TECHNICAL GUIDANCE FROM THE INTERNATIONAL SAFETY FRAMEWORK FOR NUCLEAR POWER SOURCE APPLICATIONS IN OUTER SPACE FOR DESIGN AND DEVELOPMENT PHASES

Leopold Summerer

ESA Advanced Concepts Team, Keplerlaan 1, 2201AZ Noordwijk, The Netherlands, leopold.summerer@esa.int

ABSTRACT

In 2009, the International Safety Framework for Nuclear Power Source Applications in Outer Space [1] has been adopted, following a multi-year process that involved all major space faring nations in the frame of the International Atomic Energy Agency and the UN Committee on the Peaceful Uses of Outer Space. The safety framework reflects an international consensus on best practices. After the older 1992 Principles Relevant to the Use of Nuclear Power Sources in Outer Space, it is the second document at UN level dedicated entirely to space nuclear power sources.

This paper analyses aspects of the safety framework relevant for the design and development phases of space nuclear power sources. While early publications have started analysing the legal aspects of the safety framework, its technical guidance has not yet been subject to scholarly articles. The present paper therefore focuses on the technical guidance provided in the safety framework, in an attempt to assist engineers and practitioners to benefit from these.

Key words: nuclear safety, IAEA, COPUOS, NPS.

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. [2–6] 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. [7]

The Safety Framework for Nuclear Power Source Applications in Outer Space 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).[1]

Following a lengthy consultation and negotiation period on its scopes and attributes and the drafting mechanisms and processes, the actual drafting phase started in 2007 and was concluded in February 2009. The IAEA Commission on Safety Standards approved the 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.

It has since entered into the set of international documents that form the corpus of international space law. Its legal status has been the subject of dedicated publications. [8]

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. [9, 10]) 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 2009 safety framework is thus to provide guidance on 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, it focuses on the entire application and not only on the space NPS component. It therefore also needs to be integrated into the overall missions safety assurance process from the early design and development phases of space NPS and space missions intending to use space NPS.

3. TYPE OF TECHNICAL GUIDANCE PROVIDED IN THE INTERNATIONAL SAFETY FRAMEWORK

The safety framework contains dedicated sections for guidance for governments, guidance for management and technical guidance for such NPS applications.

3.1. Technical guidance vs technical requirements

The technical guidance provided in the 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.

The guidance is based on best practices at time of drafting of the safety framework and reflects an international consensus on them. 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 it to reduce the probability of potential accidents that could release radioactive material and reduce the magnitude of potential releases and their potential consequences.

It furthermore provides guidance related to incorporating lessons learned 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.

The actual text of the safety framework is relatively high level and intentionally generic to be applicable to all types of space nuclear power source developments and applications. In this aspect it is distinct from the 1992 NPS Principles, which exclude on the one hand some types of applications of NPS and provide on the other hand some very detailed and specific, even numerical limitations.

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 applications as well as during the launch phases to mitigate accident consequences.

Engineers and space mission designers are however used to work against specific requirements. One of the current challenges for organisations involved in the design and development processes of space nuclear power sources is therefore the proper interpretation of the technical guidance provided in the safety framework and its application in form of specific, dedicated and applicable *safety requirements*.

Some of the guidance might even seem self-explanatory and obvious at first sight. Their proper application, together with the recommendation to establish these capabilities "from the earliest point in the development of a space NPS application" bear however heavy consequences on space missions intending to use NPS in terms of technical, programmatic and organisational added complexity as well as in terms of additional costs.

The inclusion of such comprehensive safety considerations from the earliest stages of space missions is relatively un-common to space missions. Furthermore, the implementation of many recommendations requires a close technical cooperation between the different main partners cooperating in space NPS applications, with an unusual amount of exchange of data. Since some of this data might not only protected for commercial reasons but also on national security grounds, especially international missions tend to start such a process very early.

The following section intends to provide additional information in form of an analysis of the high-level technical guidance provided in the safety framework to allow engineers to better interpret these in form of requirements. It draws from existing and published best practices from organisations with experience in the safety use of space NPS applications, including presentations given by US and Russian delegates in the frame of the Scientific and Technical Subcommittee of COPUOS.[11–18]

4. 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 in 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. These typically include information on existing launch vehicles and the accidental environments these can create for mission payloads. Considered accident conditions include launch pad explosions, solid and liquid propellant fires, shrapnel impacts, ground impact and reentry.

