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THE INTERNATIONAL SAFETY FRAMEWORK FOR NUCLEAR POWER SOURCE APPLICATIONS IN OUTER SPACE - USEFUL AND SUBSTANTIAL GUIDANCE

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Abstract

In 2009, the International Safety Framework for Nuclear Power Source Applications in Outer Space was adopted, following a multi-year process that involved all major space faring nations under the auspices of a partnership between the the UN Committee on the Peaceful Uses of Outer Space and the International Atomic Energy Agency. The Safety Framework reflects an international consensus on best practices to achieve safety. Following the 1992 UN Principles Relevant to the Use of Nuclear Power Sources in Outer Space, it is the second attempt by the international community to draft guidance promoting the safety of applications of nuclear power sources in space missions.

NPS applications in space have unique safety considerations compared with terrestrial applications. Mission launch and outer space operational requirements impose size, mass and other space environment limitations not present for many terrestrial nuclear facilities. Potential accident conditions could expose nuclear power sources to extreme physical conditions.

The Safety Framework is structured to provide guidance for both the programmatic and technical aspects of safety. In addition to sections containing specific guidance for governments and for management, it contains technical guidance pertinent to the design, development and all mission phases of space NPS applications.

All sections of the Safety Framework contain elements directly relevant to engineers and space mission designers for missions involving space nuclear power sources. The challenge for organisations and engineers involved in the design and development processes of space nuclear power sources and applications is to implement the guidance provided in the safety framework by integrating it into the existing standard space mission infrastructure of design, development and operational requirements, practices and processes. This adds complexity to the standard space mission and launch approval processes.

The Safety Framework is deliberately generic to remain relevantly independent of technological progress, of national organisational setups and of space mission types. Implementing its guidance therefore leaves room for interpretation and adaptation. Relying on reported practices, we analyse the guidance particularly relevant to engineers and space mission designers.

Keywords: nuclear power sources, safety, safety framework, COPUOS, STSC

1. INTRODUCTION

Nuclear power sources (NPS) have provided energy to spacecraft since the dawn of the space age. They have enabled some of the most spectacular space missions and are generally considered as key enabling technologies for space exploration [1–5]. The safety of such applications has been a priority for mission designers and engineers from the very first missions and a subject of public discussions and concern [6].

The Safety Framework for Nuclear Power Source Applications in Outer Space (the Safety Framework) is a self-standing international document, jointly prepared by the Scientific and Technical Subcommittee (STSC) of the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) and the International Atomic Energy Agency (IAEA) [7].

Following a lengthy consultation and negotiation period on its scope and attributes and the drafting mechanisms and processes, the actual drafting phase for the Safety Framework started in 2007 and was concluded in February 2009. The IAEA Commission on Safety Standards approved the Safety Framework in April 2009. It was subsequently endorsed by the COPUOS Main Committee in June 2009 and jointly published by COPUOS STSC and the IAEA in December 2009, after it had been "welcomed with satisfaction" by the UN General Assembly [8].

The work plan of the NPS WG of the STSC subsequent to the publication of the framework for the years 2010 to 2015 aims at promoting and facilitating the implementation of the Framework by providing information pertinent to challenges faced by member States and international intergovernmental organisations, in particular those considering or initiating involvement in applications of NPS. The discussion on the legal status of the Safety Framework is outside of the scope of this paper and subject to dedicated publications (e.g. [9]). The guidance provided in the Safety Framework is based on an international consensus on measures needed to achieve safety for launch, operations and end-of-service phases of all space NPS applications.

2. SPECIFIC AND UNIQUE SAFETY CONSIDERATIONS FOR THE DESIGN OF SPACE NUCLEAR POWER SOURCES

NPS applications in space have unique safety considerations compared with terrestrial applications (e.g. [10, 11]). Mission launch and outer space operational requirements impose size, mass and other space environment limitations not present for many terrestrial nuclear facilities. Potential accident conditions resulting from launch failures and inadvertent re-entry could expose NPS to extreme physical conditions. These and other unique safety considerations for the use of space NPS are significantly different from those for terrestrial nuclear systems and are not addressed in safety guidance for terrestrial nuclear applications.

The purpose of the Safety Framework is thus to provide guidance on governmental, organisational/managerial and technical elements to mitigate risks arising from the use of space NPS. Since safety must always be an inherent part of the design and application of space NPS, the Safety Framework focuses not only on the space NPS component but on the entire application, e.g. launch vehicle and spacecraft designs. Therefore the use of a space NPS needs to be integrated into the overall missions safety assurance process from the early design and development phases of both the space NPS and space NPS application (i.e. mission).

3. TYPES OF GUIDANCE PROVIDED IN THE INTERNATIONAL SAFETY FRAMEWORK

3.1. Foundation for the development of governmental frameworks

The Safety Framework contains dedicated sections providing guidance for governments, management, and technical matters for space NPS applications. It is intended to provide a foundation for the development of governmental frameworks while allowing for the necessary flexibility in adapting those frameworks to specific NPS applications.

3.2. Addressing public concern

Space NPS applications tend to create attention and interest by the general public, both related to their typically challenging mission objectives and the use of NPS. Implementation of the Framework by governmental and international intergovernmental organisations provides assurance to the global public that the space NPS application will be used in a safe manner.

3.3. Covering all phases of space NPS applications

The technical guidance provided in the Safety Framework is pertinent to the "design, development and all mission phases of space NPS applications". It specifically covers the elements of technical competence in nuclear safety, safety in design and development, risk assessments and accident mitigation.

3.4. Continuous improvement process

The Framework provides guidance related to incorporating lessons learnt from prior experience, verifying and validating design safety features and controls through tests and analyses, using risk analysis to assess the effectiveness of design features and controls and to provide feedback to the design process and to design reviews.

3.5. Applicable to all type of space NPS

The actual text of the Safety Framework is applicable to all types of space NPS developments and applications. In this aspect it is distinct from the 1992 NPS Principles, which were developed with a focus on specific NPS applications that were in use at the time these Principles were drafted.

