Nuclear and Emerging Technologies for Space, American Nuclear Society Topical Meeting
Richland, WA, February 25 – February 28, 2019, available online at http://anstd.ans.org/

NUCLEAR LAUNCH APPROVAL: OPTIONS FOR CRITERIA

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Space nuclear systems can be a key source of power and propulsion for many space exploration and science missions. The viability of space nuclear applications would benefit from a regulatory regime that is clear, cost effective, timely, and able to integrate safety into the entire lifecycle of a space nuclear system. Criteria for the safety of launching nuclear systems would inform the approval process and provide further accountability to the public that safety is being sufficiently considered.

A framework is described, which can inform criteria for the nuclear launch approval process, and is focused on leveraging the established processes used by other agencies for transportation and use of nuclear materials on Earth to inform the development of a clear, transparent and predictable launch approval process for space nuclear systems. Findings include the potential for a multi-tiered approach to nuclear launch approval that is based on the material being launched, the system that contains the material, and a comparison to previously launched systems.

I. THE NEED FOR FORMALIZED CRITERIA

All launches of nuclear material from the United States over the past several decades have required approval by the President of the United States as well as a lengthy safety review by an ad hoc interagency review panel. An analysis of this launch approval process has led to the determination that a lack of formal safety criteria adds expense and delay to this process.

The nuclear launch approval process has no formal criteria that define a tolerable level of risk. In principle, the President or his or her designee, the Director of the Office of Science and Technology Policy (OSTP), has the authority to decide what level of risk is tolerable as dictated by National Security Council Memorandum/Presidential Directive No. 25 (NSC/PD-25) and National Space Policy 2010. In practice, relatively few criteria support an approval decision, and the lack of established guidelines leaves safety reviews unbounded by anything other than budget and the launch window.

The threshold that triggers which nuclear launches require presidential approval, as defined by NSC/PD-25, does not adequately scale the required review based on the relative risks associated with launching various space nuclear systems. The trigger for requiring presidential approval for launch is sufficiently low such that all nuclear systems launched to date have been subject to essentially the same launch approval requirements, regardless of the material, quantity, and mission differences.

The combination of these challenges results in all nuclear launches going through a virtually unbounded review process and significantly increases the risk and cost of any missions using nuclear systems. These challenges have discouraged the use of space nuclear by government entities. Furthermore, if the current process were applied to the private sector, the time and cost of the launch review would be nonstarters for industry.

Both of these challenges—(1) the lack of formal safety criteria informing launch approval; and (2) the mismatch between the level of review and the relative hazard of launch—are manifestations of the same problem: ineffective or nonexistent safety criteria. In this paper, approaches are assessed to set more effective criteria to determine when further analysis is required and how to assess the outcomes of such analysis.

II. METHODOLOGY TO IDENTIFY CRITERIA

To identify potential criteria, several standards and recommendations were reviewed from sectors that use and transport nuclear systems, including standards used by the Department of Defense (DOD), Department of Energy (DOE), Environmental Protection Agency (EPA), and the Nuclear Regulatory Commission (NRC), and recommendations provided by international standards bodies such as the International Atomic Energy Agency (IAEA) and the International Commission on Radiological Protection (ICRP).

Criteria were examined as to how they could be applied to the nuclear launch approval process for government entities. Based on the identified criteria, a framework was developed to compare approaches using a common nomenclature, and then used to assess best practices for the space nuclear launch approval process.

III. FRAMEWORK FOR COMPARING CRITERIA

In this framework, approaches are separated into metrics and methodologies. Metrics are defined here as measurements that assess potential consequences, and are categorized by their relevance to a step in the chain of events that could result in a radioactive material causing an adverse health effect. Various methodologies can then

be used to implement these metrics, and are categorized by (1) consequence-based methods; (2) risk-informed methods that include both consequence and probability; and (3) comparative methods that analyze the changes between new and old technology.

III.A. Metrics to Assess Safety

Mitigating the potential adverse consequences of using nuclear systems is the foundation of most nuclear safety goals. Evaluating the extent to which consequences are mitigated requires the measurement of a given consequence. Understanding how safety analyses measure consequence is useful, as there are several different approaches to evaluate what happens during an accident involving nuclear material. Consequence metrics can be material-based, measuring mass or activity [1] of the radioactive material, system-based, measuring the system that contains or uses the material, and recipient-based, measuring the effects of release (see Figure 1).