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

This analysis is then used for the identification of potential design modifications that can enhance the missions nuclear safety. Such modifications can occur at all subsystem and system levels, and thus include the nuclear power source, its immediate environment, the design of the spacecraft, the design of the launch system and its launch abort subsystem and procedures as well as overall mission design parameter 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, but requires a continuous and integrated system level approach involving all aspects of a mission. [11]

A thorough nuclear safety review process, usually integrated into the standard mission review process, is critical to encourage 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.

4.1. 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 a close technical cooperation between the different partners cooperating for space NPS applications.

Actions under point (a) require the definition of accident scenarios and their probabilities. Such scenarios and especially their respective probabilities are crucial input parameters for the safety assessments of space nuclear power source applications. These might also be commercially sensitive in case the launch platform is also offered on the commercial launch market and these data can contain defence-restricted information. The definition of accident scenarios already at the early design phases of NPS allow deriving potential accidental conditions and thus make design choices accordingly. Similarly, their refined description leads to the estimation of the residual release probability which is used in the final approval process for the launch of of a spacecraft including a nuclear power source.

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 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. Many of these parameters are known only with relatively large uncertainty margins. (e.g. [19])

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

Actions under point (c) require another step uncommon to regular missions: the translation of the different physical conditions determined under point (b) into responses of the nuclear power source application and the nuclear power source itself. Given the relatively harsh 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 to identify and assess any 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, the spacecraft, the launch system, the overall mission and the flight rules. The competence necessary for these tasks includes expertise resting with these entities.

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

This subsection could be considered as describing the core actions necessary to achieve the overall safety objectives during all phases up to launch. These are including 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. [20] The comparison with terrestrial nuclear safety (e.g. the IAEA Safety Fundamental Principle 8 on the prevention of accidents) also reveals the absence of another important concepts 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". [20] The safety framework more generally aims at achieving the safety objectives "by establishing comprehensive design and development processes" and by fully integrating safety considerations "in the context of the entire space NPS application". [1]

This difference to the safety principles for terrestrial nuclear activities is related to the stringent requirements of space systems. 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". [20]

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 learned 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 already during early phases (e.g. phases A/B) of missions. At this moment, a technical analysis of all credible alternatives provides the justification for using nuclear power sources.

Points (a), (c) and (d) directly follow the recommendations made in section 5.1 of the safety framework. [1] 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 making these detailed risk analyses early enough in the mission design process to allow for changes. 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. [1]

The recommendations in Points (b) and (e) are of a more organisational nature. They recommend the use of lessons learned and of design reviews. Both points are standard elements of all space missions and not specific to NPS applications. The reference to prior experience without any further qualifications implies that experience gained by others than the organisation conducing the mission needs to be taken into account. The US, Russia, and China have been sharing their respective experiences in the frame of the Working Group on the Use of Nuclear Power Sources in Outer Space (NPS WG) of the STSC. Dedicated workshops and meetings of have been held during its multi-year work plan for the period since 2010. [11–18, 21, 22]

Wilcox [11] provides examples of mission design modifications for US space NPS applications using radioisotope power sources (RPS), which have allowed to keep the overall nuclear risk as low as reasonably achievable. These modifications are classified according to locations and mission types:

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 form the launch site which enhance a missions 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 swingby 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 US is mainly of organisational and not of technical nature and thus only of limited direct relevance to the purpose of this paper. It includes the conclusions to

- Develop accident scenarios in partnership with the developers of the NPS, the spacecraft and the launch vehicle to better understanding the contribution of each component to accident scenarios and to provide an objective basis for evaluating potential nuclear safety enhancements.
- Conduct coordinated rigorous nuclear launch safety analyses, reviews and evaluations with agencies involved in the launch authorisation process.
- Treat each spacecraft / launch vehicle configuration as unique since achievable risk reductions are not always predictable.
- Support a safety culture by creating incentives to continually assess and consider implementation of safety enhancements. Among these incentives in the US process, Wilcox [11] specifically mentioned
  - 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.

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

The safety framework 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.

The nuclear launch risk assessment process involves a wide range of safety tests. These include tests at the component up to subsystem level. In the case of radioisotope power sources, such safety testing tends to focused on the response of a radioisotope fuel and its immediate cladding to typical accidental conditions. Bechtel et al. [12] list the following tests conducted by the US Department of Energy in the frame of the nuclear risk assessment for US radioisotope heat sources RPS:

Explosive overpressure tests This test series evaluate the effects of a shock wave hitting the RPS or on 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 US, these tests are conducted with aluminium and titanium bullets.

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

Solid propellant fire tests Exposure to extended duration fire from a large cube of solid propellant allow characterising the heat resistance of fuel clads and protection layers.

