactors and defense nuclear facilities, respectively. By establishing a safety basis, additional analyses would only look at alterations to the technology and system as a whole that do not add significant levels of risk to a mission (as determined by the safety basis). Such a process would reduce the amount of analysis needed when using a heritage reactor design across multiple missions.

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[37] Additional analyses would be necessary if the mission was launched from a launch site or new launch vehicle not reviewed for the 2011 EA.

Similar to the DOE approval process, independent reviews could be conducted by an outside entity, such as INSRP or a sub-set of agencies and laboratories.

In order to do this, it is essential to use hardware that has been flown previously in the same configuration. It is also essential that good systems engineering practices be followed throughout.

4. Summary and Assessment of Options for Developing a Fission Approval Process

Regardless of process developed, clearly defined authorities will provide clarity to future mission owners within and outside government. For example, oversight could be limited to one or a few agencies such as the mission-owning agency for government missions, or a designated agency for commercial missions with technical expertise for reviewing requests.

PD/NSC-25 would need to be revised if fission launches are not to be subjected to the current launch approval process, including INSRP review and Presidential approval. A new National Space Policy would also need to be released. Agencies would need to update their regulations and policy documents to include the new fission launch approval process, pursuant to guidance from EOP.

Many of the options for setting out an approval process for launching fission systems, at the highest level, are similar to those for RPS: minimize unnecessary duplication and bureaucracy, have quantitative thresholds so as to bound analysis (both in scope, time and cost), and tailor analyses to the risk at hand. Table 5 summarizes these options, and notes which documents need revisions.

Table 5. Options for Change in Launch Approval Process

Stage/Topic	Option	Challenge Addressed	RPS or FPS	EOP Documents Needing Revision	Agency Documents Needing Revision
Triggering Launch Review	Raise the threshold for triggering review through the following ways: increasing the quantity allowed; using a different metric for the threshold; basing threshold on risk rather than quantities of material	Systems that do not need a formal launch approval process go through a needlessly lengthy and expensive review	RPS	PD/NSC-25	NPR 8715.3D
	Redefine a threshold for fission material in PD/NSC-25	Currently all systems with potential for fission must go through approval process	FPS	PD/NSC-25	
NEPA Review	Change timing of NEPA review to later in process	EIS done too early so less useful	RPS	None	NASA NEPA Desk Guide
	Only conduct an EA for RHUs	EIS on a RHU is unnecessarily lengthy and expensive	RPS	None	14 CFR Part 1216.3 NPR 8580.1A
	Add radioactive and fission material to NASA routine payloads EA	New EIS for each mission is redundant	RPS and FPS	None	14 CFR Part 1216.3 NPR 8580.1A
DOE Review	Adopt a gap analysis when appropriate	An entirely new EIS, SAR, and SER for a mission that is identical to another is redundant	RPS	None	None
	Establish safety basis and risk threshold	An entirely new EIS, SAR, and SER for a mission that is identical to another is redundant	RPS and FPS	None	None
	Eliminate the SAR, move EIS to later in the process, and perform an EIS and SER	Reviews are duplicative	RPS and FPS	NSP 2010	NPR 8715.3D

Stage/Topic	Option	Challenge Addressed	RPS or FPS	EOP Documents Needing Revision	Agency Documents Needing Revision
INSRP Review (SER)	Eliminate the SER, only perform an EIS and SAR	Reviews are duplicative		NSP	NPR 8715.3D
	Increase communication between INSRP, mission owners, and analysis performers	Agencies do not know which comments to prioritize; no formal process for adjudicating disagreements between INSRP and stakeholder agencies	RPS and FPS	None	None
	Define roles and responsibilities of INSRP members, mission owners, and analysis performers	Confusion over roles and responsibilities	RPS and FPS	None	None
	Develop an adjudication process for INSRP comments	No process for adjudicating disagreements	RPS and FPS	None	None
	Constrain INSRP to a specified length of time and/or specified number of meetings	Staff time and resources expended on multiple meetings over several years	RPS and FPS	None	None
	Convert INSRP to a standing committee	Lack of continuity between missions	RPS and FPS	PD/NSC-25; NSP	NPR 8715.3D
	Dissolve INSRP entirely	INSRP review is duplicative	RPS and FPS	PD/NSC-25; NSP	NPR 8715.3D
	Discourage INSRP from requiring or performing additional analysis	INSRP analysis may be duplicative	RPS and FPS	None	None
	Eliminate the SER, only perform an EIS and SAR	Reviews are duplicative	RPS and FPS	NSP	NSP 8715.3D
OSTP Approval	Eliminate requirement for Presidential approval	Presidential approval inserts uncertainty in the process	RPS and FPS	PD/NSC-25; NSP	

E. Authority to Make Changes

No single legal document outlines the entire review process for launch approval, whether for RPS or fission. In addition, there is no statutory requirement for the SAR or the SER; only the NEPA review process is mandated by Congress. This means that modifying the RPS launch approval process (or creating an approval process for fission) could be accomplished by unilateral Executive action, since no space-nuclear-specific legislation must be amended.

F. International and Commercial Space Nuclear Activity

Given the capabilities enabled both by RPS and especially fission technologies (such as shorter transit times for human missions or a sustained on-surface power source capable of night-time operations), commercial entities have expressed interest to either develop fission power systems or serve as a user of the technology. On the supply side, for example, technology contractors Aerojet Rocketdyne and BWXT were awarded a grant from NASA to help develop a conceptual design for a LEU nuclear thermal propulsion reactor. The 500 MW_{th} reactor would be used to support manned space missions (e.g., Moon or Mars) and utilize a 19.75 percent Enriched Ceramic Metallic (CERMET) Tungsten-Clad fuel (BWX Technologies, Inc. n.d.). The company has expressed interest in further developing the technology for sale to both commercial and government buyers. Additional start-ups, such as Atomos Nuclear and Space and Small Business Innovation Research (SBIR) awardee Ultra Safe Nuclear Corporation[38] are developing fission reactor technologies with potential application for space missions.

On the user side, companies such as SpaceX and Blue Origin have expressed a desire for NASA to invest space nuclear power to support their plans for future human spaceflight and other activities (Davenport 2016; Mueller 2017). However, the current PD/NSC-25 process does not explicitly outline what the launch approval process, if different, would look like for non-government entities to procure and use nuclear power and propulsion systems.

Currently, there is little regulatory direction for commercial actors interested in purchasing and using fission technologies for future spaceflight missions. The only guidance that exists is from the Outer Space Treaty, which indicates that states are responsible for their private sectors’ activities in space. The 2006 National Space Policy recognized commercial need and included guidance; however, this was supplanted by the 2010 National Space Policy, which makes no reference to commercial activities. There is

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[38] Ultra Safe Nuclear Corporation was a recipient of multiple SBIR awards from NASA for the development of technologies for nuclear thermal propulsion systems. Small Business Administration, “Ultra Safe Nuclear Corporation,” accessed March 13, 2018, https://www.sbir.gov/sbc/ultra-safe-nuclear-corporation.

a need for guidance on how commercial parties can develop and use space nuclear systems, including direction on the launch approval process.

As a launch approval process is considered and developed for commercial actors, other challenges, especially related to international activities, would need to be addressed as well:

- Regulation of non-U.S. launches. An approval process would need to consider how to regulate a U.S. nuclear system if it were to be launched from a non-U.S. launch site, in the event that an U.S. commercial company attempted to launch a space nuclear system on foreign territory.
- Incorporation of international partners (both government and commercial entities). An approval process would need to adapt to the incorporation of non-U.S. technologies or partnerships with non-U.S. entities.

7. Conclusion

In recent years, launch approval for space nuclear systems has taken between 4–7 years, and cost at least $40 million per mission.[39] This has led to the question of whether the launch approval process can be streamlined without compromising safety. In this report, we identified the key documents that guide the space nuclear launch approval process and the implementation of the process over time.

Across the eight challenges outlined in Chapter 6, we identified five crosscutting and addressable issues with the launch approval process. First, the launch approval process lacks relative risk hazard assessment. For example, a system with a few grams of radioactive material triggers the same process as a system with multiple kilograms of the same radioactive material. Second, the process requires input from multiple agencies and results in years of analyses, some of which may be unnecessarily duplicative. Third, while involvement from multiple agencies via INSRP can provide valuable input, INSRP's role and scope of work are undefined. Fourth, there are no bounds or criteria for analyses conducted. Consequently, analyses are supported until resources terminate. It is unclear that additional analyses improve the safety of the system. Lastly, analyses for new missions using RPS are conducted as if previous RPS have never flown and may not fully be leveraging past work. Options identified in this report aim to address these challenges and inefficiencies while still prioritizing the safety of the mission.

For each option, we indicate level of impact and level of effort to implement (Figure 7). The low impact items have the potential to lead to modest improvements in terms of increasing efficiency and reducing confusion, and are centered on making marginal improvements. The medium impact options have the potential to moderately improve the efficiency and clarity of the launch approval process by maintaining the current process in general, but clarifying or constraining it, either technically or in terms of the process. The high impact items have the potential to significantly increase the efficiency and cost-effectiveness of the launch approval process. These high impact options involve wholesale changes that would completely alter the RPS launch approval process as it has existed up until this point.

Not all options are easy to implement. Some may have a high impact but also take a lot of effort (e.g., removing the requirement for Presidential approval altogether). Others may take less effort but still make a big difference (e.g., establishing a safety basis and risk

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[39] This figure does not include any contributions DOE might make during the INSRP process.

threshold). High effort items are those that are likely to be met with resistance from certain stakeholders, in particular those who are invested in maintaining the status quo. Figure 7 shows some potentially good places to focus, i.e. medium and high impact options involving low to medium effort (highlighted below).

