EVOLUTION OF NASA'S NUCLEAR FLIGHT SAFETY PROGRAM TO MEET CHANGING NEEDS

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ABSTRACT

Over the past 4 years, the United States (U.S.) Government has issued several new National policies that fundamentally change the approach to nuclear flight safety for aerospace applications, including the complete revision of the Federal policy for handling launch of spacecraft containing space nuclear systems. In response, the National Aeronautics and Space Administration (NASA) is updating its nuclear flight safety program while still maintaining consistency with other Federal policies, international conventions, and NASA's own policies. To achieve this evolution, NASA is factoring in an objectives-driven and assurance case mindset to develop a risk-informed and performance-based program. NASA and others have successfully applied this mindset in other disciplines and contexts and it is being pursued here via broad cooperation within NASA and with external stakeholders. This paper will briefly describe how the NASA nuclear flight safety program is evolving to meet these changing needs.

1. GENERAL BACKGROUND

In December 2017, the President of the United States (the President) issued "Presidential Memorandum on Reinvigorating America's Human Space Exploration Program," [1] referred to as Space Policy Directive-1 (SPD-1). SPD-1 charges NASA to lead "an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities," as re-emphasized by the 2020 National Space Policy [2]. New direction specific to space nuclear power and propulsion (SNPP) was also promulgated in the same timeframe in the form of 2019's National Security Presidential Memorandum (NSPM)-20, "Presidential Memorandum on Launch of Spacecraft Containing Space Nuclear Systems" [3], which establishes an updated and risk-informed process for launching space nuclear systems, and 2020's Space Policy Directive 6, "Memorandum on the National Strategy for Space Nuclear Power and Propulsion" [4] which "establishes a national strategy to ensure the development and use of SNPP systems when appropriate to enable and achieve the scientific, exploration, national security, and commercial objectives of the United States."

This series of National policy directives enables NASA to evolve its nuclear flight safety program while still maintaining consistency with other Federal policies, international conventions, international guidance (including the Safety Framework for Nuclear Power Source Applications in Outer Space [5]) and NASA's own policies, as well as leveraging decades of experience in the area of nuclear flight safety. This paper will briefly describe the current situation and future plans, as they relate to NASA high-altitude and space flights involving nuclear or other radioactive material spanning the range from space nuclear systems to very low-activity radioactive sources.

2. HISTORICAL APPROACH

NASA's nuclear flight safety program has existed since the early 1960s. The program evolved as part of the interagency activities to ensure coordination between the Atomic Energy Commission, NASA, and the U.S. Department of Defense (DoD) as space nuclear systems were being developed and deployed for purposes such as powering navigational satellites, to support expectations from the President outlined in 1961 and 1963 National Security Action Memoranda (NSAMs) [6,7], and to respond to launch accidents or unplanned reentries that occurred during the 1960s. Through the refinement of processes to address the analysis, review, and authorization of Apollo program launches, and other historic missions like Viking and Voyager, these early activities eventually resulted in a mature process for nuclear launch authorization that was codified in National Security Council/Presidential Memorandum (NSC/PD)-25, "Scientific or Technological Experiments with Possible Large-Scale Adverse Environmental Effects and Launch of Nuclear Systems into Space," in 1977 [8]. From 1977 to 2019, the U.S. approach to handling the launch of radioactive material and its attendant reviews was fairly stable, with continual improvement features pursued through activities like the 1992 United Nations (UN) "Principles Relevant to the Use of Nuclear Power Sources in Outer Space" [9] as well as later adoption within the aforementioned NSC/PD-25 process of the International Atomic Energy Agency Specific Safety Requirements No. 6 [10] guidance (including its use of A2 values to normalize the relative hazard of differing isotopes in transport).