3.6. Technical guidance vs technical requirements

The guidance is based on best practices at the time of drafting of the Safety Framework and reflects an international consensus on those practices. Following this guidance naturally leads to practical technical nuclear safety requirements for the identification, evaluation and implementation of design features, controls and preventive measures. The purpose of these measures is to reduce the probability of potential accidents that could release radioactive material and reduce the magnitude of potential releases and their potential consequences.

Instead of prescriptive requirements, the Safety Framework focuses on the necessary *capabilities* and *competences*. It describes the *type of technical activities* that are needed during the design and development processes for space NPS and space NPS applications as well as during the launch phases to mitigate accident consequences.

Engineers and space mission designers typically work to satisfy specific requirements. One of the necessary steps for space

agencies involved in or considering involvement in a space NPS development or application is therefore the integration of guidance from the Safety Framework into the agency's existing infrastructure of design, development and operational requirements, practices and processes.

The requirements that flow from the Safety Framework are similar to other 'mission-unique' requirements that agencies face when conducting 'first-of-a-kind' missions. New requirements (and the organisations, personnel, and interfaces required for satisfying those requirements) may likely be involved in space NPS application missions compared to missions with conventional solar-powered power sources; however, as long as the mission planners recognise those requirements at the outset of the mission formulation phase, then the standard processes for defining a mission's organisation and lower level requirements can readily apply.

Not surprisingly, the additional requirements (including the attendant increase in the number of organisations and interfaces) in a space NPS application mission increase the cost and complexity of the mission relative to a mission powered by solar power. However, as indicated above, NPS has typically enabled missions that push the bounds of scientific knowledge and human capabilities in space. The incremental benefits that flow from such missions have long been one of the key justifications for incurring these additional costs and complexities. Following the guidance of the Safety Framework by considering nuclear safety "from the earliest stages of design and development" enables space agencies initiating involvement in a space NPS development or space NPS application to significantly impact the size and scope of these incremental costs and complexities.

Early consideration of the Safety Framework's guidance provides a focus on the key elements that will help ensure not only the safety of the mission, but also integration of the requirements derived from the Framework's guidance into the mission's organisational and requirements management infrastructure. This early consideration allows for potentially complex issues or arrangements (e.g. exchanging export-controlled or national security data) to be addressed in the governing instruments for the mission.

The following section provides additional information on the guidance for governments, for management and the technical guidance provided in the Framework, drawing from existing and published best practices from organisations with experience in the safe use of space NPS applications, e.g. presentations given by U.S. and Russian delegates to the STSC of COPUOS [12–19]. The focus is on highlighting practical considerations directly useful to practitioners and engineers involved in space NPS applications.

4. ANALYSIS OF RELEVANT GUIDANCE FROM THE 'GUIDANCE FOR GOVERNMENTS' SECTION

The first main section of the Framework addresses the guidance for governments and international intergovernmental organisations (e.g. regional space agencies) that authorise, approve or conduct missions which use NPS applications. It outlines the governmental responsibilities for such space NPS missions which include: having the relevant safety policies, requirements and processes; ensuring that there is acceptable justification for using a space NPS when weighed against other alternatives; establishing a formal launch authorisation process; and preparing for and responding to emergencies.

The Safety Framework lists four areas of guidance for governments:

1. Safety policies, requirements and processes;
2. Justification for space nuclear power applications;
3. Mission launch authorisation'; and
4. Emergency preparedness and response.

4.1. Practical considerations related to the guidance on safety policies, requirements, and processes

Section 3.1 of the Safety Framework specifies that governments and international intergovernmental organisations that authorise or approve space NPS missions should *establish* and *ensure compliance* with their respective safety policies, requirements and processes in order to satisfy the fundamental safety objective (to protect people and the environment in Earths biosphere from potential hazards associated with relevant launch, operation and end-of-service phases of space NPS applications) and fulfil their own safety requirements.

The policy and strategy for NPS safety should be promulgated as a statement of the government's or international intergovernmental organisation's intent and long-term commitment to safety. It should specify the scope of the government's legal and assurance framework for safety. In the case of an international intergovernmental organisation, the policy and strategy would need to specify the roles and responsibilities of the individual member governments of the organisation in relation to those of the overall organisation. Organisations and engineers involved in the design, development and use of NPS should be able to refer to the governments or international intergovernmental organisation's policy and strategy, as appropriate, in order to gain an understanding of the implications for issues such as:

(a) The types of facilities and activities that are included within the relevant legal and assurance framework for safety;
(b) The process that needs to be followed in order to ensure that the rationale for each space NPS application considers alternatives and is appropriately justified (see section 4.2 for more details);
(c) The types of authorisation or approval that are required for different activities and operations associated with space missions with NPS applications (see section 4.3 for more details);
(d) The steps to follow leading to such authorisation or approval, the technical information that needs to be provided and the timescale for decision-making (see section 4.3);
(e) The assignment of legal responsibility for safety and for ensuring continuity of responsibility when relevant safety-related activities are to be carried out by successive organisations;

(f) Independent review of the safety achievement of persons or organisations responsible for safety;
(g) Provision for preparedness for, and response to, a nuclear or radiological emergency involving a space NPS application and for the timely notification of other States that may be involved (see section 4.4 for more details);
(h) Provisions for addressing other interests unique to NPS missions such as nuclear security, the accounting and control of nuclear material, and the import and export of nuclear/radioactive material; and
(i) Responsibilities and obligations with respect to the end-of-life phase of any space NPS mission.

As an example of the application of safety policies, requirements and processes, Wilcox [12] describes several laws and processes in the U.S. which pertain to the launch and safe use of space NPS, which include the National Environmental Policy Act (NEPA) and the Presidential Launch Nuclear Safety Approval process, and numerous NASA internal orders. NEPA requires the launching organisation, NASA, to complete an environmental impact statement (EIS) early in a missions design and development phase. The EIS must assess the potential environmental impacts of the baseline design for the mission and reasonable design alternatives for accomplishing the mission's objectives.