Level of Impact		**High**		• Adopt a gap analysis when appropriate • Eliminate the SAR, and perform an EIS and SER • Establish a safety basis and risk threshold • Raise the threshold for triggering INSRP review process and Presidential approval	• Conduct a one-time EA for radioactive material similar to NASA's routine payload EA • Dissolve INSRP • Eliminate requirement for Presidential approval
		Medium	• Develop an adjudication process for INSRP comments	• Change timing of NEPA review to later in approval process • Only conduct an EA for RHUs • Define roles and responsibilities of INSRP members, mission owners, and analysis performers • Discourage INSRP from requiring or performing additional analysis • Constrain INSRP to a specified length of time and/or specified number of meetings • Eliminate the SER, and perform an EIS and a SAR	• Convert INSRP to a standing committee <u>Key:</u> NEPA Review Process Safety Analysis Process Safety Review Process Presidential Approval Process

		Low	- Increase communication between INSRP, mission owners, and analysis performers		
			Low	**Medium**	**High**
		Level of Effort			

Figure 7. Effort-Impact Matrix

Our bottom line finding is that the launch approval process for nuclear systems should reflect the different levels of relative hazards. For example, the review process for a mission that includes a RHU—which has 2 g of Pu-238—should not be treated the same as a mission that contains an MMRTG—which has over 3,000 g of Pu-238—as is currently done. Two options in our focus area of impact and effort would help to delineate between the levels of hazards found in RHUs and MMRTGs: (1) raising the threshold for triggering the INSRP review process and Presidential approval; and (2) only conducting an EA for RHUs. A third option—establishing a safety basis and risk threshold—would allow for a more nuanced assessment to determine if there is a baseline acceptable level of risk from mission to mission.

Another group of options in the focus area addresses the inherent duplication of starting the review process anew for each mission and completing three separate reviews. These options are to: (1) adopt a gap analysis when appropriate; (2) perform only two of the reviews by either eliminating the SAR or the SER; and (3) discourage INSRP from requiring or performing additional analysis.

The last group of focus area options represent process improvements that would increase the efficiency of the current system. These options are to: (1) develop an adjudication process for INSRP comments; (2) define roles and responsibilities of INSRP members, mission owners, and analysis performers; (3) constrain INSRP to a specified length of time and/or specified number of meetings; and (4) perform the NEPA review later in the process.

Several of the medium and high impact options involving low to medium effort would require EOP to modify PD/NSC-25 and National Space Policy 2010. Such options are updating and/or raising the threshold for triggering the INSRP review process and Presidential approval, and eliminating either the SAR or the SER.

The current operational framework for space nuclear systems applies to fission systems as well as RPS; however, there is currently no launch approval process in place for fission systems because no such system has launched since 1965. The process for RPS launch approval is not appropriate to retrofit for space fission systems. A nuclear reactor in launch configuration does not contain the levels of radioactivity that a radioisotope system has, so fewer precautions are needed to contain the fuel. In rare configurations, the fission reactor could conceivably achieve criticality, though even in such a case the potential for harmful radioisotope exposure to the general public would still be less than that for RPS. Nonetheless, analyses and testing would be required for the first-time fission launch approval. Many of the options for consideration outlined for RPS apply for the fission launch approval: there still needs to be a well-defined trigger to initiate launch approval; precise risk thresholds that define when analyses are complete; and a scoped INSRP review process that does not exceed its evaluation authority.

In addition to options for enhancing the RPS and fission launch approval processes, policy changes should also consider guidance for the development and use of space nuclear power and propulsion systems by U.S. commercial entities.

Appendix A. Key Terms Defined

Design Basis

A design basis is defined by DOE as a documentation of “information on the physical parameters of an operation and describes the operation and equipment that form the foundation of the safety analysis. Management controls, staffing, qualification procedures, training, emergency planning, and self-assessment programs are all part of the facility’s safety basis, though not part of its design basis” (DOE 2002).

Dose

A dose is derived from the amount of energy a human body absorbs from ionizing radiation released from the decay of radioactive materials. Dosage can either be measured based on the amount of radiation energy absorbed (radiation-absorbed-dose [rad]), or as a measure of the biological damage incurred to living tissues (roentgen equivalent man [rems] or sieverts [Sv]) (NRC n.d.).

Enriched Uranium Fuel

The uranium contained in mined uranium ore is mainly composed of three isotopes of uranium: uranium-234, uranium-235, and uranium-238. Naturally, uranium ore has an abundance of ~0.01 percent, ~1 percent, and ~99 percent of each isotope of uranium, respectively (De Bievre et al. 1993). Nuclear reactor fuels are enriched to include higher concentrations of uranium-235. Fuels that contain up to 20 percent uranium-235, by atom count relative to other uranium isotopes, are considered “low enriched uranium”; fuels containing more than 20 percent uranium-235 are considered “high enriched uranium” (NRC n.d.).

Graded Approach

A graded approach is one method for analyzing the safety and risk associated with a major action. NASA defines the approach as one where “the resources and depth of analysis are commensurate with the stakes and the complexity of the decision situations being addressed” (NASA 2017). A graded approach can help managers ensure that the level of analyses conducted add a reasonable value relative to the resources required to complete the analyses.

Probabilistic Risk Assessment

A probabilistic risk assessment (PRA) is used “to examine a complex system's potential risk and identify what problems could have the most impact on safety” (NRC 2016). Generally an assessment requires the following steps: (1) specifying the hazard under review, (2) identifying potential “initiating events,” any occurrence that could cause a hazard, and (3) an estimation of the frequency of the initiating event. The NRC uses a graded approach (PRA 1, 2 or 3), where the level of analyses required depends on the potential severity of a given hazard.

Risk

Risk is defined by the NRC as “the combined answer to three questions that considers (1) what can go wrong, (2) how likely it is, and (3) what its consequences might be” (NRC n.d.). Risk analyses often investigate a set of accident scenarios to determine the probability of a catastrophic event occurring (e.g., 1 in 10,000 chance of occurrence), the associated maximum level of severity (e.g., exposure to high, but not lethal, levels of ionizing radiation, such as 25 rems), and the uncertainties of the associated calculations (probability and severity). Risk can be introduced from “technical or programmatic sources” such as cost overruns, malicious activities, or failure to meet a technical objective (NASA 2007). Further, analyses can be conducted through either deterministic models (e.g., impact of a specific scenario) or probabilistic and stochastic models (e.g., likelihood and frequency of accident scenarios that pose a significant threat to public health).

Safety

Safety can be defined broadly to include human, environmental, and economic health. A safety assessment may include a review of the impacts of both the intended operation of a spacecraft (e.g., health impacts associated with a planned reentry into Earth’s atmosphere) and the risks associated with unintended operations or accidents. For example, in NASA procedural requirements safety is defined in a risk-informed context as “an overall condition that provides sufficient assurance that mishaps will not result from the mission execution or program implementation, or, if they occur, their consequences will be mitigated. This assurance is established by means of the satisfaction of a combination of deterministic criteria and risk-informed criteria” (NASA 2017).

Safety Basis

A safety basis is developed to identify potential hazards, evaluate their threat to health, determine the likelihood of an accidental release of the material, and finally, to determine specific hazard controls to ensure safe operation (DOE 2002). Based on the reviewed hazard and recommended controls (e.g., physical barriers), a technical envelope of characteristics and associated risk are outlined; if operations or alterations or contained within this envelope, then additional analyses are not required.

Threshold

A threshold is often a quantitative measure used to determine when additional analyses or processes are required. For example, if a mission includes enough material to exceed the threshold referenced in the PD/NSC-25, then an INSRP is empaneled. Thresholds can be used to ensure that the level of analyses and approval process is commensurate with the risk posed by a hazard.

Appendix B. Interview List

Table B-1. Individuals Interviewed by STPI Research Team

Type	Organization	Interviewee Name
Government Agency	DNFSB	Matt Forsabka
	DOD - Air Force	Sayavur I. Bakhtiyarov
	DOD - Air Force	Mark Glisin
	DOE	James M. Heffner
	DOE - Nuclear Energy	Tracey Bishop
	DOE - Nuclear Energy	Dirk Cairns-Gallimore
	DOE - Nuclear Energy	Kelli Markham
	DOE - Nuclear Energy	Mary McCune
	EPA	Chris Hallam
	NASA	Marc Gibson
	NASA HQ	Sue Aleman
	NASA HQ	Len Dudzinski
	NASA HQ	Thomas Hayes
	NASA HQ	Tina Norwood
	NASA HQ	David Schurr
	NASA HQ	Jeff Sheehy
	OSTP (former)	Steve Fetter
	OSTP (former)	Robie Samanta Roy
	NRC	Al Adams
	NRC	Michael Cheok
	NRC	Don Helton
	NRC	John Monninger
	NRC	John Nakoski
	NRC	John Segala
	NRC	Mark Thaggard
	OSTP (former)	Mike Dunlevy
Academic, FFRDC, Laboratory	NASA - Jet Propulsion Laboratory	Mark Phillips
	NASA - Jet Propulsion Laboratory	Paul Van Damme
	NASA - Jet Propulsion Laboratory	Reed Wilcox
	DOE - Idaho National Laboratory	Steve Johnson

Type	Organization	Interviewee Name
	DOE - Los Alamos National Laboratory	Steven Clement
	DOE - Los Alamos National Laboratory	Pat McClure
	DOE - Sandia National Laboratory	Allen Camp
	DOE - Sandia National Laboratory	Ronald Lipinski
	DOE - Sandia National Laboratory	Greg Wyss
	JHU - Applied Physics Laboratory	Yale Chang
	JHU - Applied Physics Laboratory	Ralph McNutt
	NASA - Glenn Research Center	John Hamley
	NASA - Glenn Research Center	Lee Mason
	NASA - Glenn Research Center	Peter McCallum
	NASA - Glenn Research Center	Tomas Sutliff
	NASA - Glenn Research Center	June Zakrajsek
	NASA - Jet Propulsion Laboratory	John Casani
	NASA - Jet Propulsion Laboratory	Reed Wilcox
	NASA - Jet Propulsion Laboratory	Mark Phillips
	NASA - Jet Propulsion Laboratory	Paul VanDamme
	NASA - Kennedy Space Center	Curtis Groves
	NASA - Marshall Space Flight Center	Mike Houts
	Oregon State University	Andrew Klein
Industry or NGO	Atomos Nuclear	Brandon Seifert
	BWX Technologies Inc.	Jonathan Cirtain
	BWX Technologies Inc.	Gene Goldman
	BWX Technologies Inc.	Joe Miller
	Nuclear Energy Institute (NEI)	Everett Redmond
	Nuclear Energy Institute (NEI)	Michael Tschilz
	Ultra Safe Nuclear Corporation	Wesley Deason
	Ultra Safe Nuclear Corporation	Michael Eades
Consultant	Global Nuclear Network Analysis	Susan Voss
	Independent consultant	Tim Frazier
	Independent consultant	Roger Lenard
	Sholtis Engineering & Safety Consulting	Joseph Sholtis

Appendix C. Safety Review Processes for Other Materials and Sectors

The PD/NSC-25 launch approval process previously discussed is the only modern safety review model that has been employed prior to the launch of nuclear material. This ad hoc process has a flexible framework; because each nuclear mission is different, a degree of flexibility can be beneficial. However, the process does not incorporate any clearly defined thresholds (e.g., to determine what risk is "tolerable") and thus the level of risk and safety analysis are not bounded from mission to mission. To date, no power system has been certified for launch by any agency, therefore the current review and approval process is repeated for each mission. Furthermore, given the unique design considerations (initiated fission reaction versus passive radioactive decay), power levels (kilowatts versus watts), and fuel source (uranium versus plutonium) of future fission-based systems relative to RPS, an alternative safety review process could be deployed for fission reactor technologies.

