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DEVELOPING A LAUNCH APPROVAL PROCESS FOR NUCLEAR FISSION REACTORS: LESSONS LEARNED FROM RISK MITIGATION AND APPROVAL PROCESSES IN OTHER SECTORS

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Nuclear fission power and propulsion capabilities currently under development (e.g., NASA's Kilopower technology demonstration project) could enable new science and human exploration missions in the United States. While fission systems have been developed in the past, there are no clear policies related to risk assessment and launch approval processes for future missions that incorporate nuclear fission power systems (FPS), and the assumption is that the processes used for radioisotope systems (RPS) can be extended to fission systems. This may not be appropriate given the technological differences between RPS and FPS. In addition to lessons learned in the previous 50 years for the launch approval process for RPS systems, practices such as bounding analyses and certifying reactor designs could be used to implement current processes outlined in PD/NSC-25 and other agency-level regulations. To identify potential launch approval approaches for fission power systems, current risk mitigation and approval processes were examined for other domains such as naval nuclear propulsion reactors, terrestrial civilian nuclear power plants, and other hazardous NASA payloads. Each process was investigated to understand the technology and risk; how the current approval process is defined and implemented; authorities (e.g. enabling legislation or executive action); resources required for the process, if available; and lessons that could be applicable to FPS.

I. INTRODUCTION

Two general approaches can be used to generate power from nuclear fuels for missions in space: radioactive decay and fission. To date, 26 U.S. missions have been powered by nuclear energy systems. Only one U.S. mission used a fission reactor (SNAP-10A reactor launched in 1965), with the remaining missions powered by radioisotope power systems (RPS).[1] Space nuclear power and propulsion systems are capable of sustaining power over a long duration, remaining independent from solar flux, and can be robust in operation (e.g., consistent performance). These attributes make nuclear systems favorable for powering certain space missions, such as deep space scientific and long duration human exploration.

Primarily because of the missions enabled beyond the moon, nuclear power and propulsion systems were identified for NASA as a high priority for technology development by the U.S. National Research Council in 2012.[2] For example, if successfully developed, NASA's Kilopower fission reactor could provide 1-10 kW_e of electrical power to support science instrumentation, propulsion systems, or additional electricity needs for human exploration missions.[3]

Although there are niches for which space nuclear may be preferred, space nuclear systems can become a challenge to include into some missions, due to safety and security concerns, high cost of fuels, and relatively low specific power (power produced per unit weight of power source). Recent advances in fission power technologies and their unique application in mission designs, relative to RPS, warrants an examination of new approaches to evaluating risk and subsequently designing an approval process prior to launch.

II. CURRENT APPROVAL PROCESS

Prior to approval for launch, missions containing nuclear material are subjected to additional safety-related requirements. A high level launch approval procedure was first formalized in a Presidential Directive in 1977 (PD/NSC-25), and was updated in 1995 and 1996. The Directive requires a multi-agency review process prior to the launch of nuclear material.[4]

Under PD/NSC-25 a nuclear safety evaluation report (SER) or an environmental impact statement (EIS), a process dictated by the National Environmental Policy Act of 1969, is required for every launch containing nuclear material with a radiation activity of over 1,000 times the A_2 value defined by the International Atomic Energy Agency (IAEA).[1] All RPS and fission systems currently contain enough radioactive material to be above this threshold. An ad hoc Interagency Nuclear Safety Review Panel (INSRP) is required to evaluate the risks associated with the mission and prepare the SER. Finally, a Presidential approval via the Office of Science and Technology Policy (OSTP) is required for any launch containing nuclear material.

