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Evolution of NASA's Nuclear Flight Safety program to infuse risk leadership and assurance framework concepts

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EVOLUTION OF NASA'S NUCLEAR FLIGHT SAFETY PROGRAM TO INFUSE RISK LEADERSHIP AND ASSURANCE FRAMEWORK CONCEPTS

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ABSTRACT

In recent 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 and policies 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. This paper will not address activities conducted under the auspice of the National Environmental Policy Act (NEPA). Such activities do provide relevant assessments relative to radiological hazards, however, NSPM-20 and Space Policy Directive 6 do not alter federal policy related to NEPA. In addition, NASA organizationally separates policy responsibility for NEPA and nuclear flight safety, though activities are closely coordinated between the two groups.

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 approval of Apollo program launches, and other historic missions like Viking and Voyager, these early activities eventually resulted in a mature process for nuclear launch approval that was codified in Presidential Directive/National Security Council (PD/NSC)-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 PD/NSC-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).

Despite these incremental improvements, the Administration saw a need for a revised policy. When issuing NSPM-20 in 2019, the Administration pointed to the fact that the previous process (i) did not provide safety guidelines to inform mission planners, designers, and launch authorization authorities, (ii) did not provide sufficient guidance for commercial use of space nuclear systems, (iii) treated almost all space nuclear systems the same, regardless of the relative risk they might pose, (iv) referenced material quantity thresholds from an outdated source, and (v) inhibited early engagement by safety evaluators with mission planners and system designers due to the ad hoc and mission-specific nature of the Interagency Nuclear Safety Review Process (INSRP) process. Note that, due to the timing of the issuance of NSPM-20, the Mars 2020 mission largely followed the pre-existing process with regard to the nuclear safety analysis and nuclear safety review. However, the actual launch authorization decision did follow the tenets of the newer NSPM-20 process.

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 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 PD/NSC-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, combined with the lack of accepted standards for safety and risk analysis methods, normative considerations in assessing risk thresholds depended on the composition of the group of individuals comprising a particular mission's INSRP, and this in turn had the effect of increasing cost and schedule uncertainty. 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 and establishes the U.S. Department of Transportation (DoT) as the licensing authority in such situations. Thus, NSPM-20 supports the future envisioned by SPD-1 where NASA's exploration programs leverage innovation and capabilities of commercial partners. What is left to be worked out is the details of how these policies will be consistently and effectively carried out.

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 Influences Affecting NASA Nuclear Flight Safety

Source / Influence	**# 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 Federal Aviation Administration (FAA)-licensed launches [12]	See FAA Advisory Circular 450.45-1	
National Security Presidential Memorandum-20	22	8
Space Policy Directive-6	3	1
Nuclear/ Radiological Incident Annex [13]	4	4
NASA Procedural Directive (NPD) 8700.1 [14]	5 (broadly speaking)	0
Department of Air Force Manual 91-110 [15]	3 (in addition to many that are equivalent to NASA requirements)	0 (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	
International Atomic Energy Agency (IAEA) / UN Safety Framework	-	11

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

Within this context NASA has re-written its own internal guidance (contained in a new NASA Procedural Requirement (NPR) document, 8715.26 [18]), has developed implementing guidance in a companion Handbook (NASA-HNDBK-8715.26 [24]), to that requirements document, and has developed accompanying training and awareness materials. NASA is also working with other government agencies to promote a "whole of government" approach to nuclear flight safety. For instance, NASA led an intergovernmental working group in 2021-2022 to address the limited standards and regulations in place specifically for space reactor design and safety. That working group concluded that "Consensus standards have value and should be pursued for space reactors," and that "The process used for standards development would benefit from broad participation by government agencies, stakeholders, consensus body organizations, industry, and academia." The working group recommended near-term action for three gaps identified as high-priority. These gaps were: (i) Safety and Risk Analysis Methods for Space Reactors, (ii) Testing Requirements for Space Reactors, including Facility Requirements, and (iii) Safe Operating Practices for Space Reactors. [19]

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 has documented its evolving standard operating procedures in a trial use guidance document [20] 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, 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 for flight of space nuclear systems. Toward this end, NASA is working to implement the new Federal launch authorization 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. As mentioned above, 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.

NASA expects development in this area to be iterative. Safety frameworks naturally drive mission-specific decisions regarding what regulatory pathways to follow for terrestrial possession and use, ground testing, ground transport, launch site integration, launch, in-space operation, and disposal. Often these determinations include an intentional choice between a government-sponsored authorization pathway versus a government-licensed commercial pathway. Once the regulatory pathway is established, accepted standards drive clarity and efficiency in executing that regulatory pathway and drive the development of the mission-specific safety activities. However, there must be a feedback loop associated with each of these flow-downs in order for the system to evolve. Figure 1 illustrates this taxonomy.