All NASA launches of spacecraft containing space nuclear systems to date have included technology developed and manufactured by the U.S. Department of Energy (DOE) and its contractors. An important aspect of this interagency partnership is the Safety Analysis Report (SAR) developed by the DOE and submitted to the NASA Administrator through the NASA mission directorate managing the mission that utilizes the nuclear system. Parallel to the programmatic efforts to develop and publish the SAR, an ad hoc Interagency Nuclear Safety Review Panel (INSRP) consisting of members from NASA, DOE, DoD, and the U.S. Environmental Protection Agency (EPA), along with a technical advisor from the Nuclear Regulatory Commission (NRC), reviewed the development of launch and mission accident scenarios, probabilities of occurrence, specification of associated environments, atmospheric transport and dispersion simulations, and consequence estimates. The INSRP evaluations of the completeness and defensibility of the SAR were documented in a Safety Evaluation Report (SER). The SER, along with the final SAR and other related documents, were submitted to the NASA Administrator for their consideration prior to requesting nuclear launch safety approval by the President or their designee, per NSC/PD-25.

This historical approach has been successful with the strong partnership between NASA and DOE's programmatic leadership driving a 'best science' approach in developing SARs. Due to the ad hoc nature of the INSRP, normative considerations in assessing risk thresholds depended on the composition of the group of individuals comprising a particular mission's INSRP. With the advent of NSPM-20, Federally-established safety guidelines now provide greater clarity in addressing public safety issues. NSPM-20 also recognizes the potential of commercial interests utilizing space nuclear systems via the U.S. Department of Transportation (DoT) providing public guidance for applicants seeking a license for a launch or reentry involving a space nuclear system. Thus, NSPM-20 supports the future envisioned by SPD-1 where NASA's exploration programs leverage innovation and capabilities of commercial partners.

3. MARRYING THE OLD AND NEW

With the new policies issued, NASA and other relevant agencies are marrying the portions of the old paradigm that continue to add value with the new direction. As a simple illustration of the varied sources of guidance and direction, Table 1 shows some of these sources along with an indication (where practical) of the number of compulsory requirements and voluntary directions that they levy on NASA nuclear flight safety.

Table 1 - External Factors for Nuclear Flight Safety

Source	# of compulsory requirements	# of additional voluntary directions
Atomic Energy Act of 1954 (as amended) [11]	Highly dependent on the specifics of the application	
14 Code of Federal Regulations for FAA-licensed launches [12]	Specific regulatory guidance for launch of space nuclear systems is under development by the FAA	
National Security Presidential Memo.-20	22	8
Space Policy Directive-6	3	1
Nuclear/ Radiological Incident Annex [13]	4	4
NPR 8700.1 [14]	5 (broadly speaking)	0
Department of Air Force Manual 91-110 [15]	1 (in addition to many that are equivalent to NASA requirements)	1 (in addition to many that are equivalent to NASA requirements)
Binding UN Conventions [16, 17]	13	1
UN Resolution 47/68	This resolution was broadly adopted in recognition that the U.S. uses equivalent practices	
IAEA/UN Safety Framework	-	11

This table is obviously quite simplified in several ways, but it conveys the point that the nuclear flight safety has a number of external factors, only some of which have been updated by the aforementioned policy changes.

Within this context NASA is working to re-write its own internal guidance (contained in a new NASA Procedural Requirements (NPR) directive), develop implementing guidance in a companion document to that new directive, and develop accompanying training and awareness materials. NASA is also working with other government agencies who are also writing new directives, in order to try and promote consistency amongst government agencies. Beyond that, NASA is also the administering agency for the newly-formed Interagency Nuclear Safety Review Board (INSRB) created by NSPM-20, which replaced the prior ad hoc interagency panels. The INSRB is also writing its standard operating procedures to promote predictability and clarity in its reviews. Finally, NASA continues to work through the United Nations and its safety and mission assurance trilateral partners (the European Space Agency and the Japan Aerospace Exploration Agency) to maintain a high level of coordination and cooperation with the international community.