A diverse team of engineers, scientists, lawyers and technical writers are involved in the production of an EIS for a mission involving the launch of an NPS. The engineers and scientists with close knowledge of the mission and the NPS prepare relevant sections of the document including mission description, assessment and applicability of alternatives, and risk assessment. The environmental specialists combine these inputs into the EIS with other relevant studies to ensure that it complies with the NEPA requirements.

The NPS working group of the STSC provides an international forum for countries to share experiences in the use and launch of space NPS. It thus offers countries and international intergovernmental organisations the opportunity to benefit from the experience of countries such as the U.S. and Russia, both of which have long and wide-ranging experience accumulated over decades on the safe use of space NPS applications. However, the wide diversity in the governmental, legal, social and industrial systems of countries considering or initiating involvement in NPS space missions implies that considerable adaptation of this experience to their respective and specific circumstances is likely to be necessary.

4.2. Practical considerations related to the guidance on justification for space nuclear power applications

Space NPS applications may pose risks to people and the environment. For this reason Section 3.2 of the Safety Framework specifies that governments and international intergovernmental organisations that authorise or approve space NPS applications should ensure that the rationale for the use of a space NPS is carefully considered against potential alternatives and is appropriately justified. Organisations and engineers involved in the design, development and use of NPS should be able to refer, as appropriate, to the government's or international intergovernmental organisation's policy and strategy for justification in order to gain an understanding of the implications for issues such as:

(a) The processes and procedures that are to be used to consider the justification for using space NPS applications in specific missions, how justification decisions will be made, and which body is responsible for making such decisions;
(b) The time-frame for reaching decisions on the justification for using space NPS applications on specific missions;
(c) The scope of the information required in order for a justification decision to be made, and who is responsible for providing it; and
(d) The mechanisms for ensuring transparency and the involvement of all relevant bodies/persons in the process of reaching a justification decision.

In the U.S. the EIS examines the rationale for the use of NPS against other alternatives and assures that this rationale is made publicly available for comment before a final decision is made on proceeding with completion of the mission's development, launch and operation.

4.3. Practical considerations related to the guidance on mission launch authorisation

Section 3.3 of the Safety Framework specifies that the government which oversees and authorises the launch operations for space NPS missions should establish a mission launch authorisation process focused on nuclear safety aspects. This process should include a detailed and thorough risk assessment and an independent review of the risk assessment.

Organisations and engineers involved in the design, development and use of NPS should be able to refer, as appropriate, to the government's policy and strategy for authorisation in order to gain an understanding of the implications for issues such as:

(a) The process and procedures that are to be used to determine whether to authorise the launch of missions using space NPS applications, how authorisation decisions will be made, and which body is responsible for making such decisions;
(b) The time-frame for reaching decisions on the authorisation of missions using space NPS applications;
(c) The scope of the information required in order for an authorisation decision to be made, and who is responsible for providing it;
(d) Adequate mechanisms for taking account of the authorisation processes covering non-nuclear and terrestrial aspects of launch safety; and
(e) The mechanisms for ensuring transparency and the involvement of all relevant bodies/persons in the process of reaching an authorisation decision.

Experience has demonstrated the effectiveness of an approval process with requirements for both a detailed safety analysis of the actual system (i.e. power source, spacecraft, launch vehicle, mission design and flight rules) and an independent review of this safety analysis involving the government authorities responsible for the mission's safety. In addition, the information underlying and flowing from this process provides information that guides the development of site-specific radiological contingency plans. [12].

Moreover, since such a process involving the highest levels in government (in the U.S. the Presidential Launch Nuclear Safety Approval Process) likely automatically involves all government agencies and bodies that have a substantive safety responsibility for various aspects of the mission (i.e. spacecraft/mission safety typically by the space agency; NPS safety typically by the manufacturer/owner of the NPS; launch site and range safety typically by the owner/operator of the launch site; and accident cleanup safety, typically by some governmental or regional body responsible for environmental protection), the development and evaluation of the safety analysis provides a focal point for coordinating the discussions and resolution of any nuclear safety issues identified during the development phase of the application.

Further discussion on the launch approval process can be found in section 6.3 of this paper.

4.4. Practical considerations related to the guidance on emergency preparedness and response

Section 3.4 of the Safety Framework specifies that the government or international intergovernmental organisation that authorises, approves or conducts space NPS missions should be prepared to respond rapidly to launch and mission emergencies that may result in potential radiation exposure of people and radioactive contamination of the Earth's environment.

Emergency preparedness activities include emergency planning, training, rehearsals and development of procedures and communication protocols, including the drafting of potential accident notifications. Organisations and engineers involved in the design, development and use of NPS should be able to refer, as appropriate, to the government's or international intergovernmental organisation's policy and strategy for emergency preparedness and response in order to gain an understanding of the implications for issues such as:

(a) The assignment of responsibilities, within the overall governmental legal framework, for preparing emergency response plans and for making arrangements for emergency preparedness and response, and for the immediate notification of an emergency to the competent authorities;
(b) The need and provision for human, financial and other resources;
(c) Designation of competent authorities that will have the responsibility and resources necessary to make preparations and arrangements for dealing with the consequences of a space NPS emergency, both during the emergency and in its aftermath;
(d) Specifying and assigning clear responsibilities for decision making in an emergency and for ensuring effective liaison between all authorised parties and the competent authorities;
(e) Provision for an effective means of communicating with the affected parties, particularly the general public, during the course of a space NPS emergency;
(f) Provision for review and assessment of the emergency response plans of organisations responsible for space NPS missions and of their state of preparedness for such emergencies; and
(g) Provision for acquiring and maintaining the necessary competence to ensure an appropriate, continuing level of emergency preparedness and response.