To identify how other sectors conduct safety reviews (including risk analyses) of nuclear or other hazardous materials prior to approving their use, STPI conducted case studies of four sectors. The processes outlined are provided to illustrate methods for developing a safety review process that is commensurate with the risk posed by the technology—duplicative or overabundant analyses are cautiously avoided without compromising safety. There is no perfectly analogous model, but case studies were identified to understand the processes used for approving various hazardous materials, at different agencies across the Federal Government. Given the unique considerations of each sector (technical, political and financial), no single process should be directly adapted for the space nuclear community. Rather each case study represents a few potential pathways that the executive branch can consider for a fission reactor approval process.

In this appendix, safety and risk analyses and subsequent approval processes are examined for the following four approval and review processes over hazardous materials and technologies. Although each process and associated technology has specific considerations, general conclusions and methods are examined for their applicability to space fission reactors. Table C-1 provides a brief overview of the processes examined.

- **NASA's routine payloads of hazardous materials:** the environmental review process for hazardous materials (e.g., hydrazine and beryllium) launched regularly on NASA space missions

- **DOE's safety review process for defense nuclear facilities:** the graded analysis and licensing process for the approval of new or significant alterations to defense nuclear facilities
- **NRC's safety review process for commercial power reactors:** the bounded licensing process for the approval of new reactor designs and licensing of civilian nuclear reactors based on previously reviewed reactor designs
- **Navy and DOE's safety review process for naval reactors:** the certification process for the approval of alterations to the naval reactors used in the U.S. naval fleet

Table C-1. Safety Review and Approval Processes Reviewed in Other Sectors

Case Study	Hazardous Material	Aspects of Interest
Launch of non-nuclear materials	Various (e.g., beryllium and hydrazine)	Routine payload designation (bounded environmental analyses)
Defense nuclear facilities	Fissile and non-fissile nuclear material (e.g., plutonium and uranium)	Safety basis development; graded analyses; unreviewed safety questions (USQs)
Commercial terrestrial nuclear reactors	Uranium (low enriched; <20% uranium-235)	Combined license process; published safety review guidance
Naval nuclear reactors	Uranium (high enriched; >20% Uranium-235)	One-time certification process; defined authorities

Approval Process for Launching Other Hazardous Materials

NASA spacecraft and launch vehicles incorporate a variety of materials and components that could pose a threat to either human or environmental health in the case of exposure (e.g., from a launch failure and subsequent dispersion of the material). In order to satisfy environmental reviews required under law,[40] NASA released an EA in 2011 to provide analysis of the potential impact (to human and environmental health) that materials and equipment commonly used in space missions (hereafter referred to as payloads) posed. After a finding of no significant impact to human and environmental health, future missions that incorporate the payloads covered by the EA—within a given envelope of technical characteristics—are not required to undergo additional environmental reviews.

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[40] National Environmental Policy Act (NEPA) of 1970.

Relevance of comparison group and hazardous material

The process developed for these potentially hazardous payloads illustrates a model for how pre-launch safety review and analyses, specifically to meet NEPA requirements, could be used to bound analyses required on similar missions. The environmental review process for hazardous materials launched regularly on NASA space missions (e.g., hydrazine and beryllium) bounds risk analyses based on analyses conducted for prior missions. Therefore, missions that are considered to contain similar hazardous materials relative to a prior mission (within an envelope of technical characteristics such as launch vehicle and quantity of hazardous material) are not required to undergo additional environmental analyses (e.g., mission specific EA or EIS). As a result of this process, since 2011 only two missions underwent additional NEPA safety reviews prior to launch.

Examples of hazardous materials covered include metals used for structures (e.g., aluminum, beryllium and magnesium), propellants (e.g., hydrazine, and ammonium perchlorate based solid propellants), and other materials (e.g., solar cells, batteries, lasers). These hazardous materials are commonly used by NASA to support mission goals. Safety analyses completed for prior missions have found that, up to certain amounts, their use does not pose a significant impact on human and environmental health. Further detail is provided on two hazardous materials, beryllium and hydrazine.

Beryllium is a light metal with conductive properties that make it desirable for use in the structure of spacecraft. For example, the metal was used in window and door frames on the Space Shuttle to add strength, and in the James Webb Telescope's mirrors due to the metal's light weight and ability to conduct electricity and heat (Gutro 2009). Beryllium metal in a powdered form is considered a Group 1 carcinogen by the International Agency for Research on Cancer (IARC) when inhaled.[41] Based on technical analyses completed by Federal agencies, in the case of a spacecraft launch, incident vaporization of beryllium is considered to be "highly improbable." However, if vaporization did occur, dispersal across the Earth's atmosphere would dilute the hazardous materials (NASA 2011). Thus the use of beryllium on spacecraft, for example on structures and electronics, is not considered to have a significant impact on human health or the environment.

Hydrazine is a combustible liquid commonly used as a propellant for spacecraft and launch vehicles. Historically, hydrazine and similar liquids (monomethyl hydrazine and nitrogen dioxide) were used as a propellant for the Titan II and IVB and Deltas II and III launch vehicles and on satellites. Hydrazine is classified by the IARC as a Group 2A carcinogen (NASA 2011), is highly flammable, and is a strong irritant; inhalation of vapors can cause severe and potentially fatal internal burns (NASA 2011). Based on technical

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[41] A Group 1 carcinogen is classified by IARC as "carcinogenic to humans." World Health Organization, "IARC Monograms on the Evaluation of Carcinogenic Risks to Humans," updated January 26, 2018. http://monographs.iarc.fr/ENG/Classification.

analyses completed by Federal agencies, in the case of a spacecraft launch incident, dispersion and oxidation of the hydrazine would be likely; under various failure scenarios involving the largest tanks available at the time (with a capacity of up to 1,850 kg of hydrazine), NASA determined that there would be less than a 1 in 10,000 chance an individual would be harmed.[42] Based on these prior risk and safety analyses, NASA determined that launching spacecraft containing less than 3,200 kg of hydrazine does not have a significant impact on human health or the environment (NASA 2011).

Current review and approval process (including guiding authorities)

To reduce paperwork, the CEQ NEPA regulations encourage Federal agencies to consolidate their environmental impact analyses for similar actions into one EA or EIS (NASA 2011). In response to CEQ and internal NASA regulations, in 2002 NASA first developed a comprehensive environmental assessment to examine the environmental impact of launching common payloads on common launch vehicles from associated launching sites; an updated EA was released in 2011 as data on new payloads, vehicles, and launch sites became available (NASA 2011).

Based on safety and risk analyses conducted for prior missions, the NASA Science Mission Directorate determined that the environmental impacts associated with the launch of certain common payloads do not have an impact on the quality of the human environment (NASA 2011). Within the EA, benchmarks are provided for various materials (examples outlined in Table C-2); any proposed missions, launched on common launch vehicles from one of five sites, that contain amounts below those specified were considered "within the purview of this EA." Therefore, their use does not necessitate additional NEPA analyses from mission to mission. Notably, systems containing nuclear material above an A2 multiple above 10 (inclusive of RPS) are excluded from this analysis due to their "unusual potential for substantial environmental impact" (NASA 2011).

Table C-2. Envelope Payload Characteristics Encompassed by 2011 EA

Subsystem	Envelope Payload Characteristics
Structure	Unlimited: aluminum, beryllium, carbon resin composites, magnesium, titanium, and other materials unless specified as limited

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[42] Under NASA Standard 8719.14, specifically Requirement 4.7, the risk of human casualty from reentry of debris must be below the threshold of 1 in 10,000. NASA determined this threshold was not reached, based on EPA's 1-hour interim Acute Exposure Guideline Level-2 (AEGL-2) of 17mg/m^3 of airborne hydrazine in an exposure period of 10 min to 8 hours.

Subsystem	Envelope Payload Characteristics
Propulsion	Liquid propellant(s); 3,200 kg (7,055 lb.) combined hydrazine, monomethyl hydrazine and/or nitrogen tetroxide Solid Rocket Motor (SRM) propellant; 3,000 kg (6,614 lb.) Ammonium Perchlorate (AP)-based solid propellant
Communications	Various 10-100 Watt (Radio Frequency) transmitters
Science Instruments	Unlimited Solar cells (e.g., 5 kilowatt-Hour (kW-hr) Nickel-Hydrogen (NiH2) or Lithium ion (Li-ion) battery)
Other	10 kilowatt radar American National Standards Institute safe lasers U. S. Department of Transportation (DoT) Class 1.4 Electro-Explosive Systems (EEDs) Radioactive materials in quantities that produce an A2 mission multiple value of less than 10 Propulsion system exhaust and inert gas venting

Source: Adapted and summarized from Table 2.1 in NASA, "Final Environmental Assessment for Launch of NASA Routine Payloads," *NASA Headquarters*, Washington, DC (2011).