Working with these partners, where relevant, NASA is seeking to clarify tailoring expectations, enhance transparency in safety-related decision making, and further promote consistency in agency policy and implementing standards and guidance. More specifically, the Office of Safety and Mission Assurance is recalibrating its posture as it relates to the launch of very small quantities of radioactive material from a posture of always requiring explicit approval to a posture of quantitatively pre-determining situations where risk is sufficiently low on a categorical basis such that a notification-only posture is warranted. For space nuclear systems, NASA is working to implement the new Federal launch approval process in a manner that better leverages existing safety practices and processes (such as peer reviews that are already conducted, and that are also required by NSPM-20) to augment the interagency review. NASA is also working with others to explore the role of voluntary consensus standards as a means of developing accepted standards that will improve the efficiency of analysis preparation and review, and that can promote an inherently more consistent experience for end-users who are considering different regulatory pathways (e.g., government-sponsored versus commercial launches). The codification of a safety goal in the form of the NSPM-20 Safety Guidelines facilitates the adoption of such accepted standards once they are developed.

4. TRANSITIONING TO OBJECTIVES-DRIVEN

The term "objectives-driven approaches" is used here to encompass a broad range of approaches that include safety cases, assurance cases, and objectives hierarchy formulations, as well as a broad range of documentary approaches including goal structured notation and claim-argument-evidence notation. The underlying theme is that the approach and execution of safety is better performed in a rigorous and structured case-specific context, rather than a prescriptive fashion. Prescriptive approaches favour repeatability and verbatim compliance and are often termed checklist or procedural approaches. They do have certain advantages, and particularly in situations where there is a lower degree of understanding required of end users or where variability in application cannot be tolerated (e.g., the case where a reviewer needs to review numerous applications in a limited amount of time, and it is therefore important that every application be very formulaic). However, prescriptive approaches will generally result in less teamwork during application and less innovation over time, by their nature. Since space flight is complex and not routine, and since space flight of a space nuclear system is even more complex and infrequent, objectives-driven approaches have the potential to emphasize teamwork and innovation without an unacceptable loss of predictability or compliance. This is especially true when they are executed within a systems engineering approach to life-cycle and requirements management, as is the case at NASA.

NASA's Office of Safety and Mission Assurance is moving toward objectives-driven approaches in a phased and cautious manner. Advantages to the use of objectives-driven approaches across its safety and mission assurance activities enable innovative practices like model-based mission assurance, model-based systems engineering, and digital transformation. However, understanding and acceptance of these advantages and opportunities varies. For this reason, the aforementioned NPR under development still relies on a prescriptive mindset in many ways, while also proposing an objectives-driven approach in some instances. Meanwhile, NASA is developing a companion document which seeks to both provide greater specificity into what one would do to meet requirements and how one would apply an objectives-driven approach to do so.

To illustrate the basic concepts of how an assurance case can be used within nuclear flight safety, Figure 1 shows a sample space flight project assurance case at its highest level, that of a top objective with associated context. Figure 2 shows the same top objective along with 4 supporting strategies, where the term "S&MA Plan" could refer to either a conventional safety and mission assurance implementation plan or a safety and mission success assurance case for the entire mission.

