

GENERIC STUDY OF SAFETY AND SUSTAINABILITY

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ABSTRACT Based on the data base and experiences gathered in the United States a respective accident-mode analysis including relevant safety test campaigns, analysis and justifications will be outlined. In addition, mission goals will be assessed taking into account the respective requirements for the needed energy system.					
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Table of Abbreviation and Acronyms

ALARA	Acceptable and as low as reasonably achievable
BISO	Bi-isotropic
EIS	Environmental impact statement
ENSaF	European space nuclear safety framework
GPHS	General purpose heat source
IAEA	International atomic energy agency
IAEA-STSC	Scientific and Technical Subcommittee
NEPA	National environment protection act
NPS	Nuclear power sources
RHUs	Radioisotope heater units
RPS	Radioisotope power system
RTGs	Radioisotope thermoelectric generators
TRISO	Tri iso-structural
UN COPUOS	United Nations Committee on the Peaceful Uses of Outer space
UN GA	United Nations General Assembly

1. Reference documentation:

[R 1]	FP7-SPACE-2011-284081 Grant agreement core; annex I DOW; annex II;.... signed 18/10/2011
[R 2]	www.DiPoP.eu
[R 3]	Joint Expert Group of the Scientific and Technical Subcommittee (of the United Nations Committee on the Peaceful Uses of Outer Space) and the International Atomic Energy Agency: Development of a Safety Framework for Nuclear Power Source Applications in Outer Space, 3rd IAASS (International Association for the Advancement of Space Safety) Conference, Rom, Italy, Oct. 2008
[R 4]	Wilcox, R.: "Safety in the Design and Development of United States Space NPS Applications", In Proceedings of the forty-eighth session of the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space, Vienna, February 2011.
[R 5]	Summerer, L.: ESA-ESTEC ACT
[R 6]	Bechtel, R.D. and Lipinski, R.J. and Smith, J.A. and Bartel, T.J. and Potter, D.L. and Radel, T.E. and Bixler N.E. and Rutger, L.L.: "U.S. Approach to Risk Assessment and its Role in Implementing an Effective Safety Program for Space Nuclear Power Sources Applications", In Proceedings of the forty-eighth session of the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space, Vienna, February 2011.
[R 7]	Abstract of U.S. Presentation on "Safety in the Design and Development of U.S. Space NPS Applications"
[R 8]	Abstract of U.S. Presentation on "U.S. approach to Risk Assessment and its Role in Implementing an Effective Safety Program for Space NPS Applications"
[R 9]	Abstract of Argentina's presentation on "Safety Workshop for Space Nuclear Power Sources: the roadmap for its implementation in a special case for Argentina".
[R 10]	Committee on the Peaceful Uses of Outer Space, General Assembly: "Safety Framework for Nuclear Power Source Applications in Outer Space" A/AC.105/934, 19 th May 2009
[R 11]	Summerer, L. and De Winne, F.: "Considerations on Safety and European Options Regarding Nuclear Power Sources for Space" In Proceedings of the 1st IAASS Conference, Nice, France, October 2005.
[R 12]	Space Radioisotope Power Systems Safety, NASA and DOC
[R 13]	United Nations Office for Outer Space Affairs: "United Nations' Treaties and Principles on Outer Space", 2008.
[R 14]	"Workshop on the Use of Nuclear Power Sources in Outer Space: Safety in the design and development of United States nuclear power source applications in outer space", <i>Paper submitted by the United States of America</i> , In Proceedings of the forty-eighth session of the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space, Vienna, February 2011.
[R 15]	Summerer, L.: "ENSaF - Steps towards a European Space Nuclear Safety Framework", Proceedings, TRISMAC 2008 - 15 April 2008, ESTEC.
[R 16]	Summerer, L., Gianfiglio, G.: "ESA's Approach to Nuclear Power Sources for Space Applications" European Space Agency ESTEC- Advanced Concepts Team, 2201 AZ, Noordwijk, Netherlands.
[R 17]	Deutscher Bundestag: „Stenografischer Bericht: 117. Sitzung“, Tagesordnungspunkt 4, Berlin, June, 30 2011, <i>in German</i> .
[R 18]	The National Diet of Japan, Fukushima Nuclear Accident Independent Investigation Commission: "The official report of The Fukushima Nuclear Accident Independent Investigation Commission - Executive summary", Tokyo, June 2012, <i>in English</i> .