Since 2011, only two NASA missions, OSIRIS-REx and Mars 2020, have undergone additional analyses to meet NEPA requirements (NASA n.d.-g). Additional analyses were required since both missions contain hazardous payloads that are not covered by the 2011 EA. Analyses were limited for the OSIRIS-REx mission to an environmental assessment to examine the impacts of returning asteroid samples to the Earth's surface; a finding of no significant impact was published (NASA 2013). Given the use of radioisotope isotope power systems and plan to return Martian soil to Earth, the second mission—Mars 2020—underwent more rigorous environmental analyses and public reviews, with the publication of an environmental impact statement.

Applicable lessons for space fission systems

The 2011 EA illustrates a model for bounding risk analyses. Within the EA, a threshold is provided for the amount of hazardous material that is acceptable—considered to not pose a significant risk to human health or the environment—for missions launched on common launch vehicles. Risk analyses are thus bounded, only requiring additional risk analysis if new hazardous materials are incorporated into a mission's design. Therefore from mission to mission, mission designers and owners are able to reasonably predict whether additional environmental analyses, and thus financial resources, are required from the start of the mission (pending launch vehicle choice).

Figure C-1 provides a comparison of the environmental review process that is required for the routine payloads relative to other materials.

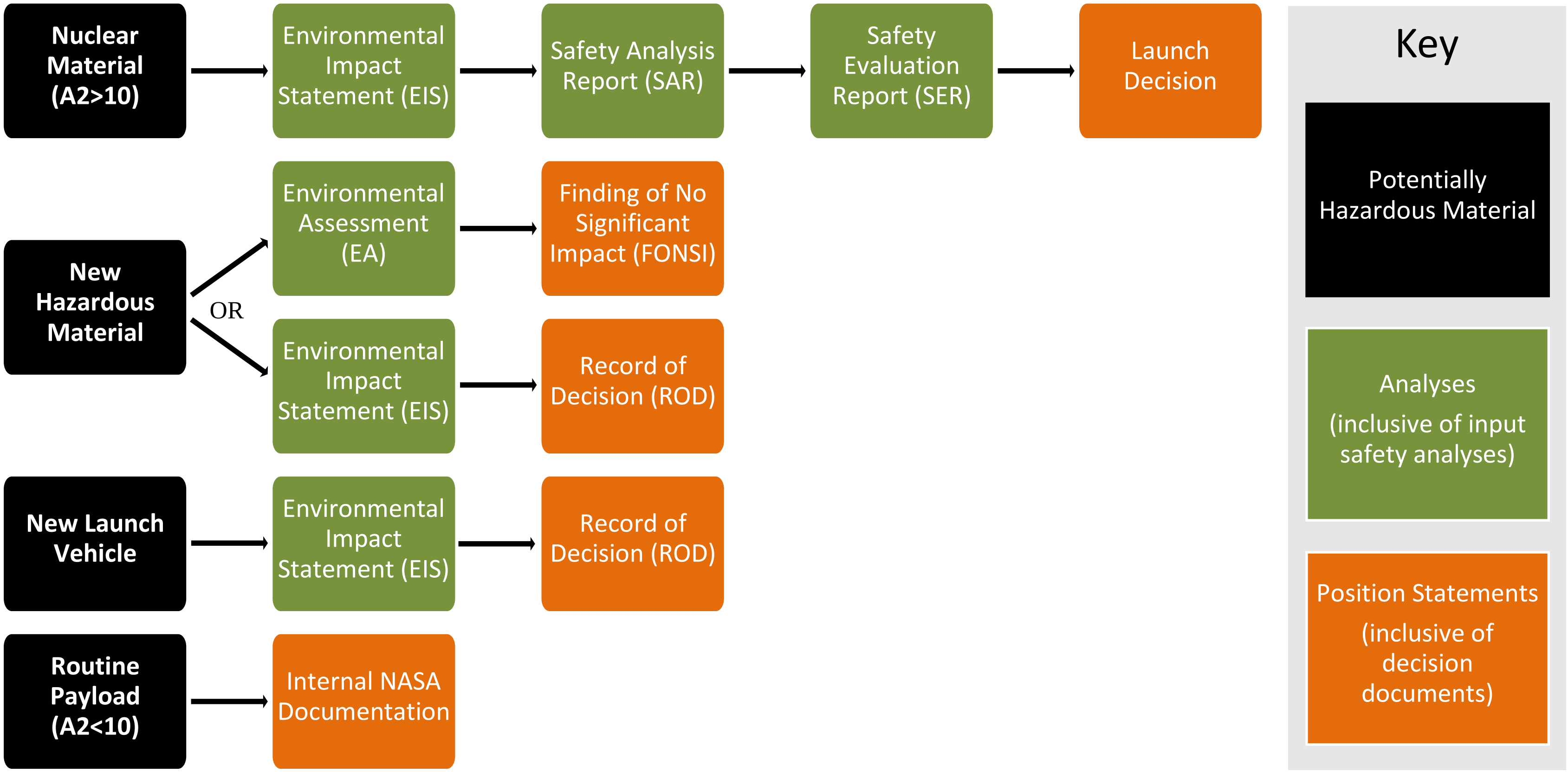

Figure C-1. Overview of Environmental Review Process for Various Potentially Hazardous Materials

Clear standards and thresholds for acceptable risk were referenced throughout the 2011 EA, based on NASA Standards, standards from other Federal entities (e.g., EPA), or the best available research and analysis. For example, EPA's acute Exposure Guideline Level-2 (AEGL-2) for hydrazine was used by NASA to determine a threshold for an acceptable amount of exposure to hydrazine in the case of a launch failure—leading to the 3,200 kg figure. NASA was able to justify their finding of no significant impact, released as a result of the EA analyses, by referencing the established and published safety thresholds. Additional, and potentially duplicative, safety analyses (in an Environmental Impact Statement) were not required for missions containing these hazardous materials.

Although the model currently excludes nuclear material categorically with radioactivity (mission multiple above 10),[43] lessons from this approach could be used to reduce, rather than eliminate, the analyses required prior to launch of fission based systems. Based on expert interviews, a programmatic EA is under development for RHUs. In a similar approach to the routine payloads, prior safety analyses will be used to cover the environmental review requirements under the NEPA. Subsequent missions within a certain envelope of characteristics (e.g., no earth return or operations in Earth's orbit) that contain RHUs would not need additional environmental reviews (e.g., EA or EIS).

Limitations of comparison to space fission systems

Bounded analyses are possible since the risk posed by the hazardous materials is determined to be minimal; if a finding of significant impact were found, this model would not be applicable. Additional analyses would be required through an EA or EIS, potentially specific to the mission, and a decision would be necessary to determine if the risks posed are acceptable given the goals and benefits of a mission.

New launch vehicles are not currently covered by the EA referenced. New analyses would be required to determine what unique risks are enabled due to new vehicle designs. However, prior analyses could be incorporated, as was done between the 2002 and 2011 EA, reducing duplicative analyses for materials or subsystems that have not changed significantly.

Safety Review of Defense Nuclear Facilities

Prior to operation or when a significant alteration is considered, defense facilities with nuclear (fissile and non-fissile) material undergo a three-step review and approval process. The process incorporates environmental reviews and risk assessments for proposed actions

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[43] Currently, the amount of radioactive material that produce an A2 mission multiple value of less than 10 is approximately 30 g of Pu-238; this is exclusive of most radioisotope heater units, power systems, and fission reactors.

to be completed by the facility's contractor, and is governed by DOE with oversight from the Defense Nuclear Facilities Safety Board (DNFSB).

Relevance of comparison group and hazardous material

DOE operates 10 defense nuclear facilities that are designed to handle radioactive materials. An additional four sites, where operations have ceased, are also under DOE's jurisdiction as post-operation environmental remediation continues (DNFSB n.d.). Various types of fissile and non-fissile radioactive materials are handled at these sites to support activities such as nuclear stockpile stewardship, nuclear fuel production, and research and development on nuclear technologies and weapons. Therefore, safety and risk analyses are developed to prevent and mitigate the release of nuclear material at these sites in an effort to prevent health issues associated with ionizing radiation and nuclear proliferation.

Current review and approval process (including guiding authorities)

In response to regulations outlined in 10 CFR 830, DOE has developed a three-stage framework to identify potential hazards, analyze and develop a basis for safe operations, and review alterations to existing equipment (Figure C-2). Specific aspects of the process are further outlined in agency-level regulations. Throughout the process, the DNFSB, an independent Federal entity established by Congress, provides analyses and review of the DOE's defense nuclear facilities.[44]

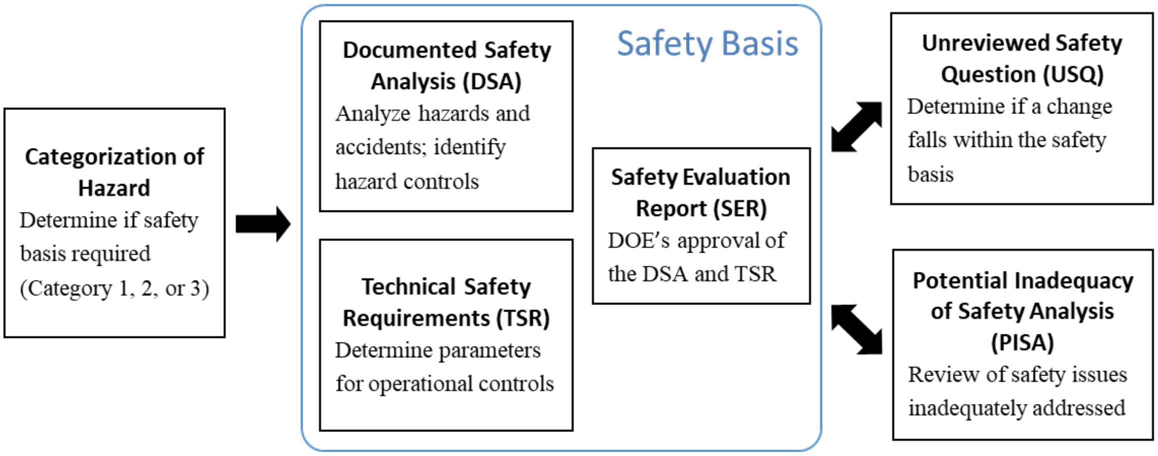

Figure C-2. Overview of 10 CFR 830 Process for Defense Nuclear Facilities

To guide the level of safety and risk analyses required, a hazard is first categorized based on the level of consequence perceived possible. Hazards are categorized into three categories. Category 1 is considered to have the highest potential for harm; in the event of

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[44] 42 U.S.C. § 2286.

a severe accident, the health consequences would extend beyond the facility. Currently only two research reactors are elevated to this level. A majority of facilities and reactors are classified as either Category 2 or 3; in the event of a severe accident, the health consequences would have significant onsite consequences or remain localized (e.g., to a room), respectively.