In the case of the U.S., accidents involving space NPS applications have been included in its comprehensive National Response Framework (NRF) for preparing and responding to disasters and emergencies. For such accidents, the U.S. considered the agencies which would normally be applied to a terrestrial nuclear or radiological emergency at a government facility. It then adapted those normal procedures and agencies to apply to the unique situation of a launch accident involving a space NPS at a NASA facility. [12, 20].

Further discussion on mitigating and managing consequences of potential accidents can be found in section 6.3 of this paper.

5. ANALYSIS OF RELEVANT GUIDANCE FROM THE 'GUIDANCE FOR MANAGEMENT' SECTION

The second main section of the Safety Framework addresses the organisations "involved in space NPS applications", and specifically their management setup. The scope is wide and the formulations used are encompassing with the aim to include all those entities actually involved.

Based on experience gained with missions using space NPS, all organisations involved in such a mission are to some degree affected by the use of nuclear power sources on that mission, even if their involvement is limited to the hardware or software elements not directly related at first view.

The Safety Framework lists three, non-exclusive specific tasks for management:

1. Taking 'prime responsibility' for safety;
2. Providing 'adequate resources' for safety; and
3. Promoting and sustaining a 'robust safety culture'.

It then provides some additional guidance separated into guidance related to:

1. Responsibility for safety; and
2. Leadership and management for safety.

5.1. Practical considerations related to the guidance on the prime responsibility for safety

Section 4.1 of the Safety Framework recommends that "the organisation that conducts the space NPS mission has the prime responsibility for safety" and further specifies that "that organisation should include, or have formal arrangements with, all relevant participants in the mission (spacecraft provider, launch vehicle provider, NPS provider, launch site provider etc.) for satisfying the safety requirements established for the space NPS application."

The practical consequence of requiring to take into account nuclear safety from "the earliest point in the development of a space NPS application" is that all main organisations involved in the development of a space project considering using space NPS need to agree on which organisation will assume prime responsibility according to the terms of the Safety Framework. This implies the establishment of formal relations which include provisions to achieve the fundamental safety objective, with 'relevant participants in the mission' early in the space project's formulation phase.

According to U.S. experience, the nuclear safety considerations exist in all elements and phases of a space NPS application. Safety-relevant changes can be introduced by all main entities involved in the design of a mission: For example, the developers of the NPS can engineer inherent design safety features into the space nuclear power source taking into account accident scenarios. Similarly, the developers of the NPS application can modify and optimise spacecraft and/or mission designs as well as integration processes to mitigate or reduce the probability or severity of potential failures that could lead to the release of radioisotopes. The organisation responsible for the launch of the NPS application can mitigate or reduce the probability or severity of pre-launch processing or launch accidents that threaten the containment of the nuclear power source [19].

Given the potential range of NPS, spacecraft, mission and launch vehicle designs and configurations (many of which are unique), determining with confidence the primary threats to NPS fuel containment is not immediately apparent or intuitive. This leads to the risk of potentially erroneous assumptions by one element of the mission team about another mission element and as a result, the need for all participants in a mission with an NPS application to assume some level of responsibility for nuclear safety. Following the guidance provided by the Safety Framework therefore implies that nuclear safety considerations need to be taken into account into the governing instruments for space NPS applications. In the U.S. experience this leads to, for example, all mission participants explicitly agreeing to support, as appropriate, the definition and satisfaction of the mission's nuclear safety requirements and criteria that are incorporated into the mission's organisational and requirements structures and engineering review processes [19].

According to experience shared by the U.S., this does not necessarily require the development of new organisational structures or processes to replace those that typically exist for multilateral non-NPS missions. Rather it requires existing organisations to incorporate NPS safety requirements, such as the establishment of a nuclear safety culture, at the earliest stage of a mission's development. This is particularly relevant for countries and international intergovernmental organisations considering or initiating involvement in space NPS development and/or space NPS applications, since the necessary expertise and competence to complement existing processes typically involves 'long-lead' times.

In countries without experience in the use and launch of space nuclear power sources, the existing authorisation and approval processes might lack the expertise or participation of governmental agencies or officials necessary to adequately address the breadth of potential requirements or issues involved in ensuring a mission's nuclear safety. In this case, an action for mission managers early in the development phase of such a mission would be to identify organisations with the requisite capabilities, and identify organisational arrangements to integrate them in the NPS application development phase. This could lead to the identification of incremental analytical requirements and processes which are not part of non-NPS missions [19].

The Safety Framework provides some general managerial responsibilities for the organisations involved in space NPS applications, such as:

(a) Establishing and maintaining the necessary technical competencies;
(b) Providing adequate training and information to all relevant participants;
(c) Establishing procedures to promote safety under all reasonably foreseeable conditions;
(d) Developing specific safety requirements, as appropriate, for missions that use space NPS;
(e) Performing and documenting safety tests and analyses as input to the governmental mission launch authorisation process;
(f) Considering credible opposing views on safety matters; and
(g) Providing relevant, accurate and timely information to the public.

From a practical standpoint, all points except point (d) are also present in non-NPS missions to some degree. However, since space NPS application missions have been and are expected to remain relatively rare occurrences, it would be impractical to put in place and maintain completely independent processes, procedures and infrastructure for such missions. As a consequence infrastructure and processes for NPS missions tend to be conceived and built as augmented aspects to existing non-NPS mission infrastructure and processes.

Launch system reliability and failure effects analysis and modelling are such an example. These would use the existing tools characterising launch failure modes but "delve further into the physical environments created by and the sequence of potential threats to NPS containment resulting from a launch accident". Similarly, the potential "environmental impacts of releases of radioactive material are assessed using the same meteorological databases and, in some cases, highly similar models for understanding the impacts of accidents involving large-scale accidental releases of launch vehicle propellants" and "NPS

contingency plans follow standard protocols for responding to any large accident that would potentially involve multiple agencies and levels of government" [12, 15, 19].