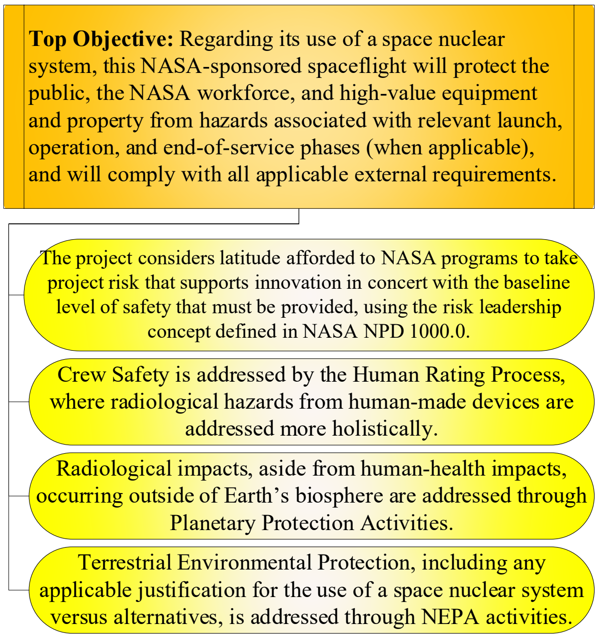

Figure 1. Top Objective and Context

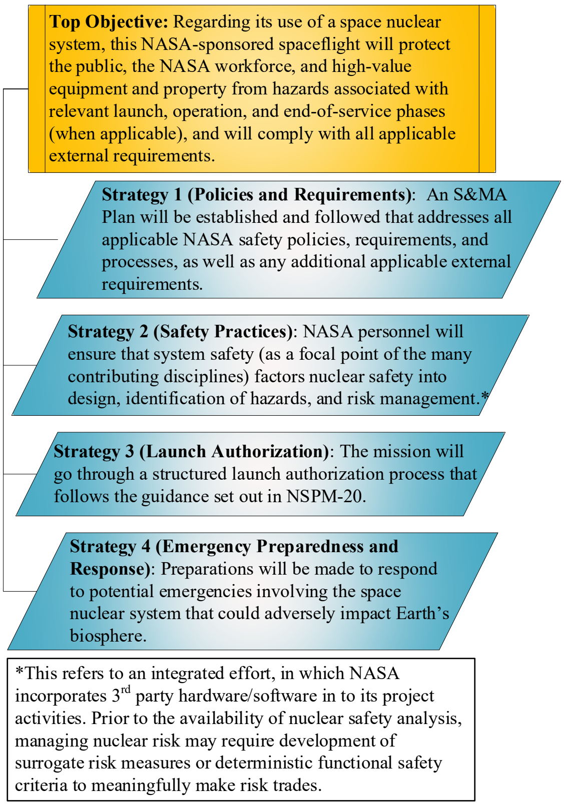

Figure 2. Top Objective and Supporting Strategies

Figure 3 and Figure 4 show a further drill down of the first 2 of these strategies in order to illustrate the point further. These figures also illustrate how this assurance case can be coupled to standard life-cycle management practices, in the form of callouts to gate products and reviews ("evidence"), in this case those that apply to a NASA space flight project following NPR 7120.5, "NASA Space Flight Program and Project Management Requirements" [18]. Of note, Strategy 1 shows a situation that mixes compliance items and key coordination instruments, while Strategy 2 focuses on a more technical and free-form activity, both using the same underlying assurance case construct. (Both figures use some acronyms that are incidental to their inclusion in this paper, such as "LCR" for Life Cycle Review. These acronyms are defined in NPR 7120.5).