After a hazard is categorized, two documents are developed containing the Documented Safety Analysis (DSA) and Technical Safety Requirements (TSR), to systematically assess the hazard and develop parameters and safeguards to ensure safe operations. Within the DSA, hazards are analyzed and accident scenarios are evaluated to determine which controls are necessary for a given technology or substance. Based on these analyses, controls are developed and outlined in the TSR to outline what would be considered permitted for normal operations. The two documents are prepared by DOE contractors and evaluated by DOE, and the approved controls are outlined in the SER. Once these analyses are completed and accepted by DOE, the documents constitute a "safety basis." Any alterations to the design of the facility, as long as they are within the technical parameters outlined in the documents that constitute the safety basis, do not require additional review or approval from DOE.

Once a safety basis is developed and approved, two processes are outlined by DOE to determine whether additional analyses are required: if (a) a change, not explicitly referenced in the safety basis, is proposed or (b) an analysis is found to be incorrect (e.g., due to advances in the scientific understanding of a certain material). In the first scenario, a series of seven high level yes/no questions are asked through the USQ process. For example, one question asks if the proposed change will increase the probability of an accident occurring. In the case that a question fails to reach a positive response, additional safety analyses are required; however if all questions are answered in the affirmative, no additional analyses are required. Finally, in the case that an inadequacy is identified in analyses completed for the safety basis, additional analyses are completed and the results are added to the safety basis.[45] Thus, the safety basis is consistently being updated as new knowledge and safety concerns are identified.

Applicable lessons for space fission systems

Through the development of a technology (or facility) specific safety basis, design alteration or use of a similar technology at other sites requires fewer safety and risk analyses. Once a safety basis is developed, a clear set of technical attributes are outlined to give clarity to what is included within a safety basis. Use of the USQ and PISA processes help facility owners to understand if alterations to designs require additional analyses.

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[45] The results of additional analyses are completed by the contractor and reported to DOE through an Evaluation of the Safety of the Situation (ESS) document.

Additionally, the use of a graded approach ensures the level of safety and risk analysis triggered is commensurate with risk posed by technology. For example, the analyses and level of resources required for a Level 1 facility is significantly higher than a Level 3 facility. Therefore, contractors are able, early in the process, to identify the amount of analysis required to receive approval for their actions.

Limitations of comparison to space fission systems

The current DOE process is designed for facilities that often operate for multiple decades near populous areas. Therefore, the exact safety basis developed and analyses conducted include considerations for operations that would not be directly relevant to space missions (e.g., transport and handling of nuclear waste, ensuring safe operations for workers).

Licensing and Safety Review of Terrestrial Civil Nuclear Power

Prior to operation, terrestrial nuclear power plants undergo a multi-year licensing process outlined by the NRC. The licensing process incorporates environmental reviews and risk assessments for proposed nuclear power reactors.

Relevance of comparison group and hazardous material

Clearly outlined processes are set out by the NRC in agency communications and guidelines that a designer (often commercial actors) can use when developing safety analysis reports. Analyses required, and targets for tolerable risk are articulated for commercial actors prior to their development of a SAR. The licensing process that follows, for the approval of additional reactors based on a previously licensed design, provides an example of a bounded safety analysis that is clearly defined. A new reactor's license articulates technical aspects that are considered within an envelope—when a new reactor is built, if it is within the scope of the standard design certification, fewer safety analyses are required to be duplicated.

Although this process can take over a decade to complete for reactor designers and operators and cost up to a billion dollars, the process provides an example of a bounded licensing and risk assessment process that could be adapted for future space nuclear reactors. Given that the current scope of the fission safety analyses is focused mainly on launch activities (and not on the safe operation of reactors outside earth's orbit), additional oversight by NRC exists that is outside the scope of this report (e.g., waste transit and disposal, the operation of reactors, and workplace safety). This section focuses on safety analyses and the process undertaken to determine whether a reactor design is safe, inclusive of both activity prior to and during operation.

Civilian nuclear reactors are designed to provide commercial power or to support non-power activities (e.g., research and testing). Within the U.S., low enriched uranium is used in a majority of civilian reactors (fuel is, on average, composed of 3–5 percent of the uranium-235 isotope); the remaining reactors are research reactors that use highly enriched uranium (fuel is composed of at least 20 percent of the uranium-235 isotope). Once a fission reaction is initiated in a reactor, radioactive materials and ionizing radiation is produced and contained within the reactor core; only when containment structures are severely damaged are the radioactive materials and radiation released. Exposure to airborne radioactive material and contaminated soils or water can be fatal (NCI n.d.). Therefore when reactor designs are evaluated for a license by the NRC, safety features must be developed that would limit radiation exposure, in the case of an accident, to a “once in a lifetime accidental or emergency dose,” estimated to be 25 rem total effective dose equivalent within a 2-hour period.[46]

Current review and approval process (including guiding authorities)

Pursuant to the Atomic Energy Act of 1954, and the Energy Reorganization Act of 1974, the NRC has developed regulations to outline a licensing process for all terrestrial nuclear reactor designers and operators.[47] Prior to 1989, the NRC required nuclear power plants to undertake a two-step licensing process. The first step, the construction permit, requires preliminary safety analyses, an environmental review, and financial and antitrust statements. The permit is reviewed by NRC, an independent Advisory Committee on Reactor Safeguards (ACRS), and the general public through public meetings. The second step, the operating license, incorporates a final safety analysis report and environmental report based on final design and location details. In addition to NRC and ACRS, the Federal Emergency Management Agency (FEMA) reviews the operation application prior to approval (NRC 2004).

In 1989, additional regulations were developed to simplify the licensing process into a combined process.[48] Under a combined license review, reactor designers and operators can reference a previously awarded early site permit, standard design certification, both, or neither to simplify the process. Figure C-3 provides a high-level overview of the combined license review process. The reactor design is analyzed through an environmental review and safety analysis. Once a design is certified, the NRC can only change the certified design in limited circumstances that are clearly outlined to the designer. A standard design certification is valid for 15 years and can be renewed for an additional 15 years. Thus, if a

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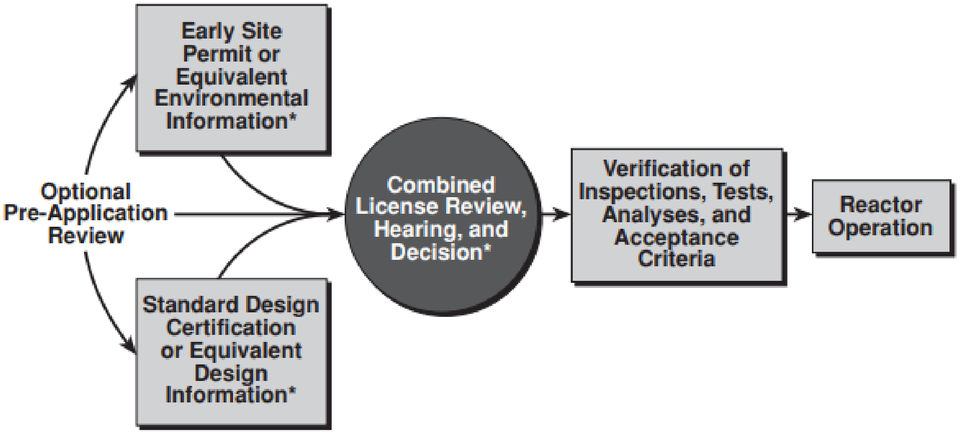
[46] 10 C.F.R. 50.34.

[47] 10 C.F.R. 50.

[48] 10 C.F.R. 52.

similar reactor design is used at multiple locations, only one single "standard design certification" would be necessary.



Source: U.S. Nuclear Regulatory Commission, "Nuclear Power Plant Licensing Process," Washington, DC, rev. 2 (2004).

Figure C-3. Combined License Review Process Overview

Additionally, through an early site permit one or more sites with similar attributes are approved for a given nuclear reactor technology, independent of a construction or combined license. Therefore if an operator seeks to build multiple reactors of the same type at various sites, an early site permit could be granted to encompass current and future sites that meet parameters set out in the license. An early site permit is valid for 10–20 years, and can be renewed for an additional 10–20 years.

To bound safety analyses, the NRC publishes goals for risk analyses; risk assessments are evaluated against these goals. For example, two metrics are used in risk analyses, the core damage frequency (CDF) and large early release frequency (LERF), the expected frequency of a reactor core will be compromised or radioactive materials will be released, respectively, during a year of a reactor's operation. The NRC has set a goal for its licensees to demonstrate that the risk associated with their reactor's design has CDF of less than 1×10^{-4} per year[49] and a LERF of less than 1×10^{-5} per year (Bengtsson et al. 2011). Further, fatalities from nuclear disaster must not exceed one-tenth of one percent (0.1 percent) of fatality risks from resulting from other accidents that "the U.S. population are generally exposed" (Bengtsson et al. 2011).