Similarly, best practices show that NPS-specific safety reviews and approvals should be handled as incremental requirements for standard mission approvals, even if they involve the highest levels of government as is the case in the U.S.. The practical implication for the management of such missions is that these additional processes, which all require specific competencies, expertise, resources, and time need to be included in the overall planning for the mission. Space mission managers therefore should strive to define and clarify the different additional roles and processes as early as possible in the mission phases to reduce uncertainty and schedule/cost risk in the overall planning.

5.2. Practical considerations related to the guidance on leadership and management for safety

Subsection 4.2 of the Safety Framework addresses internal organisational aspects of the organisations involved in space NPS applications. It lists five specific points that need to be included in the required safety culture of an organisation conducting a space NPS mission:

(a) Clear lines of authority, responsibility and communication;
(b) Active feed back and continuous improvement;
(c) Individual and collective commitment to safety at all organisational levels;
(d) Safety accountability of the organisation and of individuals at all levels; and
(e) A questioning and learning attitude to discourage complacency with regard to safety.

Points (c) to (e) are mirroring the three points listed as essential for a proper safety culture by the IAEA Fundamental Safety Principles for terrestrial nuclear applications, namely the individual and collective commitment to safety on the part of the leadership, the management and personnel at all levels; the accountability of organisations and of individuals at all levels for safety; and measures to encourage a questioning and learning attitude and to discourage complacency with regard to safety [21]. The NPS Safety Framework, includes two additional points, (a) and (b), related to the need for clear lines of authority, responsibility and communication, and for active feedback and continuous improvement.

The former, while necessary for ensuring an efficient design/development process involving multiple organisations, is especially important for assuring the efficient and effective management of contingencies during the launch phase of a mission. The latter is important for future NPS missions since NPS application missions typically don't occur more than once or twice a decade.

6. ANALYSIS OF TECHNICAL GUIDANCE

This section follows the structure of Chapter 5 of the Safety Framework and is thus divided into subsections, each dealing in detail with one of the following elements:

1. Establishing and maintaining a nuclear safety design, test and analysis capability;
2. Applying that capability in the design, qualification and mission launch authorisation processes of the space NPS application (i.e. space NPS, spacecraft, launch system, mission design and flight rules);
3. Assessing the radiation risks to people and the environment arising from potential accidents and ensuring that the risk is acceptable and as low as reasonably achievable;
4. Taking action to manage the consequences of potential accidents.

Due to their relatively long development times, space nuclear power sources tend to be designed well in advance of specific target NPS applications. Development times tend to be on the order of one decade. The primary focus regarding safety during the early development phases of space NPS is on the containment of NPS fuel under a wide range of potential accident scenarios. Accident environments include explosive overpressures, solid and liquid propellant fires, shrapnel impacts, ground impact and reentry.

The risk analysis process of missions involving space nuclear power sources focuses on detailed risk assessments of the integrated NPS application (i.e. NPS, spacecraft, launch system, mission design, flight rules).

This analysis provides an objective basis for identifying and assessing potential design modifications that can enhance the mission's nuclear safety. Such modifications can occur at a subsystem and/or system level and thus include the nuclear power source, its immediate environment, the design of the spacecraft, the design of the launch system (including its abort subsystems and procedures) as well as overall mission design parameters such as trajectories.

Current best practices have shown that the overall objective to keep the radiation risk of nuclear power source applications as low as reasonably achievable, cannot be achieved via design choices of either the NPS or the NPS application alone. It requires a continuous and integrated system level approach involving all aspects of a mission [12].

A thorough nuclear safety review process, integrated into the standard mission review process, is critical to encouraging continual evaluation and consideration of safety enhancements during the entire design, development and approval process.

The following subsections provide further details for each of the four elements listed above.

6.1. Establishing and maintaining a nuclear safety design, test and analysis capability

Under this provision the Safety Framework specifies the competence to:

(a) Define space NPS application accident scenarios and their estimated probabilities in a rigorous manner;

(b) Characterise the physical conditions to which the space NPS and its components could be exposed in normal operations, as well as potential accidents;

(c) Assess the potential consequences to people and the environment from potential accidents; and

(d) Identify and assess inherent and engineered safety features to reduce the risk of potential accidents to people and the environment.

All four points require close technical cooperation between the power source, payload and launch system providers.

Actions under point (a) require the definition of accident scenarios and their probabilities. Such scenarios and their respective probabilities are crucial input parameters for the safety assessments of space nuclear power source applications. (The launch vehicle data required to define these scenarios and probabilities can be defence-restricted or commercially sensitive.) The definition of accident scenarios in the early phases of a mission can influence the design of the NPS (if it has not already been finalised) and help inform design trades involving the spacecraft and/or launch system. In the later phases of the mission's development, refined accident scenario descriptions and sequences are used to estimate the residual probability of an accident which can lead to a potential release of NPS nuclear material.

The *competence* to define these scenarios and their probability typically include expertise from the launch vehicle manufacturer(s) and from the spacecraft manufacturer(s).

Actions under point (b) require detailed engineering competence, mainly in the form of sophisticated modelling of the propagation of effects from initiating accidents. For regular missions such modelling is limited to the extent necessary for traditional range safety purposes such as the trajectory ranges of fragments in case of accidents. The relevant physical conditions in case of launch accident scenarios for space NPS applications however include also temperature, pressure, chemical reactions, energetic (particle) impacts and various combinations thereof. (e.g. [22]).

The *competence* to characterise the physical conditions resulting from defined accidental conditions described in point (a) typically involves expertise from the spacecraft manufacturer, the nuclear power source manufacturer as well as specific physics and chemistry expertise.

Actions under point (c) require another step uncommon to non-nuclear missions: the translation of the different physical conditions determined under point (b) into responses of the NPS in terms of release probabilities and the potential amount, form and location of a release. Given the extreme conditions of launch accidents, these physical parameters are on the limit of typical engineering knowledge for material responses and thus tend to require additional tests and experiments.