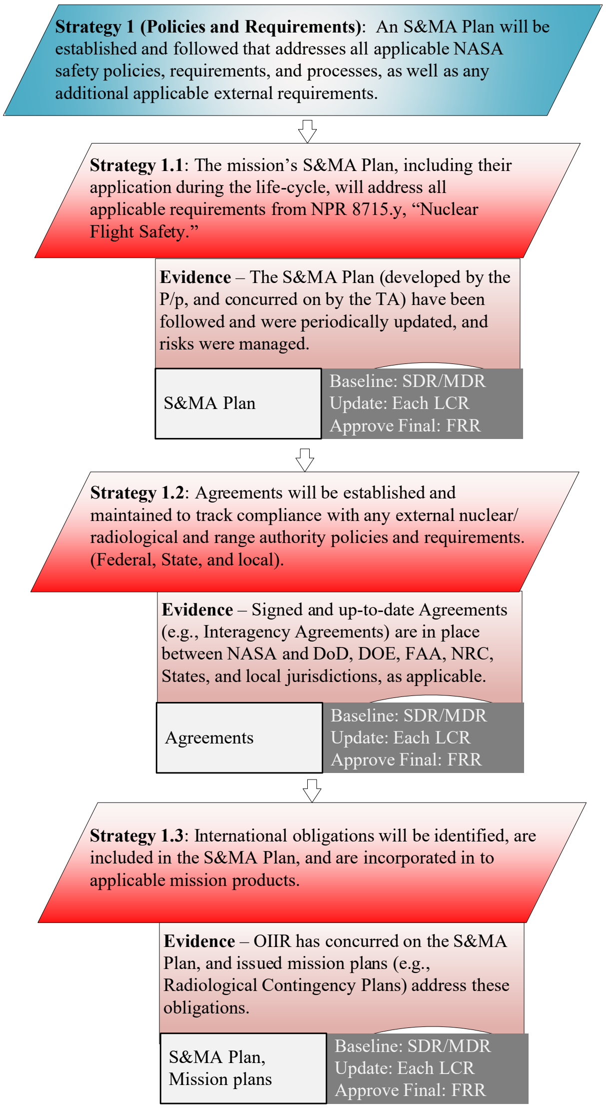

Figure 3. Strategy 1 Decomposition

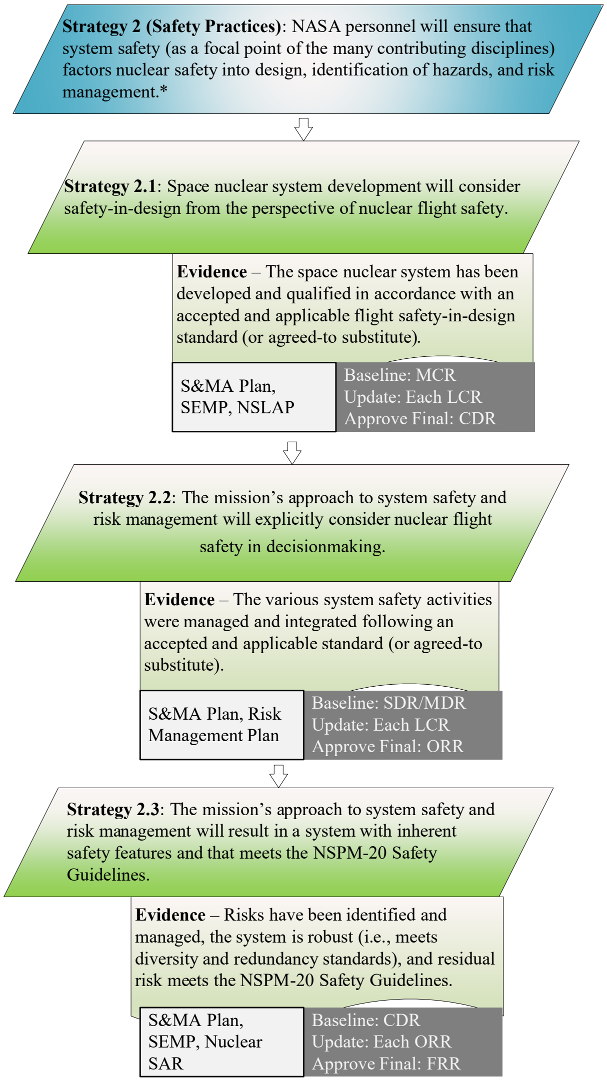

Figure 4. Strategy 2 Decomposition

This depiction of the assurance case addresses its integration into life-cycle management to some degree, but it does not address all aspects of that integration. To establish and maintain the validity of the case itself, the elements of the assurance case would need to be agreed to at key points in the process and verified at later points in the process. This likely would include formal concurrence by relevant parties on the approach (i.e., a validation step), as well as definition of success criteria and the role of independent review in verifying the intent has been met (i.e., a verification step), likely needing to recur in each major life-cycle phase. While some of these aspects would be the subject of overarching agency processes, some aspects (e.g., specific success criteria for evaluating specific pieces of evidence) would require a lower level of detail within the assurance case itself.

Another key aspect of successfully implementing this approach is reliance on accepted standards to ensure that the doers, the peer reviewers, the interagency reviewers (where applicable), and the decision authority all have a common basis on "what" should be done to fulfil various needs. Accepted standards promote efficiency by providing a common frame of reference. In this way, accepted standards serve as landmarks that allow teamwork and innovation to occur in a suitably bounded environment. For this reason, NASA is also partnering with other government agencies with a stake in this area to align on what gaps and overlaps exist in the already-available standards, and what steps (if any) should be taken to reduce overlaps and fill these gaps. That all said, it is not always practical to establish accepted standards in a timely manner, and mission-specific agreements of acceptable practices may be necessary.