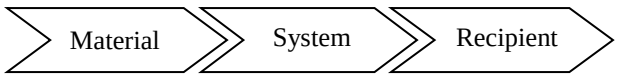

Fig. 1 Categorization of Metrics by Consequence

Material-based metrics identify potential consequence based on the amount and characteristics of the nuclear material itself, such as activity or potential for criticality. The nuclear launch approval process has historically used material-based metrics to define the trigger threshold for presidential approval. For instance, the 1977 version of NSC/PD-25 uses maximum activity to trigger presidential approval requirements. Material-based metrics are valuable due to direct and easy measurement, but do not capture the whole safety picture such as the effect of safety controls.

System-based metrics characterize the ability of the system to prevent adverse consequences. These metrics can reflect positive system characteristics that limit the release of radioactive material, or negative characteristics where a system inadvertently releases radiation. For example, metrics that focus on the iridium cladding around Plutonium-238 in a Radioisotope Thermoelectric Generator (RTG) can inform how the material will be contained in an accident. In the transportation sector the IAEA sets standards for temperature and pressure and testing of the packaging seals before the shipment of any package based on the type of radioactive material inside [5]. System-based metrics provide an opportunity to clearly define requirements for system designers and operators.

Recipient-based metrics measure potential consequences to people and the environment. There are several metrics available to measure the potential consequences of a release of material. Differences include variations in defining the recipient (e.g., individual vs. population), the type of effect (e.g., exposure vs. death), and the timing of the effect (e.g., immediate to unbounded). An example of recipient-based metrics includes the safety criteria for non-nuclear space launches. For these launches, the DOD uses two casualty metrics to limit risk: probability of casualty [2] and expectation of casualty [2].[3] Recipient-based metrics are most closely linked to the consequences that the public and decision-makers care about, as they focus on the effects of a release of radioactive material.

Choosing between implementing material-, system-, and recipient-based metrics requires evaluating the benefits to different actors, including the public, decision-makers, and system designers and operators. Recipient-based metrics are most likely the easiest to communicate, as reducing adverse effects to individuals and the environment are goals across sectors.

While easy to communicate, recipient-based metrics are difficult to implement. They may complicate regulations and increase confusion for the actors required to go through the launch approval process, because there is no general agreement about the relationship between system design constraints and effects to an individual. It may be beneficial to initially establish clear material- and system- based metrics that can clarify the safety expectations for system designers, mission owners, and safety reviewers.

III.B. Methodologies to Implement Metrics

Metrics assess safety by measuring the potential for consequence and its effects; however, safety is not solely defined by the severity of a potential consequence but also its probability of occurrence. How one assesses safety relies on a mix of consequence and probability, and how both of those factors are determined. Three methods to assess risk were identified based on how government agencies assess and regulate activities: consequence-based, risk-informed, and comparative.

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[1] Activity refers to a material's decay rate, which is defined as the average number of decays per unit of time. It is measured in Curie (Ci), 3.7 x 10^{10} decays per second, or Becquerel (Bq), 1 decay per second.

[2] Probability of casualty is defined as the risk of launch-related fatality or serious injury [2].

[3] Casualty expectation is defined as expected average number of human casualties per commercial space mission. The FAA calculates casualty expectations as the summation of: probability of event occurrence, casualty area of impacting debris, and the population density at area of risk [4].

A consequence-based approach considers events without calculating their likelihood. Consequence-based approaches can describe planned exposure situations,[4] where occurrence is certain and thus likelihood is irrelevant. For instance, in planned exposure situations the ICRP recommends using a maximum effective dose limit of 1mSv in a year for the public.[5] A consequence-based approach can also assess the maximum consequence of a potential exposure,[6] regardless of its likelihood. For instance, the NRC requires that non-power reactor facilities consider a Maximum Hypothetical Accident scenario even though these facilities are designed to be of low consequence to the public. This scenario informs facility operations and helps check that operations remain within acceptable limits [8].[7] This approach is effective for facilities or scenarios where the consequence is small enough that even extremely unlikely scenarios do not have a significantly harmful effect.

A risk-based approach considers both consequence and likelihood. The launch approval process already uses a risk-informed approach, as the DOE uses a probabilistic risk assessment to conduct the Safety Analysis Report (SAR), and the Interagency Nuclear Safety Review Panel (INSRP) assesses the risk of various accident scenarios when reviewing the SAR for the Safety Evaluation Report (SER). Identifying a risk-informed constraint could contextualize the outputs of the SAR and SER by defining a tolerable level of risk for different accident scenarios. Furthermore, risk-informed constraints are currently recommended by international standards, as the ICRP suggests setting requirements based on the probability of radiation related death for a defined exposure,[8] and recommends a risk constraint of $1x10^{-5}$ per year for potential exposures to the public [6].