2. Introduction: Use of NPS in Outer Space

Nuclear Power Sources (NPS) are used to enable, or to significantly enhance, interplanetary missions that would otherwise be limited or unfeasible if restricted to solar power. Examples include long-duration missions to the outer planets and extended Mars surface exploration missions. NPS can be of different types like the following examples:

- Radioisotope Heater Units (RHUs)
- Radioisotope Thermoelectric Generators (RTGs)
- Fission Reactor Systems
- Fusion Reactor Systems

Currently fission reactors are not in flight on any mission but they have flown in the past (on SNAP-10 in 1965 in US, on Topaz up to 1988 in Russia) . There are no immediate plans to use them in very near future but they are contemplated for scientific and exploration missions to Moon, Mars or other solar system destinations requiring high power. [R 3]. Moreover the Russian program NPPS started in 2011 with a megawatt level fission reactors consider also missions for NEO deflection or space debris removal.

2.1 Scope of NPS technologies

Every type of NPS can only cover a certain thermal power range due to technical limitations. Therefore different applications are usually limited to one type of NPS. The typical applications are shown in figure 1 together with some examples of terrestrial systems of the same power.

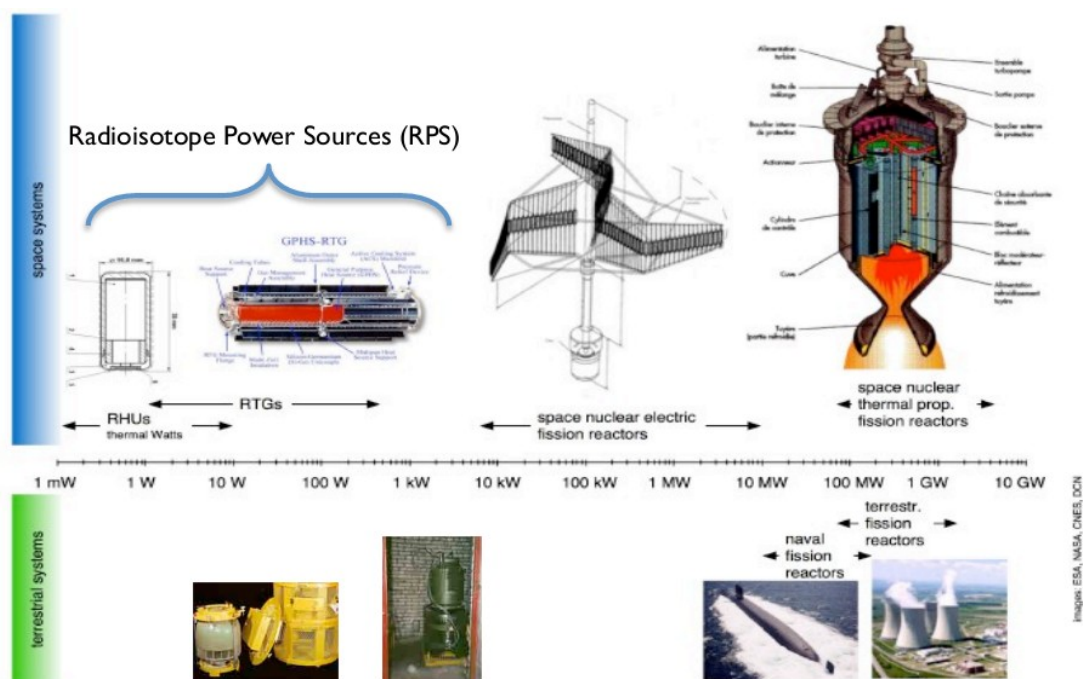


Figure 1: NPS technologies and applications [R 5]

2.2 RTGs and RHUs

Until today RTGs and RHUs have been used safely on a number of successful missions as illustrated for US missions in figure 2.