The NRC publishes a series of recommendation and guidance documents, accessible for license applicants and NRC staff, outlining further technical details on approaches considered acceptable to meet regulations outlined by the NRC. The regulatory guides and

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[49] Less than 1 in 10,000 chance a reactor will be compromised within one year of operation.

branch technical positions provide an overview of what is recommended (rather than required) for the analyses conducted for the safety analysis reports prepared by licensees. For example, the *Standard Review Plan* is a document that outlines the “methods or approaches that the [NRC] staff found acceptable for meeting NRC requirements” (NRC 2007). The *Standard Review Plan* was rigidly developed for light-water reactors (LWR), and provides a structure for the content and analyses that are expected in the Safety Analysis Report submitted by licensees.

Additional guidance has been published for test and research reactors, which have designs more diverse than LWR. For example, for research and test reactors the *Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors* document outlines procedures that are technology neutral (NRC 1996).

Additional licensing pathways are outlined by the NRC, but are seldom used.[50] For example, the American Nuclear Society through its Nuclear Grand Challenges project identified that novel reactor technologies could be first constructed as a prototype plant with enough safety measures to justify a near-term NRC approval (for the construction of a prototype). A license-by-prototype approach has been proposed to ease and shorten design certification processes (American Nuclear Society 2017).

Applicable lessons for space fission systems

Although the current terrestrial process may be onerous, the licensing process has clearly defined risk analyses and metrics (e.g. level of risk that is acceptable), and can be generalized to a nuclear reactor design (e.g. standard design certification). Rigid requirements and thresholds develop a relatively clear and predicable process for licensees. Entities applying for licenses have an understanding of what risks are deemed acceptable by NRC—they do not change from application to application.

NRC’s combined license review is one methodological approach that could be adapted for space fission reactors that are relatively similar in design. The NRC model provides an illustration of how a reactor design can be approved once, only requiring additional review if modifications that lie outside a pre-determined envelope are made in future uses. Mission specific considerations could undergo additional analyses, conducted outside the design certification (e.g., analogous to an early site permit).

Limitations of comparison to space fission systems

The necessary safety considerations for the operation of a nuclear reactor and the handling of its waste are not directly relevant for space missions—especially unmanned missions. For example, the process outlined nuclear power plants was developed for

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[50] 10 C.F.R. 50 and 10 C.F.R. 52.

reactors that operate at higher power outputs (megawatts rather than kilowatts) and for longer lengths of time near populous regions relative to space fission reactors.

Interviewees indicated that although relative flexibility is provided through the combined licensing process, safety analyses and license proposal reviews take at least a decade and cost on the order of billions of dollars. However, these costs are inclusive of analyses completed to ensure safety of operations at a facility near a populous regions—a consideration that is not relevant for space missions.

Additionally, the current NRC licensing process was designed based on risk and safety considerations specific to the technical designs of generation I and II reactors; thus it is relatively inflexible to new reactor designs and concepts. Interviewees indicate that it currently is expensive and time consuming to meet the NRC technical safety requirements, especially for newer reactors (e.g., Gen III and IV) that have different technical aspects—some of which reduce safety concerns while opening new safety vulnerabilities not previously considered.

Licensing and Safety Review of Naval Reactors

Although technical details on the approval process are not publicly available, the Naval Nuclear Propulsion Program (NNPP) provides a unique model for incorporating non-Federal contractors to support personnel and project management during risk assessment and operations.

Relevance of comparison group and hazardous material

Naval reactors are designed to both operate under harsh battle conditions and near sailors who live in close proximity to the reactors. A majority of naval reactors are manufactured based on a pressurized water reactor design; the underlying technology has been widely adopted by the commercial terrestrial nuclear power industry with a long history of safe operations. To endure combat situations, the nuclear reactors are specifically designed to withstand shock loads greater than 10 times the earthquake shock load used for designing commercial terrestrial nuclear plants in the United States, and use highly enriched fuel to provide enough energy to allow for a single fuel loading over the service time of a ship (e.g. 30 years) (DOE 2014).

Current review and approval process (including guiding authorities)

The NNPP is jointly run by the Navy and National Nuclear Security Administration (NNSA) as defined by Executive Order 12344 and U.S. law. The program has cradle-to-grave responsibility for nuclear propulsion reactors used by the Navy. In 2015, the NNPP operated 96 nuclear reactors across the Navy, with a history of over 6,700 reactor-years of operation.

Unique to the program, the prime contractor Bechtel Plant Machinery Inc. is employed to provide technical oversight, and is responsible for the design, purchase, quality control, and delivery of nuclear reactors (Naval Nuclear Propulsion Program 2015). The company primarily contracts with BWXT to develop reactors. The reactors, developed and tested by BWXT, are currently produced at a rate of 2.4 per year with a staff of approximately 5,000. Historically nearly 500 reactors have been built; to date, the program reports that no nuclear reactor incidents or activities have released any level of radioactive material that would have an adverse effect on human health or the environment based on EPA guidelines (NNSA n.d.).

Reactors currently in use by the Navy were certified for safety multiple decades ago, when the program first began. Recertification of the reactor design has not been required since, as it has remained similar in design. Thus when a reactor is manufactured, testing is completed in-house by BWXT and no additional safety approval processes are required, as long as the reactor is manufactured within a set of predetermined design requirements determined by both DOD and DOE. In the event of alterations to a reactor design, clearly defined criteria are set out by NNPP to indicate scenarios for which additional review is required.

Applicable lessons for space fission systems

The program contracts with a dedicated prime, who has a viewpoint of the entire lifecycle of the nuclear reactor fleet. By contracting with the same equipment manufacturers for decades and developing a trained class of sailors with expertise on nuclear technology, the program is able to sustain a continued expertise while controlling supply chains to reduce risk throughout manufacturing and testing.

Certification of one design early on has simplified the development and deployment of numerous reactors to battle-ready ships. If fission reactors were widely deployed on future space missions, the use of one uniform reactor model could help streamline the safety and risk analysis process.

Further, in the case of a new reactor design (and thus the need for a new certification), the current process for naval reactors only requires the oversight and approval of two agencies—the DOD and DOE. As both the mission owners and reviewers, they are able to provide oversight and incorporate other Federal agencies as they see fit.

Limitations of comparison to space fission systems

Current demand for naval reactors, driven by national security considerations, enables a consistent and predictable manufacturing process—development of reactors is not one off. Additionally, given national security requirements, costs required to ensure that the naval reactors are at peak performance may be easier to justify relative to other non-defense oriented missions.

The safety considerations related to the operation of a nuclear reactor in close proximity to sailors, and the handling of its waste, are not directly relevant for space missions—especially unmanned missions. Although outside the scope of this report, future manned space missions that incorporate fission technology (e.g., power or propulsion) could incorporate lessons learned from the NNPP (e.g., ensuring the safety and of a trained workforce working and living alongside fission reactors).

Takeaways from Case Studies

Case studies were developed to illustrate potential pathways for resolving challenges for launch approval of space nuclear fission (propulsion and power) systems; however, no model is perfectly analogous. A selection of high-level lessons on relevant processes from each sector is provided in Table C-3.

Table C-3. Relevant Lessons for Space Nuclear Community, by Sector

Case Study	Lessons on Approaches and Methods
1. Launch of non-nuclear materials	Bounded analyses, based on thresholds, reduce duplicative analyses Clearly defined thresholds provide clarity to mission owners
2. Defense nuclear facilities	Safety basis develops a technology specific certification, reducing duplicative analyses in future uses A graded approach ensures the level of analysis triggered is commensurate with risk posed by technology USQ and other processes isolate additional analyses
3. Commercial terrestrial nuclear reactors	Combined license process separates certification, and thus analyses, of reactor technology from specific use case Published safety review guidance and risk threshold goals provide clarity to licensees, reducing unnecessary analyses
4. Naval nuclear reactors	Use of the same reactor design has required only one certification over past few decades Clearly defined authorities facilitate clear communication of expectations between user and manufacturer/tester

Appendix D.
Radiological Contingency Planning

Radiological Contingency Plans (RCP) are in place to prepare for a scenario where there is a release of radioactive material. The RCP process serves three main purposes: (1) identify whether radiologic release has occurred after a launch or on-orbit accident and estimate the magnitude, nature, and dispersion path of the material that has been released; (2) prepare for what to do in the case of an accident, including the development of scenario-specific response plans, implementation procedures for those plans, and preparedness exercises for responders; and (3) establish communication channels to notify the appropriate authorities (e.g., local responders) and the public of an accident and disseminate accurate information on what to do in the case of an accident.[51]

This process builds on the emergency response plans that are already in place for other launches.[52] Some activities are specific to RCP as compared to general contingency planning, such as modelling the potential dispersion of radiologic particles. These models are needed in addition to gas distribution models that are used to analyze the dispersion of propellants during a potential launch area accident and will have slightly different results. Other RCP activities include equipping and training field monitoring teams to do radiologic surveys. This includes placing ECAMs, which select for particle sizes that can be inhaled and retained in a human lung, to identify whether a radiologic release has happened. ECAMs improve the rate of feedback to the control centers during a launch and reduce the human footprint that is required to take air quality samples (NASA n.d.-e).

According to RPS Program Budget Development estimates, RCP requires around $8.2 million dollars for launches involving RTG and/or RHU systems. RCP begins around 3 years prior to a mission's launch date and is run in parallel to the launch approval process.[53] RCP activities are primarily coordinated at the Radiological Control Center at

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[51] To see the stated goals in the National Response Framework that dictate radiological contingency planning, see: United States Department of Homeland Security, National Response Framework, January 2008, http://www.fema.gov/NRF, "Nuclear/Radiological Incident Annex", Page 1.

[52] The RCP process builds on planning protocols that are in place for any mission and is dictated by the NRF. The requirements for contingency planning specific to radioactive payloads can be found in the Nuclear/ Radiological Incident Annex of the NRF. In addition to the NRF, agency requirements further assign roles and responsibilities for RCP (e.g., NASA Procedural Requirements (NPR) 8715.3D chapter 6.2).