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[1] A2 refers to the radioactivity limits in terabecquerel (the unit of radioactivity) for Type A packages for "non special form" material. Type A packages are those intended to provide a safe and economical means of transporting a well-defined, but significant, minor quantity of radioactive material. "Non-special form" material has the potential to become airborne and inhaled in the event of an accident. Source: http://www-pub.iaea.org/MTCD/publications/PDF/TCS-01_4th_web.pdf

With vague wording on the safety analyses required within the EIS or SER, Federal agencies have flexibility in their implementation of the launch approval and risk assessment process. A launch approval process has been developed (and has evolved) for launching RPS units. This current process takes an average of 4 years to complete. The ad-hoc INSRP includes representatives from six Federal agencies and is organized into six working groups. Analyses completed can cost tens of millions of dollars for each mission.[5] In 2017, for the Mars 2020 mission, DOE announced in a memo that a new gap analysis approach would be undertaken given similarities to the prior Mars Science Lab mission launched in 2011.[6]

The same documentation applies to fission as it does to RPS. However given significant differences in the technical capabilities and designs of potential fission power systems (FPS), relative to current RPS technology, it may not be appropriate to transfer all aspects of the RPS process to FPS. In particular, the RPS review process is executed without bounds or limits to the level of risk analysis conducted. Additionally, RPS systems are designed to contain their highly toxic and radioactive fuel plutonium-238, in the case of any abnormal launch issues. However, FPS systems would be designed to ensure the nuclear fuel, typically highly enriched uranium, does not reach criticality[2] (that is, goes in a stable configuration producing constant power) before exiting Earth's orbit. Since the unreacted fuel itself does not have comparable radiological or chemical toxicity, containment is less essential.[5]

III. MODELS FOR RISK ASSESSMENT AND APPROVAL

The launch approval process for RPS is the only modern model for space nuclear power. This ad hoc process has a flexible framework; because each nuclear mission is different, a degree of flexibility can be beneficial. However, without bounds to the analysis, it is unclear if the process is unduly burdensome. Without pre-determined risk limits, the review process can become lengthy and costly.

Risk mitigation and approval processes undertaken for other materials and technologies can provide additional lessons and models for how an FPS launch approval process could be formulated. In this paper, risk mitigation and approval processes are examined for NASA payloads that include hazardous materials such as hydrazine and beryllium, terrestrial civilian nuclear power plants, and naval nuclear reactors. Although each technology and process has specific considerations, general conclusions and methods are examined for their applicability to space fission reactors.

III.A. Launch of Other Hazardous NASA Payloads

NASA has developed a list of hazardous payloads, called NASA Routine Payloads (NRP), that are commonly launched for space missions, and thus have already undergone rigorous safety and environmental reviews and analyses. NASA spacecraft containing these materials undergo a relatively simplified process for environmental and safety review prior to launch. Missions are only required to undergo a gap analysis, providing new analyses for hazardous materials or launch vehicles not previously reviewed. The process developed for these hazardous payloads is a model for how pre-launch safety review and analyses, specifically to meet National Environmental Policy Act (NEPA) requirements, can be bounded from mission to mission.

NASA missions are required, under the National Environmental Policy Act of 1969, to undergo an environmental review prior to launch. The National Environmental Policy Act of 1969 states "all agencies of the federal government shall…(c) include in proposal for legislation and other major Federal actions significantly affecting the quality of the human environment, a detailed statement by the responsible official on – (i) the environmental impact of the proposed action."[7] To reduce paperwork, the Council on Environmental Quality's (CEQ) NEPA regulations encourage Federal agencies to consolidate their environmental impact analyses for similar actions into one environmental assessment (EA) or environmental impact statement (EIS).[8] 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.[8]

Based on the analyses included and referenced in the 2011 EA, the NASA Science Mission Directorate determined that the environmental impacts associated with the launch of NRPs would not have an impact on the quality of the human environment; [9] therefore missions that meet the NRP criteria outlined in Appendix C of the 2011 EA (inclusive of its payload, launch vehicle, and site), are not required to undergo additional NEPA analyses (EA or EIS). For example, included in these analyses are hazardous materials such as beryllium and hydrazine.