Figure 1 – Illustration of Safety Flow-down

Finally, the NASA Office of Safety and Mission Assurance (OSMA) has also re-calibrated its posture as it relates to the launch of very low-activity sources of radioactive material from a posture of always requiring explicit authorization 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.

4. TRANSITIONING TO OBJECTIVES-DRIVEN APPROACHES

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 favor 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). In fact, NASA is retaining this prescriptive approach when handling nuclear flight safety concurrence for space flights with small radioactive sources. 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 OSMA is moving toward objectives-driven approaches in a phased and cautious manner, so as not to be overly disruptive to already-established programs and projects or interfaces with other disciplines, and to allow for familiarization with these approaches. 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 NASA nuclear flight safety NPR still relies on a prescriptive mindset in many ways, while also proposing an objectives-driven approach in some instances. For instance, the NPR still prescribes specific deadlines for specific products (subject to tailoring), as this maintains NASA's traditional approach to systems engineering in managing a program or project's life cycle. Conversely, the NPR requires an assurance case-based approach for radiological contingency planning that only specifies the process and features of a to-be-negotiated mission-specific plan, because this is an area that is well-suited for such an approach given the high degree of planning complexity and mission-specificity.

Meanwhile, NASA's companion Handbook [24] provides strategies, means of effective argumentation, and means of documenting that argumentation when taking an objectives-driven approach to meeting safety objectives associated with higher-level requirements. The ultimate goal is to arrive at an NPR that flows down external requirements and establishes goal-oriented safety objectives, a set of accepted standards that document strategies and unambiguous measurables when arguing that those safety objectives have been met, and a Handbook that gives practical advice to NASA personnel when performing their work. Figure 2 overlays this document structure on to the safety flow-down structure previously depicted in Figure 1.

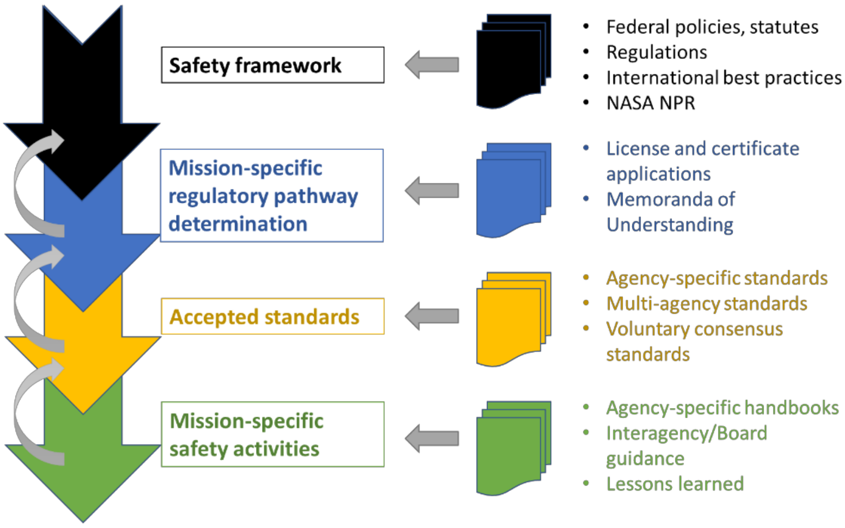

Figure 2 – Overlay of Key Documents on to Safety Flow-down Structure

To illustrate the basic concepts of how an assurance case can be used within nuclear flight safety, Figure 3 shows a notional space flight mission assurance case at its highest level, that of a top objective with associated context. Figure 4 shows the same top objective along with 4 supporting strategies, where the term "S&MA Plan" (S&MA stands for Safety & Mission Assurance) could refer to either a conventional safety and mission assurance implementation plan or a safety and mission success assurance case for the entire mission.

Top Objective: Regarding its use of a space nuclear system, this NASA-sponsored spaceflight protects the public, the NASA workforce, high-value equipment and property, and the environment during launch, operation, and end-of-service phases by demonstrating that relevant safety risks are below established thresholds of acceptability, that the mission is as safe as reasonably practicable, and that all applicable external requirements have been met.