[53] See the white paper, "United States Preparedness and Response Activities for Space Exploration Missions Involving Nuclear Power Sources," from the 49th session of the UN Committee on the

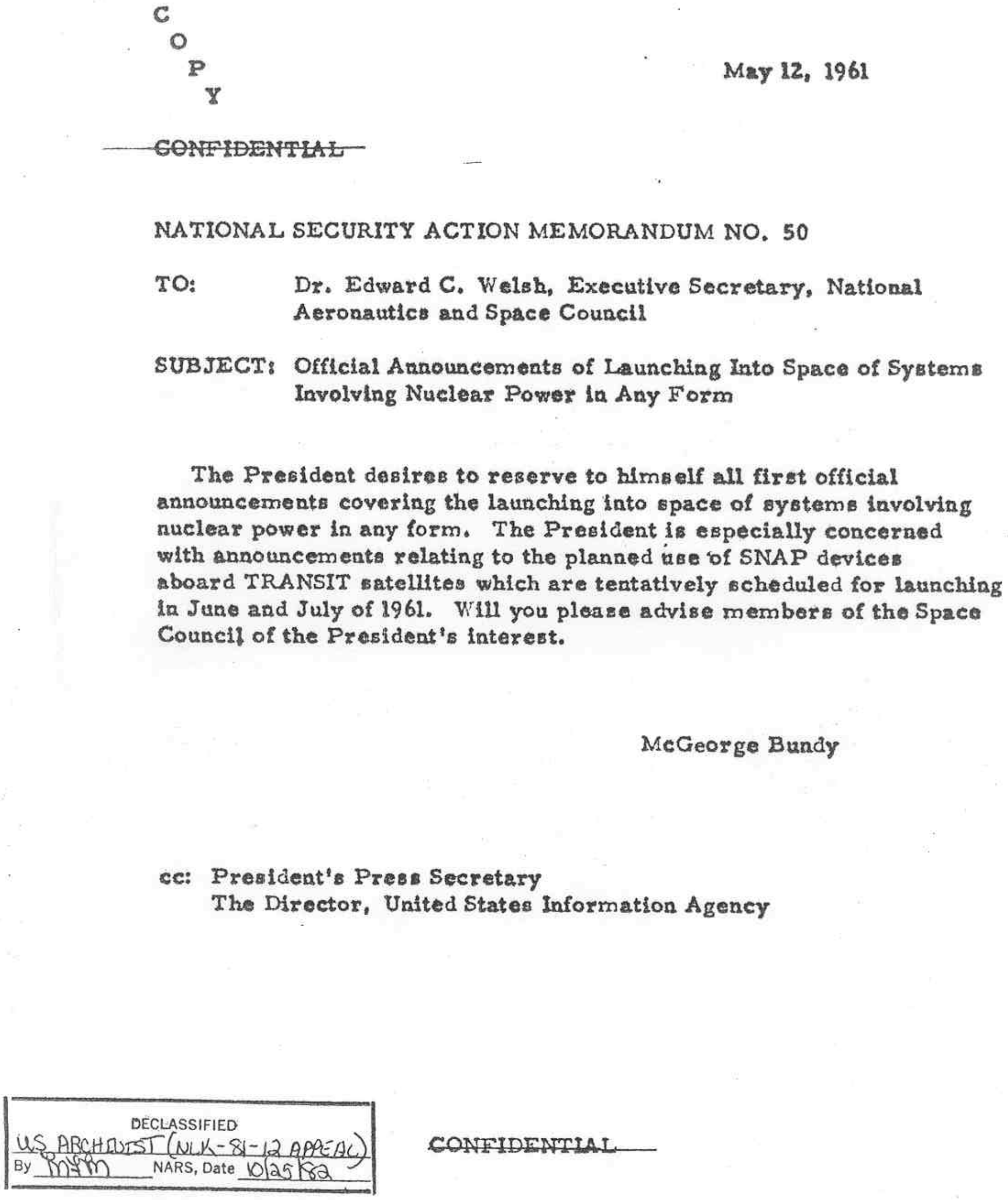
the Kennedy Space Center. Three years prior to launch, a multi-agency working group is established to define a concept of operations that is consistent with the NRF and agency requirements. Participants of the working group include agencies at the Federal, State, and local level. Part of the working group's function includes identifying and reviewing lessons-learned from previous missions. About 2 years prior to launch, NASA designates the individual who will be the mission lead for RCP. This individual is called the coordinating agency representative. The working group then works under the coordinating agency representative to develop scenario-specific RCPs, implementation procedures, and joint-agency communication plans. By 1 year prior to launch, a multi-agency review and approval process finalizes and obtains signature-approval for the RCPs and conducts training programs and exercises.

RCP overlaps with the launch approval process in a couple of key ways. First, RCP depends on the results from the NRA and the SAR to develop the scenario-specific response plans. For instance, the NRA provides a potential range of outcomes that enable the RCP team to start drawing up contingency plans. Because the NRA often happens before the launch vehicle has been selected, the estimates for the dispersion of radiologic material may change after the NRA is finished. RCP teams rely on results from the SAR to improve the contingency plans before the launch and get a more accurate estimation of release, which can improve planning. For instance, data from the SAR enables the RCP team to create more accurate models of the potential dispersion of radiologic particles and set up the ECAMs in the best locations to get an accurate reading in the case of an accident. Another link between RCP and launch approval occurs at the end of the launch approval process. Prior presentations to OSTP have often included a specific section on contingency planning.[54] Enabling the development of comprehensive radiological contingency plans is therefore important for launch approval, as RCP helps provide evidence to the decision makers that safety has been effectively integrated into the system.

Peaceful Uses of Outer Space (2012) for a visual chart comparing the RCP timeline in relation to launch approval.

[54] Interview with Subject Matter Expert

Appendix E. National Security Action Memorandum (NSAM) No. 50



C
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May 12, 1961

~~CONFIDENTIAL~~

NATIONAL SECURITY ACTION MEMORANDUM NO. 50

TO: Dr. Edward C. Welsh, Executive Secretary, National Aeronautics and Space Council

SUBJECT: Official Announcements of Launching Into Space of Systems Involving Nuclear Power in Any Form

The President desires to reserve to himself all first official announcements covering the launching into space of systems involving nuclear power in any form. The President is especially concerned with announcements relating to the planned use of SNAP devices aboard TRANSIT satellites which are tentatively scheduled for launching in June and July of 1961. Will you please advise members of the Space Council of the President's interest.

McGeorge Bundy

cc: President's Press Secretary
The Director, United States Information Agency

DECLASSIFIED
U.S. ARCHIVIST (NLK-81-12 APPEAL)
By ____ NARS, Date 10/25/82

~~CONFIDENTIAL~~

Appendix F. Presidential Directive/National Security Council (PD/NSC) 25

THE WHITE HOUSE
WASHINGTON

December 14, 1977

PRESIDENTIAL DIRECTIVE/NSC-25

TO:
The Secretary State
The Secretary of Defense
The Secretary of Energy
The Secretary of the Interior
The Secretary Agriculture
The Secretary of Commerce
The Secretary of Health, Education, and Welfare
The Secretary of Transportation
The Acting Director, office of Management and Budget
The Assistant to the President for National Security Affairs
The Chairman, Council on Environmental Quality
The Director, Office of Science and Technology Policy
The Director, Arms Control and Disarmament Agency
The Administrator, Environmental Protection Agency
The Administrator, National Aeronautics and Space Administration
The Director, National Science Foundation
The Chairman, Nuclear Regulatory Commission

SUBJECT: Scientific or Technological Experiments with
Possible Large-Scale Adverse Environmental
Effects and Launch of Nuclear Systems into Space

Two earlier Presidential memoranda dealt with the conduct of scientific or technological experiments that might have large-scale or protracted effects on the physical or biological environment (NSAM 235 of April 17, 1963) and the launching into space of systems involving nuclear power (NSAM 50 (revised) of April 10, 1965). These two NSAMs are hereby rescinded. The general purpose, however, behind these two directives--to give the President the opportunity to consider all factors before any such experiment is carried out-remains valid. The President has approved the policy and procedures below to accomplish that purpose.

It should be understood that experiments which by their nature could reasonably be expected to result in domestic or foreign allegations that they might have major and protracted effects on the physical or biological environment, or other areas of public or private interest, are to be included under this policy even though the sponsoring agency feels confident that such allegations would in fact prove to be unfounded.

Where such experiments constitute major action either licensed or funded by Federal Agencies that significantly affect the quality of the human environment, an environmental impact statement will be prepared. The data from such statement may be used in complying with the following procedures which do not affect the requirement to comply with the provisions of the National Environmental Policy Act:

1. The head of any agency that proposes to undertake a large-scale scientific or technological experiment that might have major and protracted effects on the physical or biological environment, or on other areas of public or private interest, will call such proposals to the attention of the Director of the Office of Science and Technology Policy (hereafter the Director). The Director will consult with the Chairman of the Council on Environmental Quality (hereafter, the Chairman). Notification of such experiments will be given sufficiently in advance that they may be modified, postponed, or canceled, if such action is judged necessary in the national interest.

2. In support of proposals for such experiments, the sponsoring agency will prepare for the Director a detailed evaluation of the importance of the particular experiment and the possible direct or indirect environmental effects that might be associated with it. The data from an environmental impact statement may be used in complying with this procedure.

3. The Director in consultation with the Chairman will review the proposals and supporting materials presented by the sponsoring agency in order to assure that the need for the experiment has been properly weighed against possible adverse effects.

4. On the basis of this review, the Director in consultation with the Chairman will recommend to the President what action should be taken on the proposed experiment. If the Director, in consultation with the Chairman, judges that inadequate information is available on which to make a judgment, the Director may request that additional studies be undertaken by the sponsoring agency or may undertake an independent study of the problem. Agencies will be notified if an extended delay is anticipated in approval.

5. In the case of experiments that have major national security implications, the head of the sponsoring agency will notify me so that I may determine on an individual basis the procedure to be followed in reviewing these experiments.