The 2011 EA classifies any amount of beryllium, and up to 3,200 kg of hydrazine as a NRP. Beryllium metal in a powdered form is considered a Group 1 carcinogen by the International Agency for Research on Cancer. Based on analyses conducted for the EA, in the case of a

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[2] Technically speaking, criticality in a nuclear system is a state where the number of neutrons produced from fissions equals their loss through absorption or leakage.

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.[8] 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. A similar analysis was completed for hydrazine, a highly flammable substance that is a strong irritant; although hazardous, based on risk analyses completed for prior missions, NASA determined that there would be less than a 1 in 10,000 chance an individual would be harmed by spacecraft containing less than 3,200 kg of hydrazine. Therefore, the agency found that hydrazine below this threshold does not pose significant threat to human health or the environment.

Since 2011 only two NASA missions, OSIRIS-REx and Mars 2020, have undergone additional analyses to meet NEPA requirements.[10] Additional analyses were required since both missions contain hazardous payloads that are not covered by the 2011 EA, thus requiring additional analyses. 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 (FONSI) was published.[11] Given the use of radioisotope isotope power systems the second mission, Mars 2020, underwent more rigorous environmental analyses and public reviews, with the publication of an environmental impact statement.

The NPS 2011 EA described above 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.

III.B. Terrestrial Nuclear Reactors

Prior to operation, terrestrial nuclear power plants undergo a multi-year licensing process outlined by the U.S. Nuclear Regulatory Commission (NRC). The licensing process incorporates environmental reviews and risk assessments for proposed nuclear power reactors. 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 another example of a bounded licensing and risk assessment process that could be adapted for future space nuclear reactors.

Pursuant to the Atomic Energy Act of 1954, and the Energy Reorganization Act of 1974, the NRC has developed regulations (10 CFR Part 50) to outline a licensing process for all terrestrial nuclear reactor designers and operators. 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 standing 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.[12]

In 1989, additional regulations were developed to simplify the licensing process into a combined process (10 CFR Part 52). 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 1[12] provides a high level overview of the combined license review process.

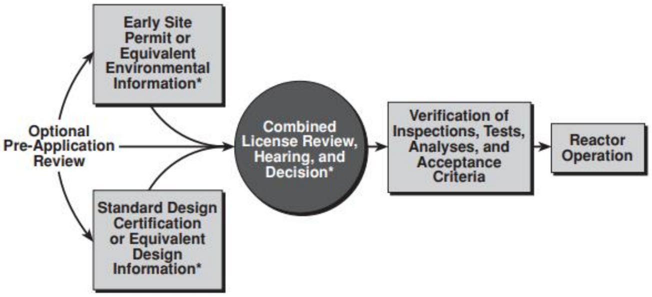

Fig. 1: Combined License Review Process Overview

Through a standard design certification, a reactor designer can receive a license for a nuclear power plant design, independent of a site approval or a construction permit. The 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.

Additionally, through an early site permit (ESP) 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 ESP could be granted to encompass current and future sites that meet parameters set out in the license. An ESP is valid for 10-20 years, and can be renewed for an additional 10-20 years.

Additional licensing pathways are outlined by the NRC (10 CFR 50 and 10 CFR 52), but are seldom used.

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). Additionally a license-by-prototype approach has been proposed to ease and shorten design certification processes.[13]

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 costs billions of dollars. 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) outlined in NRC guidance documents,[14] and can be generalized to a nuclear reactor design (e.g. standard design certification).

III.C. Naval Nuclear Reactors

In 2015, the Naval Nuclear Propulsion Program (NNPP) operated 96 nuclear reactors across the Navy, with a history of over 6,700 reactor-years of operation.[15] Although technical details on the approval process are not publically available, the NNPP provides a unique model for incorporating non-Federal contractors to support personnel and project management during risk assessment and operations.