5. THE CURRENT ROADMAP

To promote coherency in how evolution of the NASA nuclear flight safety program proceeds, the authors have also developed a basic roadmap (or staged timeline). There are five categorical areas addressed within this roadmap: OSMA guidance activities, technical issues, mission support, INSRB activities, and other interagency coordination. Since much of the roadmap's contents reflect work-in-progress activities with other government agencies, only a notional version is presented, in Figure 5.

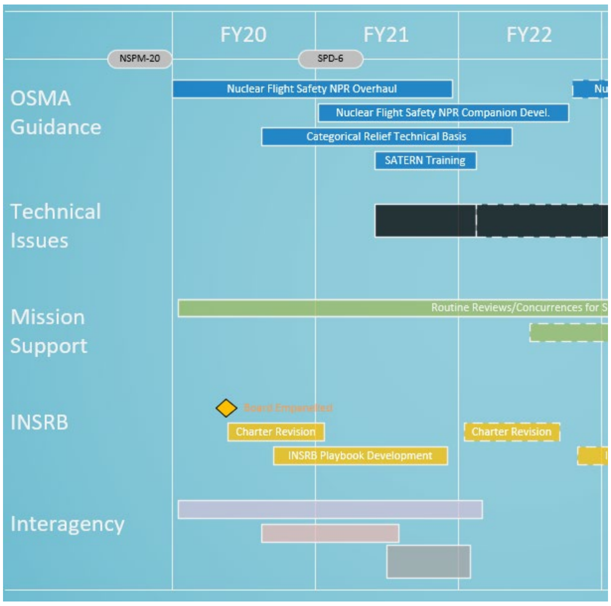

Figure 5. Notional Illustration of Roadmap

As this figure infers, interagency coordination in this area is key. NASA is one of two government agencies that currently sponsors launches involving radioactive material (along with the DoD), while the DoT is the licensing authority for the flight of radioactive material in commercially-sponsored launches. In addition, the

DOE and the NRC are key stakeholders due to their terrestrial authorities, their deep technical knowledge of nuclear matters, and in the case of the DOE, their capabilities and facilities. Finally, the Department of State and the EPA play key roles in communication and coordination in general, as well as in the event of a mishap involving radiological material. NASA interacts with these other six agencies routinely (along with others, as applicable), and the seven agencies all participate on the INSRB.

6. THE DESIRED END-STATE

The activities described in this paper are focused on moving NASA's nuclear flight safety program toward a new era of insight into NASA's nuclear flight activities and support of interagency and international nuclear flight activities. As with other programs within the Office of Safety and Mission Assurance, the primary goals are to support the needs of NASA's programs and projects, and to provide independent insight to NASA leadership, while also supporting NASA's interagency and international partners. The move toward object-driven approaches in this areas allows us to accomplish this in a manner that is fully consistent with NASA's policy on "risk leadership," which has the goal of increasing decision velocity within a proper risk posture, implemented by defining appropriate technical standards (or equivalents), and communicating clearly on risks and benefits. The use of objectives-driven approaches, when combined with the newer nuclear space policy that operationalizes a measure of "how safe is safe enough?" is key to achieving risk leadership in the space nuclear area.

In addition, NASA is committed to encouraging commercial activities and a "whole of government" approach. Through sustained interactions with a number of interagency partners, and through exploration of the use of common standards and equivalences, NASA's Office of Safety and Mission Assurance is seeking to harmonize its nuclear flight safety practices with the practices of the DoT, the DoD, the DOE, and the NRC, to the greatest extent practicable.

7. SUMMARY

This paper has described ongoing activities within NASA's Office of Safety and Mission Assurance related to evolving the nuclear flight safety program in a direction that recognizes internal and external drivers and promotes risk leadership.

The authors wish to acknowledge the outstanding work performed by the many NASA personnel who support programs and projects that use nuclear technology. These individuals have the primary responsibility for safety and are integral to achieving NASA's values of both safety and excellence.

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