- The project considers latitude afforded to NASA programs to take project risk that supports innovation in concert with the baseline level of safety that must be provided, using the risk leadership concept defined in NASA NPD 1000.0.
- This assurance case applies to a robotic mission (i.e., crew safety / human-rating are not included).
- Radiological impacts occurring outside of Earth's biosphere are addressed through Planetary Protection activities.
- Terrestrial environmental impacts that do not affect human health or property use, including any applicable justification for the use of a space nuclear system versus alternatives, is addressed through NEPA activities.

Figure 3 – Notional Assurance Case Top Objective and Context

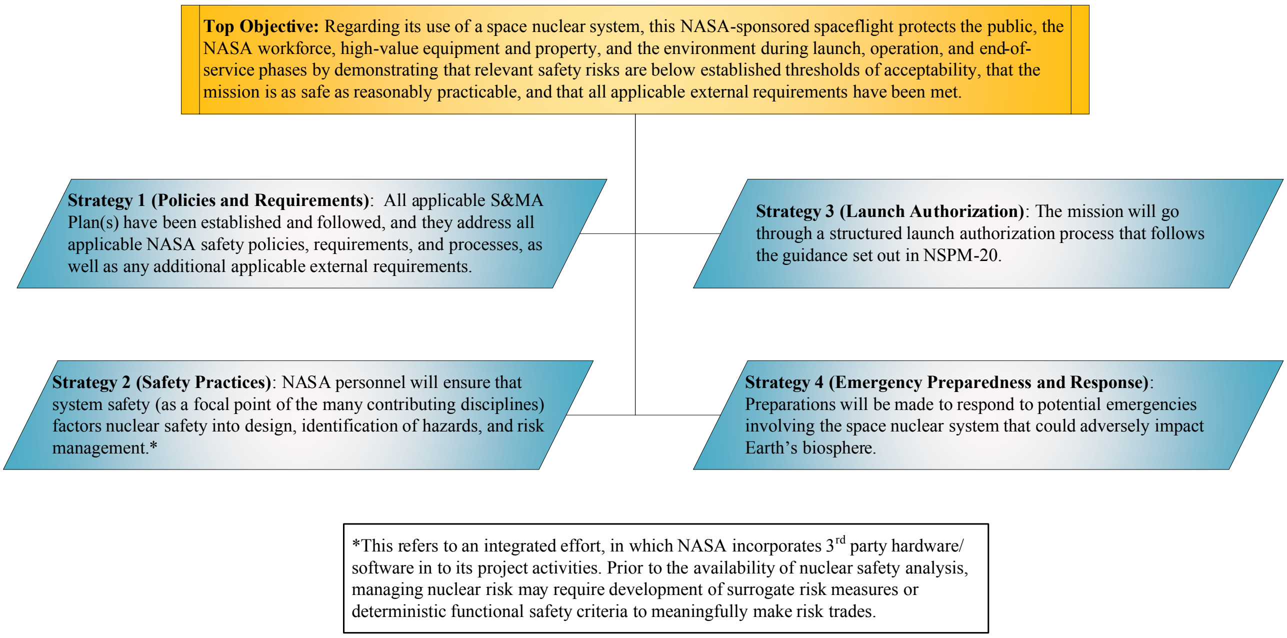

Figure 4 – Notional Assurance Case Top Objective and Supporting Strategies

Figure 5 and Figure 6 show a further drill down 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" [22]. Of note, Strategy 1 shows a situation that mixes compliance items and key coordination instruments. Strategy 2 focuses on a more technical activity which more directly addresses the demonstration of adequate safety and consideration of "as safe as reasonably practicable." Strategy 3 dives further into the analysis, review, and authorization processes, co-mingling process elements with demonstration of safety. Strategy 4 addresses emergency preparedness and response, a key feature of ensuring the overall activity is "as safe as reasonably practicable," while invoking the process in NPR 8715.26, which itself is assurance case-oriented. All of these breakdowns fit within the same underlying assurance case construct, which ensures that each piece of evidence has traceability back to the top objective.

Color key:
Red – generally denotes a required item
Green – generally denotes a best practice
Yellow – a constraint or boundary condition

*This refers to an integrated effort, in which NASA incorporates 3rd party hardware/ software in to its project activities. Prior to the availability of nuclear safety analysis, managing nuclear risk may require development of surrogate risk measures or deterministic functional safety criteria to meaningfully make risk trades.