The *competence* to assess the potential consequences to people and the environment from accidents thus usually includes expertise from the space nuclear power source manufacturer, from the launch site operator and its meteorological and environmental services.

Some of the extreme environments a nuclear power source can be exposed to in case of accidents might not be able to be mitigated via careful material engineering and protective layer measures.

Actions under point (d) therefore require identifying and assessing measures that could potentially lower the residual risk levels. Maintaining this competence includes maintaining functioning, iterative information exchange processes between the different entities responsible for the design of the NPS (if it has not already been finalised), the spacecraft, the launch system, the overall mission and the flight rules. The *competence* necessary for these tasks includes expertise resting with these entities.

6.2. Application of nuclear safety capability in the design, qualification and mission launch authorisation processes of the space NPS application

This subsection describes the core actions necessary to achieve the overall safety objectives during all phases up to launch. These include the design and development processes necessary to keep the risk from normal operations and from potential accidents to as low as reasonably achievable.

These provisions include the ALARA ('as low as reasonably achievable') principle omnipresent in *terrestrial* nuclear safety [21]. The comparison with terrestrial nuclear safety (e.g. the IAEA Safety Fundamental Principle 8 on the prevention of accidents) reveals the necessarily different approach to an important concept in terrestrial nuclear safety: the concept of "defence in depth", which in the IAEA Safety Fundamental Principle 8 is described as the "primary means of preventing and mitigating the consequences of accidents" [21]. While space NPS system designs naturally also follow this approach in principle, sometimes there is no practical way to implement the required redundancy that would "ensure that no single technical, human or organisational failure could lead to harmful effects". [21] The Safety Framework, however, recognises that it is impractical, if not technically infeasible, to achieve the safety objective of a space NPS application by simply focusing on the safety of the NPS. Instead, mission planners achieve the safety objective "by establishing comprehensive design and development processes" and by fully integrating safety considerations "in the context of the entire space NPS application" [7].

The Safety Framework recommends that the design and development processes include:

(a) Identifying, evaluating and implementing design features, controls and preventive measures that:
   (i) Reduce the probability of potential accidents that could release radioactive material;
   (ii) Reduce the magnitude of potential releases and their potential consequences;

(b) Incorporating lessons learnt from prior experience;

(c) Verifying and validating design safety features and controls through tests and analyses, as appropriate;

(d) Using risk analysis to assess the effectiveness of design features and controls and to provide feedback to the design process; and

(e) Using design reviews to provide assurance of the safety of the design.

The actions under this recommendation are also required as inputs to the mission launch authorisation process, especially those related to point (e). While the nuclear launch authorisation process occurs relatively close to the launch, the principal decision to include nuclear power sources into the (baseline) design occurs during early phases (e.g. phases A/B) of missions. During these phases, a technical analysis of credible alternatives can help provide the justification for base-lining the use of nuclear power sources.

Points (a), (c) and (d) directly follow the recommendations made in section 5.1 of the Safety Framework [7]. The identification, evaluation and implementation of design features, controls and preventive measures to reduce on the one hand the probability of accidents, and on the other hand the magnitude of potential releases and their potential consequences typically requires multiple technical iterations during all design phases of space mission.

This aspect is specifically highlighted by point (d) with the recommendation "to provide feedback to the design process". This implies establishing and exercising a risk analysis capability early enough in the mission design process to allow alternative designs to be compared. Point (c) specifically refers to the use of both, tests and analyses for the process of "verifying and validating design safety features and controls". It thus directly connects to the recommendation made under point (c) of Section 5.1 of the Safety Framework [7].

The recommendations in points (b) and (e), and in particular (b), have more of an organisational nature. They recommend the use of lessons learnt and of design reviews. Both points are standard elements of all space missions and not specific to NPS applications. Design reviews are particularly important for establishing the performance requirements for design safety features since risk analyses need to explicitly assess design safety features. The reference to prior experience without any further qualifications (i.e. tests) typically requires close scrutiny to ensure that experience gained by others is, in fact, relevant and comparable to the NPS mission application being assessed [12–20, 23].

Reported examples of mission design modifications for U.S. space NPS applications using radioisotope power sources (RPS), which have allowed the U.S. to keep the overall nuclear risk as low as reasonably achievable can be classified according to locations and mission types [12]:

launch phase Examples specific to the launch area with the aim to limit the potential crushing forces and fire hazards associated with the intact impact of the entire flight system (i.e. launch vehicle and its RPS application payload) include:

- Enhancing the visibility and telemetry for commanded destruct systems;
- Shortening response times for commanded launch destruct systems; and
- Adding redundant and automated launch vehicle destruct systems.

locations downrange from the launch site Examples specific to reducing the risk at locations downrange from the launch site which enhance a mission's likelihood of mitigating on-orbit anomalies that could result in uncontrolled reentry and ground impact of an RPS application include:

- Increasing the likelihood of spacecraft control in on-orbit or post- injection anomalies; and
- Deploying ground-commanding resources for increasing the likelihood of spacecraft control in on-orbit anomalies.

missions involving Earth swing-by Examples to reduce the risks related to Earth swing-bys include:

- Minimising operations during critical manœuvres; and
- Biasing Earth swing-by trajectories away from Earth.

The first example helps limit the likelihood of having an anomaly that could pose the risk of Earth impact while the second example limits the likelihood that any anomaly could result in an Earth impact.

The essence of the "lessons learned" provided publicly by the U.S. is mainly of an organisational nature. This is indicative of the importance attributed by the U.S. to maintaining a continuity of processes, procedures and organisational relationships between missions that, as indicated above, occur intermittently with different personnel. They include:

- Developing accident scenarios in partnership with the developers of the NPS, the spacecraft and the launch vehicle to better understand the contribution of each component to accident scenarios and to provide an objective basis for evaluating potential nuclear safety enhancements.
- Conducting coordinated rigorous nuclear launch safety analyses, reviews and evaluations with agencies involved in the launch authorisation process.
- Treating each spacecraft / launch vehicle configuration as unique since achievable risk reductions are not always predictable.
- Supporting a 'safety culture' by creating incentives to continually assess and consider implementation of safety enhancements. Wilcox [12] specifically calls out these aspects of the U.S. process:
  - Vesting final nuclear launch safety authorisation in the highest office of the government;
  - The absence of pre-defined 'acceptable' levels of safety; and
  - Subjecting nuclear safety assessments to independent review.