6. While the final decision to conduct such experiments must continue to reside with the government, the National Academy of Sciences and, where appropriate, international scientific bodies or intergovernmental organizations may be consulted in the case of those experiments that might have adverse effects beyond the US. When experiments are expected to have such impacts in foreign countries the Secretary of State will be notified. In arriving at decisions on specific projects, foreign policy considerations should be taken into accounts. Recommendation on the advisability of the courses of action will be made by the Director in consultation with the Chairman and with the sponsoring agency and the State Department as appropriate.

7. Any large scale scientific or technological experiment that may involve particularly serious or protracted adverse effects will not be conducted without the President's approval. Any experiment that may involve serious or protracted adverse effects will not be conducted without the approval of the head of the department or agency involved, with, in appropriate cases, the advice of other concerned agencies.

8. To the extent that it is consistent with national security, and subsequent to approval of the experiment there should be early and widespread dissemination of public information explaining the purpose, benefits, and assessments of impacts.

9. A separate procedure will be followed for launching space nuclear systems. An environmental impact statement or a nuclear safety evaluation report, as appropriate, will be prepared. In addition, the President's approval is required for launches of spacecraft utilizing radioactive sources containing more than 20 curies of material in Radiotoxicity Groups I and II and for more than 200 curies of material in Radiotoxicity Groups III and IV (as given in Table I of the NASC report of June 16, 1970 on "Nuclear Safety Review and Approval Procedures." An ad hoc Interagency Nuclear Safety Review Panel consisting members from the Department of Defense, Department of Energy, and National Aeronautics and Space Administration will evaluate the risks associated with the mission and prepare a Nuclear Safety Evaluation Report. The Nuclear Regulatory Commission should be requested to participate as an observer when appropriate. The head of the sponsoring agency will request the President’s approval for the flight through the Office of Science and Technology Policy. The Director is authorized to render approval for such launchings, unless he considers it advisable to forward the matter to the President for decision.

Zbigniew Brzezinski

Appendix G. Mission Failures with Space Nuclear Systems

Over the past five decades, the United States has flown hundreds of RHUs on various space missions, 46 RTGs on 27 missions (and one more planned for Mars 2020), and one mission with a fission reactor (Cataldo et al. 2011). Out of these missions, three missions containing RPS experienced confirmed failures.[55] For all three missions, the failures were caused by reasons unrelated to the nuclear system itself.

The first major failure involving nuclear material was in 1964 when a Navy navigational satellite, TRANSIT 5BN-3, suffered a computer failure that prevented it from achieving orbit. As a result, the satellite, which was carrying a little less than a kilogram of Pu-238, reentered earth's atmosphere. The system burned up as it was designed to do, releasing approximately 20,000 Curies of Pu-238 into the atmosphere. Traces of Pu-238 were detected in the area a few months later. Despite the release, no human health threat resulted. Subsequently, engineered safety features were changed, and RTGs were designed to survive impact instead of breaking down and dispersing in the event of accidental reentry.

Four years later, at the launch of the meteorological satellite NIMBUS B-1, the launch vehicle was destroyed to avoid an erroneous launch trajectory. The launch vehicle, upper stage, and the spacecraft were destroyed, but the two RTGs onboard remained undamaged. In fact, the systems onboard were so robust that the Pu-238 contained within the two RTGs was recovered and later used on other missions.

Finally, in 1970, en route to the moon, Apollo 13 was terminated due to an oxygen tank explosion. On board the lunar module of Apollo 13 was a SNAP-27 RTG. Upon reentry, SNAP-27 remained undamaged and sank into the South Pacific Ocean where it remains today. No amount of radioactivity above what is considered normal background

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[55] A fourth, unconfirmed, accident involving nuclear material may have occurred on-orbit. The fission reactor SNAP 10A was launched in 1965 and operated successfully for 43 days after which the reactor followed a shutdown procedure after receiving an erroneous signal from a malfunctioning voltage reactor onboard the spacecraft. The spacecraft with the reactor was left in the orbit at 1,300 miles where it is expected to remain for about 4,000 years. However there are indications that in about 1979, the spacecraft broke up into pieces (about 1,700 pieces larger than 1 cm). It is also believed that the debris is from the rocket rather than the reactor, and that the reactor core is intact. There was identification of a debris cloud from the nuclear powered SNAPSHOT satellite with haystack radar measurements, http://www.sciencedirect.com/science/article/pii/S027311770700261X?via%3Dihub

noise has been detected in the area. The cask remains intact on the seabed and is expected to contain the fuel for hundreds of years.

Trends that can be observed from historical mission failures involving nuclear systems include (1) the relative infrequency of release of radioactive material, and (2) the effects of engineered safety on the potential for release of radioactive material. Documenting the historical accident rate and subsequent impacts matters, as this evidence diverges from a common perception that the use of nuclear power systems in space constitutes a high radiation risk to the public. The use of RPS and RHU systems is a relatively mature discipline, and out of the three accidents on record, none has had a significant impact on human health.

The historical trends also emphasize the multifaceted nature of safety. The launch approval process is only one component of the overall safety of the launch of a nuclear system. The risk analyses that are conducted to inform the launch approval decision are one of many factors that support a culture of safety and are additional to the use of engineered safety elements (e.g., an iridium clad that contains the Pu-238 fuel) and other safety procedures. For instance, radiological contingency planning is conducted to prepare for the scenarios in which a release of radioactive material did occur to minimize the public's exposure to radioactive material.[56] Analyzing the launch approval process within this context is important in order to evaluate how this process adds value to the overall commitment to safely using nuclear power systems in space.

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[56] See Appendix D for more information on the RCP process and its relationship to the launch approval process.

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Appendix I. Abbreviations

ACRS	Advisory Committee on the Reactor Safeguards
AEC	Atomic Energy Commission
CatEx	Categorical Exclusion
CDF	Core damage frequency
CEQ	Council of Environmental Quality
CFR	Code of Federal Regulations
CONUS	Contiguous United States
Ci	Curies
DNFSB	Defense Nuclear Facilities Safety Board
DOD	Department of Defense
DOE	Department of Energy
DOT	U.S. Department of Transportation
DSA	Documented Safety Analysis
DSAR	Draft SAR
EA	Environmental Assessment
ECAM	Environmental continuous air monitor
EIS	Environmental Impact Statement
EOP	Executive Office of the President
EPA	Environmental Protection Agency
ERDA	Energy Research and Development Administration
FACA	Federal Advisory Committee Act
FC	Fuel Clad
FEIS	Final Environmental Impact Statement
FEMA	Federal Emergency Management Agency
FONSI	Finding of No Significant Impact
FPS	Fission Power System
FSAR	Final SAR
GPHS	General Purpose Heat Source
HEU	Highly Enriched Uranium
HS-PUO2	heat-source plutonium dioxide
IAEA	International Atomic Energy Agency
IARC	International Agency for Research on Cancer
IDA	Institute for Defense Analyses
INL	Idaho National Laboratory
INSRP	Interagency Nuclear Safety Review Panel
ISRU	in situ resource utilization
JHU	John Hopkins University
LEU	Low Enriched Uranium
LERF	large early release frequency
LWR	Light Water Reactor

MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
MOU	Memorandum of Understanding
MSL	Mars Science Laboratory
MW	Megawatt
NASA	National Aeronautics and Space Administration
NASC	National Aeronautics and Space Council
NEP	Nuclear Electric Propulsion
NEPA	National Environmental Policy Act
NERVA	Nuclear Engine for Rocket Vehicle Application
NFSAM	Nuclear Flight Safety Assurance manager
NGO	Non-Government Organization
NIMS	National Incident Management System
NNPP	Naval Nuclear Propulsion Program
NNSA	National Nuclear Security Administration
NPR	NASA Procedural Requirements
NRA	Nuclear Risk Assessment
NRC	Nuclear Regulatory Commission
NRF	National Response Framework
NSAM	National Security Action Memorandum
NSP	National Space Policy
NSPWG	Nuclear Safety Policy Working Group
NTP	Nuclear Thermal Propulsion
NUREG	Nuclear Regulatory Commission Regulation
OSTP	Office of Science and Technology Policy
PD/NSC	Presidential Directive/National Security Council
PD/NSC-25	Presidential Directive/National Security Council Memorandum 25
PISA	Potential Inadequacies in the existing Safety Analysis
PPD-4	Presidential Policy Directive 4
PRA	Probabilistic Risk Assessment
PSAR	Preliminary SAR
Pu-238	Plutonium-238
R&D	Research and Development
RCP	Radiological Contingency Plan
REC	Record of Environmental Consideration
RHU	Radioisotope Heater Unit
ROD	Record of Decision
RPS	Radioisotope Power System
RTG	Radioisotope Thermoelectric Generator
SAR	Safety Analysis Report
SBIR	Small Business Innovation Research
SEI	Space Exploration Initiative
SEP	Solar Electric Propulsion
SER	Safety Evaluation Report
SMD	Science Mission Directorate
SNAP	Systems for Nuclear Auxiliary Power

SNL	Sandia National Laboratories
STPI	Science and Technology Policy Institute
TSR	Technical Safety Requirements
U-235	Uranium -235
UN	United Nations
USQ	Unreviewed Safety Question

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14. ABSTRACT

OSTP tasked STPI with reviewing the space nuclear launch approval process for radioisotope power systems (RPS) and proposing a potential process for fission power and propulsion. The goals of this project were to examine the key statutory, regulatory, and policy basis for the current launch approval process, identify how the time and cost of the launch approval process breaks down, and analyze if and how the current system might be changed to allow for a safe, timely, and affordable launch approval process. STPI used a multi-modal data collection approach that included hosting a workshop with government stakeholders, performing a literature review, and interviewing nearly 60 subject matter experts to determine options for change to address challenges in the launch approval process. This report presents several options for revising the RPS Launch Approval Process.

15. SUBJECT TERMS

Interagency Nuclear Safety Review Panel; Presidential Directive/National Security Council Memorandum 25; radioisotope heater units (RHUs); radioisotope power systems (RPS); space nuclear launch; space nuclear power and propulsion

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