Figure 5 – Notional Assurance Case Strategy Decomposition (Part 1)

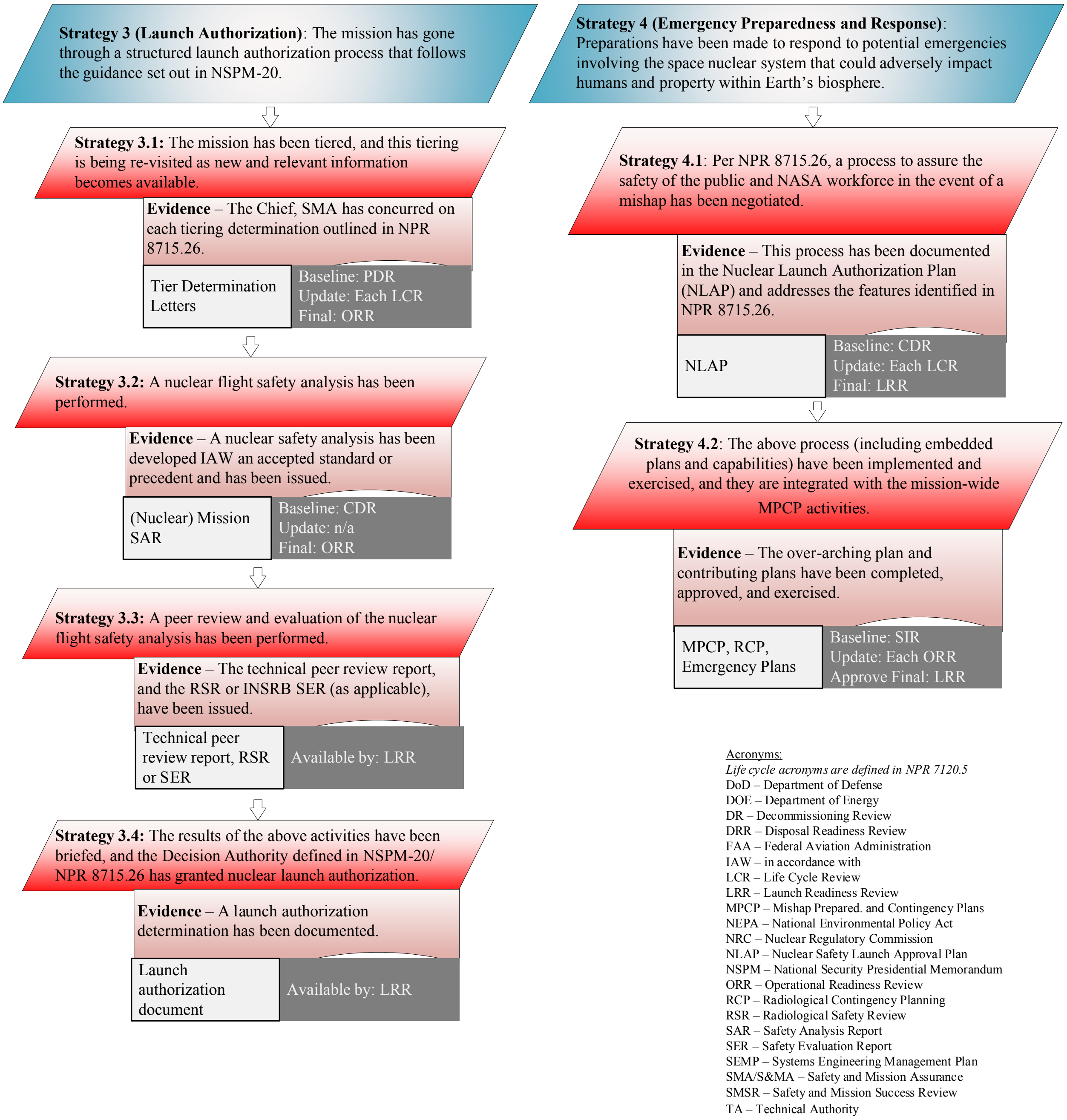

Figure 6 – Notional Assurance Case Strategy Decomposition (Part 2)

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. Importantly, the assurance case is not a one-time deliverable, it is a living document that serves as the basis of safety and mission success assurance at life-cycle reviews. This topic, as well as other aspects of the higher-level assurance framework within NASA's evolving acquisition strategies and systems engineering practices can be found in [23].

Another key aspect of successfully implementing this approach is reliance on accepted standards to ensure that the performers, the peer reviewers, the interagency reviewers (where applicable), the acquirers, 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, and as discussed previously specific to space reactors, 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. SUMMARY AND 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 OSMA, 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 objectives-driven approaches in this area allows OSMA 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 enhancing the effectiveness of the space nuclear area within that "appropriate risk posture."

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 OSMA 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.

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