Risk-informed constraints are already employed by launch range commanders for some launch requirements. For non-nuclear launches, Air Force Instruction (AFI) 91-217 requires that the individual Probability of Casualty (P_c) not exceed $1x10^{-6}$, and that the collective Expectation of Casualty (E_c) not exceed $100x10^{-6}$ [2].[9] Per AFI 91-110, launch commitment criteria for nuclear launches align to these values, as the risk of radiation exposure to the general public must not exceed an individual P_c of $1x10^{-6}$ or an E_c of $100x10^{-6}$ [1].

Risk-informed constraints can not only serve as guidelines for tolerable risk, but can also inform further safety analysis requirements. For instance, DOE Standard 3009 distinguishes between events by likelihood and consequence when preparing a documented safety analysis [3]. In this process, DOE establishes an adequate protection limit of 25 rem to a maximally exposed offsite individual for events that have greater than 10^{-4} likelihood of occurrence, calculated as a Total Effective Dose, which applies over a period of 50 years after exposure. This protection limit triggers further requirements for safety controls and reviews.

The final approach, comparative, is not explicitly consequence-based or risk-informed but rather builds on consequence and risk analyses to compare a system to one that has been designated as safe. This methodology becomes most applicable once accepted safety criteria establish a boundary within which it is safe to operate.

The DOE has historically used a comparative approach by establishing a "safety basis" for their nuclear facilities. The "safety basis" for a facility is defined as the documented safety analysis and hazard controls that provide reasonable assurance that a DOE nuclear facility can be operated safely in a manner that adequately protects workers, the public, and the environment (10 CFR 830.3). Proposed changes to the facility, along with new activities or discoveries about safety, are then compared to the defined safety basis. If the proposed change is found to be within the defined safety basis, then the change is considered safe and no further analysis is required.

A comparative approach to evaluate Radioisotope Heater Units (RHUs) using a programmatic environmental assessment (EA) has been considered at NASA. The programmatic EA defines a level of hazardous materials that have a finding of no significant environmental impact (e.g., hydrazine and ammonium-perchlorate propellant). Future missions that incorporate the materials covered by the EA, within a given envelope

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4 The ICRP defines planned exposure situations as situations where radiological protection can be planned in advance, before exposures occur, and where the magnitude and extent of the exposures can be reasonably predicted [6].

5 To define the public, the ICRP recommends using the concept of a Representative Person [7].

6 The ICRP defines potential exposure situations as exposures that are not planned to occur, although the situation is planned [6].

7 The NRC Standard Review Plan defines an MHA as a non-credible scenario that represents the worst possible scenario [9].

8 Probability of radiation related death is defined as the product of the probability of incurring the dose in a year and lifetime probability of radiation related death from the dose.

9 Expectation of Casualty is the mean number of casualties predicted to occur as a result of an operation [2].

of technical characteristics, would not be required to undergo additional environmental reviews.

IV. APPLICATIONS TO LAUNCH APPROVAL

Metrics and methodologies can be combined to create a multi-dimensional approach to assess safety (see Table 1).

Table 1. Options to Implement Methodologies

Metric	Methodology		
	Consequence-based	Risk-Informed	Comparative
Material	**A:** Use material quantity (e.g., Pu-238 A_2 value) to trigger review requirements	**B:** Infer risk of mission using quantity and type of material	**C:** Compare material in current mission (e.g., quantity of Pu-238) to past missions
System	**D:** Limit potential for system failure (e.g., Pu-238 package controls)	**E:** Limit risk of system failure (e.g., limit risk iridium clad melts)	**F:** Compare new and old systems (e.g., compare robustness to stress and strain)
Recipient	**G:** Limit maximum consequence to public (e.g., limit total effective dose to a person below 5 rem)	**H:** Limit risk of effect on public (e.g., limit risk of 100 mrem dose to 10^{-6})	**I:** Compare risk to public between missions (e.g., change in risk to maximally exposed individual)

The combination of the metrics and methods creates discrete approaches that have different benefits depending on the goal of a safety assessment. In this section we discuss a few options for ways to use the approaches outlined in Table 1 to arrive at a clear, predictable and less costly launch approval process: establishing criteria that can be used to bound the extent of required analysis, or establishing multi-tiered risk thresholds that can be used to scale the required analysis.

IV.A. Criteria for bounding analysis

One of the challenges with the current launch approval process is the lack of bounding criteria for analysis: there are no standards for when risk is tolerable to inform an approval decision.

Multiple approaches could be used to provide guidelines for safety reviews and inform approval decisions. For planned operations, most agencies use a consequence-based, recipient standard (see Table 1, Option G). For abnormal operations, we see three principal options: (1) set a risk goal; (2) identify system-based standards for nuclear devices and launch vehicle environments; and (3) implement a comparative approach and require additional analysis for missions that exceed a pre-determined safety basis.