The NNPP is jointly run by the Navy and National Nuclear Security Administration (NNSA) as defined by Executive Order 12344 and U.S. law.[16] The program has cradle-to-grave responsibility for nuclear propulsion reactors used by the Navy. 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 U.S. 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).[17]

Historically, the NRC and ACRS have provided independent reviews of naval reactor designs. 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.[18]

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.[15] To ensure quality, NNPP reports that a majority of their equipment manufacturers and suppliers have supported the program for several decades.[15] 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.

IV. CONCLUSION AND DISCUSSION

Missions incorporating FPS will have new and unique safety and risk considerations, relative to RPS, however a risk assessment and approval process must be developed based on its unique features. Considerations and thus approval processes may differ based on the power output, amount of fuel on-board, or the mission type. A science mission, for example, may only need to ensure a reactor does not reach criticality prior to exiting the Earth’s atmosphere. Alternatively, a human exploration mission may require additional safety regulations, to ensure the safety of astronauts during launch.

A review of licensing and certification in other domains illustrates that subject matter experts can be engaged to develop evidence-based bounds, determining what is “safe enough,” through processes similar to those undertaken by NRC for terrestrial reactors and NASA for hazardous payloads. Specific bounds could be developed after an initial risk assessment to indicate what alterations to a system, especially fission system designs planned for multiple missions, would require additional analyses. For example, a certification or envelope process could be developed. A fission reactor, such as Kilopower, would go through a rigorous review when first developed, but then go through an expedited process for subsequent missions if within a pre-determined risk threshold. Practices such as bounding analyses and certifying reactor designs could be incorporated into agency level regulations to streamline and implement the current process required in PD/NSC-25.

Finally, the NNPP provides an example of how the approval of multiple nuclear reactors can be managed, especially as new designs emerge. By ensuring long-term relationships between reactor equipment providers and the user (NNPP), a knowledge base surrounding the safety considerations, requirements and standards is preserved.

REFERENCES

1. “Nuclear Reactors and Radioisotopes for Space,” World Nuclear Association (2017).
2. R. Colladay, “NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space,”

National Academies of Sciences, Washington, DC, 2012.

3. M. Gibson, D. Poston, P. McClure, S. Oleson, "NASA's Kilopower Reactor Development and the Path to Higher Power Missions," *NASA* (2017).
4. The White House, "Presidential Directive/NSC-25," Washington, DC (1965).
5. S. Voss, A. Camp, "Considerations for Launching a Nuclear Fission Reactor for Space-based Missions," AIAA SPACE and Astronautics Forum and Exposition, AIAA SPACE Forum, (2017).
6. T. Bishop, "Memorandum: Radioisotope Power Systems Nuclear Launch Safety Analysis Guidance," *Department of Energy* (2017).
7. 42 U.S.C. § 4321 et seq. (1969).
8. NASA, "Final Environmental Assessment for Launch of NASA Routine Payloads on Expendable Launch Vehicles from Cape Canaveral Air Force Station, Florida and Vandenberg Air Force Base, California," *NASA Headquarters,* Washington, DC (2011).
9. NASA, "Routine Payloads Finding of No Significant Impact," *NASA Headquarters,* Washington, DC (2002).
10. NASA, "NEPA News," *NASA Headquarters,* Washington, DC.
11. NASA, "OSRIRIS-REx Finding of No Significant Impact," *NASA Headquarters*, Washington, DC (2013).
12. U.S. Nuclear Regulatory Commission, "Nuclear Power Plant Licensing Process," Washington, DC, rev. 2 (2004).
13. American Nuclear Society, "Expedite Licensing," LaGrange Park, IL (2017).
14. NRC, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition," NUREG-0800, 2007.
15. Naval Nuclear Propulsion Program, "The United States Naval Nuclear Propulsion Program," Washington, DC (2015).
16. 42 U.S.C. § 7158; 50 U.S.C. § 2406
17. Office of Naval Reactors, "Report on Low Enriched Uranium for Naval Reactor Cores," *Department of Energy* (2014).
18. National Nuclear Security Administration, "Concern for the Environment," Washington, DC (accessed 2017).