The U.S. places considerable emphasis on this combination, which ensures a strong, continuous, and concerted effort by all involved agencies of the government in a space NPS application

(especially, NASA which, as the agency conducting the mission, has the primary responsibility for the mission's safety) to assure the nuclear safety of the space NPS mission application.

6.3. Risk assessments - Potential consequences to people and the environment from potential accidents

The Safety Framework specifies that risk assessments are essential for the mission launch authorisation process. It recommends that the radiation risks to people and the environment from potential accidents during relevant launch, operation and end-of-service phases of space NPS applications should be assessed and uncertainties quantified to the extent possible. It further specifies that risk assessments are essential for the mission launch authorisation process.

In the case of the U.S. launch approval process, three distinct document types are key in leading to launch approval. First a "Launch Vehicle Databook" is prepared by NASA specific to each mission. It includes the detailed reference design of the mission, launch vehicle, spacecraft, launch complex, mission time-line and trajectory. It also identifies the range of potential accident scenarios (including their sequence of events), and related accident environments (explosion overpressure, fireball, fragment, impact, and reentry) and probabilities. It is the basis for the nuclear safety analysis conducted by the Department of Energy in its Safety Analysis Reports (SAR) for the launch approval process.

Second, a "Safety Analysis Report" (SAR) is prepared by the U.S. Department of Energy which assesses the nuclear safety and potential mission risks. The SAR contains a detailed probabilistic risk assessment of the mission and is documented in three iterative (preliminary, draft, final) levels as part of the launch approval process.

Third, a "Safety Evaluation Report" (SER) is made by an independent group. In the U.S. process this *ad-hoc* group is called the "Inter-Agency Nuclear Safety Review Panel", which reviews the databook and the Safety Analysis Report and performs an independent evaluation of the mission's nuclear risk. The SAR and the SER are the primary documents used by the leadership of the government agencies involved in the mission and by the Office of the President in deciding whether to approve the nuclear launch safety for the mission.

The flow of data that leads to the final risk evaluation of a mission has been documented by Bechtel et al. [13]. They provide a working example of how to clearly delimit the different tasks in this process and thus how to allocate technical and functional work packages [13, 24].

The response of the NPS (i.e. its containment hardware and nuclear material) to the accident scenarios defined in the databook is estimated using using models based on a wide range of safety tests. These include tests at the component up to power-system level. In the case of RPS, such safety testing tends to focus on the response of the radioisotope fuel and its protective layers of cladding to typical accidental conditions. In the U.S. process, the following tests have been conducted by the U.S. Department of Energy to calibrate RPS response models: S [13, 24]:

Explosive overpressure tests This test series evaluates the effects of a shock wave hitting the RPS or one of its components as the result of an explosion.

Fragment projectile tests Fragment tests determine the effects of small fragments and projectiles impinging on the RPS as a result of a launch vehicle explosions. In the U.S., these tests are conducted with aluminium and titanium bullets.

Drop tests Drop tests from high altitudes allow determining terminal velocities and examining tumbling behaviours.

Impact tests These tests allow the determination of the responses to impacts against different media (e.g. for accidents on-pad or during early ascent) and the response to the atmospheric reentry and subsequent Earth impact experienced in the aftermath of an orbital abort. Such tests involve heating, ablating and hot impact at different angles. Entire RPS system impact tests also produce safety relevant test data on distortions and their variability.

Large fragment and flyer plate tests These tests involve the impact of a large fragment and of flyer plates from a launch vehicle casing onto different sides of a simulated section of an RPS. Such tests typically are conducted using rocket sleds. RPSs are heated to pre-launch temperatures just prior to the time of impact.

Solid propellant fire characterisation tests Such tests investigate and characterise the environments underneath and near various types of solid propellants when burning in atmospheric conditions, and measure the response of various isotopic materials or surrogates and their protective layers of containment to those environments [13, 24].

The response to such tests is usually reported in terms of protective cladding distortions, crack dimensions, and released fuel particle size distributions, with the overall goal to determine the size and character of the source term which could be released given an accident.

Since the range of accident conditions and combinations thereof is much larger than those that can be tested, a substantial part of the analysis needs to rely on simulations. Dedicated mathematical models and codes need to be developed for this purpose (e.g. [25]) to model all major potentially damaging environments such as the blast from the launch destruct event, the impact of the NPS hardware on the ground, the impact of debris and solid propellant fragments onto the NPS hardware, and the response of the power system due to reentry. These codes produce a set of look-up tables which allow determining the source term for a given accident scenario. Under most cases, the safety features of the NPS should prevent a release of material. For cases under which a release might occur, an analysis needs to determine how far any released material might be transported and what health effects or environmental effects

might result. In the U.S. process this is done by transferring the source term to a consequence suite of codes modelling transport of material, health effects and environmental effects. The final product of such a risk assessment contains calculated 'best estimates' of the probability of an accident, the probability of release given an accident, possible consequences in terms of potential individual and population radiation doses and land contamination, overall risk (i.e. probability times consequences) calculations, and uncertainty distributions around the various estimates [13, 24].

Clayton et al. [26] report that for radioisotope power systems, the initial typical sequence for these environments is a blast overpressure, followed by a fragment field, and lastly a fireball. All are strongly dependent on the moment of the initiation of the accident. The blast overpressure depends on the altitude of the event and the amount and location of propellant from the launch vehicle. The fragment field defines the mass, dimensions, origin and velocity of the fragments. The fragment properties are dependent on the blast and the accident outcome conditions. The resulting fireball is calculated based on the amount and types of fuel remaining in the launch vehicle. The size and type of fireball affects the particle size distribution and the amount of vaporised material.