Impact tests These tests allow determining 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 potentially experienced in the aftermath of an orbital abort. Such tests involve heating, ablating and hot impact at different angles. Entire RPS subsystem 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 different sides from a launch vehicle casing against a simulated section of an RPS. Such tests typically are conducted on (rocket) sled tests. RPS are heated to pre-launch temperatures at time of impact.

Ductility testing These tensile tests at a variety of temperatures allow to better understand the properties of the cladding material.

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 to measure the response of various isotopic materials or surrogates to those environments. [12]

The response to such tests is usually reported in terms of distortions, crack dimensions, and fuel particle size distributions.

The safety framework specifies that risk assessments are essential for the mission launch authorisation process. In the case of the US 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 timeline and trajectory. It also already identifies the range of potential accidents, 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 (SARs) for the launch approval process.

Second, "Safety Analysis Reports" are made by the manufacturer of the NPS (in the US the Department of Energy) which assesses the nuclear safety and potential mission risks. These safety analyses are documented in such reports at three iterative (preliminary, draft, final) levels as part of the launch approval process.

Third, a "Safety Evaluation Report" is made by an independent group. In the US it is called the "Interagency Nuclear Safety Review Panel", which reviews the databook and the safety analysis report and performs an independent safety assessment of the mission.

The flow of data that leads to the final risk evaluation of a mission as reported by Bechtel et al. [12] is particularly useful for engineers since it provides a working example of how to clearly delimitate the different tasks in this process and thus allocate technical and functional work packages:

The launch vehicle and accident probabilities and environments (described in the databook provided by the organisation that conducts the mission) serve as primary input to the calculations. Phenomenological codes maintained by the nuclear power source manufacturer determine the response of the NPS hardware to blast, impact, fires, and reentry. These codes produce a set of look-up tables which are used as an inputs to determine the source term for a given accident scenario. Under most cases, the safety features of the NPS prevent a release of material. Should a release occur, the source term is transferred to a consequence suite of codes to determine how far any released material might be transported and what health effects or environmental effects might result. The final product of such a risk assessment is a distribution of probability of accident, probability of release, possible consequences, mean values, and an estimate of the risk.

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 models and codes have been developed for this purpose. (e.g. [23]) These attempt to model all main potentially damaging environments such as the blast from the launch destruct event, the impact of the NPS hardware on the ground, and the impact of debris and solid propellant fragments onto the NPS hardware.

Clayton et al. [24] report that for radioisotope power systems, the 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. [24] further describe that in the case of the US code used for this analysis (Launch Accident Sequence Evaluation Program (LASEP)), the next element after the determination of the state of the RPS is to determine the RPSs and all other fragment trajectories to the ground. The fragment field is then evaluated to determine any impact with the RPS 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 RPS and the impact surface. The RPS 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 RPS and RPS components. Solid propellant fires will also impact the particle size distribution and amount of material that is vaporised. [24]

4.4. 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 Earths 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 recommendation areas of the technical guidance section of the framework deal with measures to prevent accidents, the last one makes recommendations regarding the preparedness in case of accidents and thus measures to limit and mitigate their consequences. These need to be done integrated and as part of the safety process for space NPS applications.

Points (a) to (f) provide the large categories for these actions. The information provided by countries with experience on launching space nuclear power sources gives some additional information more directly useful to engineers and space mission designers. According to Bechtel and Smoker [22], one of the major functions of this process is to identify the requirements basis for the contingency response plan and develop the timelines for development of effective plans and timely procedures for addressing an accident or incident that could result in a radiological release. According to information from past US NPS mission applications, detailed radiological contingency planning starts about three years prior to a scheduled launch.

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. [22]

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

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, diplomatic services as well as maritime services (e.g. coast guards) in case of a launch close to coasts. The efficient coordination of information flow typically requires one lead organisation and one specific person (usually of the lead organisation) to serve as coordinator and primary interface. This person and his 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) are probably those that are most direct technical recommendations since they require specific technical competence, expertise, facilities and also equipment. Technically, it is important that the coordinating team has at any moment, 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. [22]

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 in this case on the dispersion of radioisotopes. The surroundings of launch sites are therefore equipped with (potentially automated) ambient air sampling devices that allow to determine in real time if radioisotopes are present. These are placed around the launch site according on expected plume characteristics depending on short-term meteorological forecasts.

5. CONCLUSIONS AND FUTURE WORK

The international safety framework for nuclear power sources 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 relatively generic recommendations requires a number of specific technical activities to be included into the regular mission review and launch approval processes. Some of these are un-common in missions not involving the use of nuclear power sources. Analyses on its legal aspects have been published. The present paper attempts a first analysis of its technical guidance and information of its implementation in countries with experience in using space nuclear power sources and how it could help engineers and practitioners to benefit from it.

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