Setting a risk goal could clarify whether the values calculated in the current safety analyses are tolerable. If a risk constraint were set, we see the benefit of applying the risk goal to the recipient to enhance the clarity for the public (see Option H, Table 1). There is also benefit to limiting risk to the individual as compared to limiting risk to a population given the potential to overestimate the risk to some individuals and underestimate the risk to others when estimating an average dose for a population. This thought is in line with ICRP publication 103, which recommends using collective risk assessment methods primarily as an instrument for optimization and the comparison of radiological technologies rather than as a constraint for activities [6].

Deterministic standards could further inform the decision-maker about how safety is accounted for during launch and clarify the expectations for mission planners and designers. For example, guidelines could be set for the types of accidents an RTG should be built to withstand and limit when space nuclear reactors are allowed to go critical (see Option D, Table 1).

There is also value in implementing comparative approaches to further leverage lessons learned and reduce duplication of effort. A comparative approach that accounts for both changes in deterministic qualities (see Option F, Table 1), and the changes in risk between missions (see Option I, Table 1), could provide a more holistic picture of the need for further safety review.

In addition, none of these approaches needs to be implemented in isolation. Instead of relying on one metric or category of metric to determine acceptable safety, multiple criteria could be combined to inform a final approval. Together probabilistic and deterministic analyses could create a more comprehensive picture of the risk involved in launching a nuclear system.

IV.B. Scaling analysis with risk

Another challenge with the current launch approval process is that the level of review does not scale with the relative hazard of launch. One option is to continue to use a material-based value such as a multiple of A_2 (see Option A, Table 1), because it is easy to compare to a system with virtually no analysis. However, a material-based value can only capture the maximum possible

consequence, without regards to likelihood of release, which is affected by safety features.

Two additional options would be to use a recipient-based, risk-informed metric (see Option H, Table 1) or to use a comparative analysis to see if a new application or device diverges from previously established safety bases (see Options F and I, Table 1).

It is not readily apparent, however, that the material-based approaches to trigger launch approval requirements should be abandoned. Any attempts to implement new approaches must be carefully considered, including a comparison of how much review time would be saved from exemptions compared to how much further analysis would be required to assess whether a nuclear system requires additional review. An effective review system may use one or more of these approaches in a multi-tiered system that has easy entry points but increases in stringency based on the results of additional analysis.

V. CONCLUSION

The framework outlined in this paper is based on the regulations and practices of Federal Departments and Agencies that regulate hazardous activities such as operation of a nuclear power plant, transportation of nuclear materials, or the launch of non-nuclear hazardous payloads. The examples of these processes are enlightening for nuclear launch approval, but should not be relied on without adjustment.

The launch of space nuclear material involves a myriad of factors that are not captured in the other industries that we examined such as the duration of launch, the implications of high-altitude accidents, atmospheric re-entry and ocean submersion of nuclear materials, complexity and size of the nuclear system, and technology variability in the nuclear device and the systems that implement that device. While lessons can be applied, decision-makers should be cautious of directly applying a one-size-fits-all model to space nuclear launch approval, and even more cautious in applying quantitative criteria that may not adequately capture the uniqueness of launch and its time intervals.

Despite the uniqueness of the launch environment, many approaches from other sectors can still be applied to inform tolerable risk levels and bound the required safety analyses. A risk-informed framework that leverages information from previous analyses could provide context for outputs of the SAR and SER, and inform the constraints for government and eventually nongovernment designers and operators.

By following the example of other regulatory and approval processes, space nuclear launch approval can become more certain, approval decisions can be made based on meaningful criteria, and the process can potentially become quicker and less expensive.

REFERENCES

1. DOD Air Force. 2015. “Air Force Instruction 91-110: Nuclear Safety Review and Launch Approval for Space or Missile Use of Radioactive Material and Nuclear Systems.”
2. DOD Air Force. 2014. "Air Force Instruction 91-217: Space Safety and Mishap Prevention Program."
3. DOE. 2014. “DOE Standard 3009: Preparation of Nonreactor Nuclear Facility Documented Safety Analysis.”
4. DOT FAA. 2000 “Advisory Circular 431.35-1: Expected Casualty Calculations for Commercial Space Launch and Reentry Missions.”
5. IAEA. 2012. "Regulations for the Safe Transport of Radioactive Material. *No. SSR-6*.
6. ICRP. 2007. “The 2007 Recommendations of the International Commission on Radiological Protection.” *Annals of the ICRP Publication 103*.
7. ICRP. 2006. “Assessing Dose of the Representative Person for the Purpose of the Radiation Protection of the Public.” *Annals of the ICRP Publication 101*.
8. NRC. 1996. “Nureg-1537 Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors.” Part 2.
9. NRC. 2002. "Nureg-1520 Standard Review Plan for the Review of a License Application for a Fuel Cycle Facility."