Clayton et al. [26] further describe that in the case of the U.S. code used for this analysis (Launch Accident Sequence Evaluation Program (LASEP)), the next element after the determination of the state of the NPS is to determine the NPS's and all other fragment trajectories to the ground. The fragment field is then evaluated to determine any impact with the NPS during the flight to the ground.

The models for evaluating the effect of the ground impact need to take into account the impact orientation of the NPS and the impact surface. The NPS may then be impacted by falling debris. For accident scenarios where the liquid propellant does not ignite in the air, ground fires, along with blast over-pressures need to be calculated. Some accidents will require application of a model to determine the effects of solid propellant impacts and fires when fragments of the solid propellant land in proximity to the NPS and NPS components. Solid propellant fires will also impact the particle size distribution and amount of material that is vaporised [26].

6.4. Mitigating and managing the consequences of potential accidents

The Safety Framework recommends that as part of the safety process for space NPS applications, measures should be evaluated to mitigate the consequences of accidents with the potential to release radioactive material into Earth's environment. The necessary capabilities should be established and made available, as appropriate, for timely support of activities to mitigate the consequences of accidents, including:

(a) Developing and implementing contingency plans to interrupt accident sequences that could lead to radiation hazards;
(b) Determining whether a release of radioactive material has occurred;
(c) Characterising the location and nature of the release of radioactive material;
(d) Characterising the areas contaminated by radioactive materials;
(e) Recommending protective measures to limit exposure of population groups in the affected areas;
(f) Preparing relevant information regarding the accident for dissemination to the appropriate governments, international organisations and non-governmental entities and to the general public.

While the previous three subsections of the technical guidance section of the Safety Framework deal with measures to prevent accidents, the last one makes recommendations regarding the preparedness in case of accidents and the measures to limit and mitigate potential accident consequences. These need to be integrated into the safety process for space NPS applications.

Points (a) to (f) identify the major elements of a radiological contingency planning process. The information provided by countries with experience on launching space nuclear power sources also provides information that is useful to engineers and space mission designers. According to U.S. experience, one of the major functions of this process is to identify the requirements basis for the contingency response plan and develop effective plans and timely procedures for addressing an accident or incident that could result in a radiological release. According to information from past U.S. NPS mission applications, detailed radiological contingency planning starts about three years prior to a scheduled launch [20].

Mission specific support plans are drafted and matured over the three years up to launch in an iterative process. These include areas such as: data management plans, out-of-launch area contingency plans, source recovery plans, data assessment plans, logistics support plans, and field monitoring [20].

The development of these radiological contingency plans needs to be based on the same data and analysis from the approval process for launches of NPS applications. It thus needs to be gradually updated taking into account updates to the safety analysis and evaluation reports that are prepared for the nuclear launch safety approval process.

The radiological contingency plans need to be coordinated among all entities involved in the case of a potential release. These normally include: the organisation conducting the mission; the organisation manufacturing the nuclear power source; state, provincial, and local officials with roles in civil security (e.g. local emergency management representatives); the launch site; environmental protection agencies; meteorological services; and diplomatic services as well as maritime services (e.g. coast guard) in case of a launch close to coasts. The efficient coordination of information flow typically requires one lead organisation and one specific person (usually from the lead organisation) to serve as coordinator and primary interface. This person and his/her team, containing representatives of all relevant organisations involved, act as the focal point for on-site and off-site operations, including the coordination, approval and dissemination of information and recommendations involving the

status of the radiological materials on the mission.

Recommendations (b) to (d) require specific technical expertise, facilities and also equipment. It is important that the coordinating team has centralised, reliable real-time information. This includes telemetry, trajectory and tracking data for the mission launch vehicle and, if an accident/incident occurs with the launch vehicle during any phase of the launch to orbit, information on the accident parameters, the predicted impact locations of the spacecraft and associated debris, including the NPS. This information combined with local meteorology can be used to help predict the potential dispersion of any radioactive material and related ground concentrations and radiation doses [20].

In addition to mission and launch specific information, the radiological contingency planning and coordinating team needs reliable information on whether a release has occurred and, if so, on the dispersion of radioisotopes. The surroundings of launch sites are therefore equipped with (potentially automated) ambient air sampling devices that allow real-time detection of radioisotopes. These are placed around the launch site based on expected plume characteristics depending on short-term meteorological forecasts.

7. CONCLUSIONS AND FUTURE WORK

The Safety Framework for Nuclear Power Source Applications in Outer Space represents a global consensus on best practices for activities related to ensuring the safety of such missions. It provides guidance for governments, management as well as technical guidance.

Applying its recommendations requires augmenting the non-NPS space application mission review and launch approval processes with additional requirements, organisations and processes. Relying extensively on reported best practices within the U.S. and to a certain degree, the Russian Federation, so far the only two countries with long-standing experience in space NPS mission applications involving all phases, the present paper has attempted to summarize the guidance and highlight points of particular relevance to engineers, designers and managers of space missions involving nuclear power sources.

ABBREVIATIONS AND ACRONYMS

ALARA As Low As Reasonably Achievable

COPUOS Committee For the Peaceful Uses of Outer Space

DOE Department of Energy (U.S.)

EIS Environmental Impact Statement (U.S.)

ESA European Space Agency

IAEA International Atomic Energy Agency

JPL Jet Propulsion Laboratory (U.S.)

LASEP Launch Accident Sequence Evaluation Programme (U.S.)

NASA National Aeronautic and Space Administration (U.S.)

NEPA National Environmental Policy Act (U.S.)

NPS Nuclear Power Source

NPS WG Working Group on the Use of Nuclear Power Sources in Outer Space (within the STSC)

NRF National Response Framework (U.S.)

OOSA Office of Outer Space Affairs

RPS Radioisotope Power Source

STSC Scientific and Technical Subcommittee of COPUOS

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