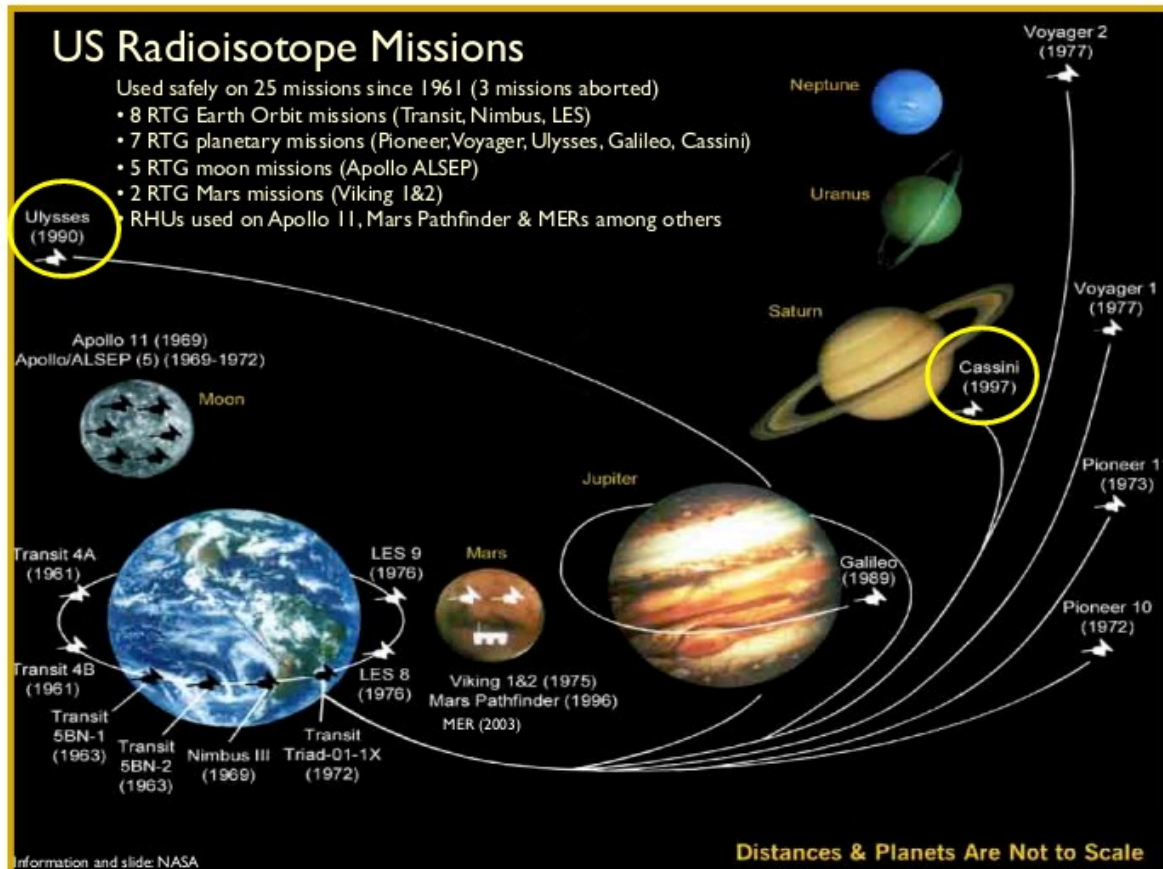


Figure 2: US Radioisotope missions [R 4]

3. Status of preparatory work for NPS safety

3.1. UN COPUOS/IAEA

In 1992 the UN GA Resolution (GA Res. 47/68) "Principles Relevant to the Use of Nuclear Power Sources In Outer Space" was accepted. Most relevant for NPS safety concerns is Principle 4 (Safety assessment):

“A launching State [...] shall, prior to the launch, through cooperative arrangements, where relevant, with those which have designed, constructed or manufactured the nuclear power sources, or will operate the space object, or from whose territory or facility such an object will be launched, ensure that a thorough and comprehensive safety assessment is conducted. This assessment shall cover as well all relevant phases of the mission and shall deal with all systems involved, including the means of launching, the space platform, the nuclear power source and its equipment and the means of control and communication between ground and space.” [R 13]

Sine 1992 preparations have been made to adopt this resolution on UN /IAEA level:

- **2003:** Adoption of a work plan within STSC to "develop an international technically based framework of goals and recommendations for the safety of nuclear power source applications in outer space"
- **2006:** IAEA-STSC Workshop on Space NPS
- **2007:** Creation of Joint STSC-IAEA NPS Expert Group for the development of the framework
 - *Drafting of the first version during 2007, the draft was relatively high level (similar to IAEA SF-1)*
- **2010:** Adoption of the UN-COPUOS/IAEA Safety Framework
 - *Safety Framework is congruent with US Safety Standards for NPS*
- **2011 and 2012:** UN COPUOS NPS Workshops
 - *US reports on Safety Standards for NPS*
 - *Russia does not, but must have a standard [R 5]*

“The fundamental safety objective is to protect people and the environment in Earth’s biosphere from potential hazards associated with relevant launch, operation and end-of-service phases of space nuclear power source applications.” [R 10]

3.2. Implementation

Implementation is done on mid level in Europe which includes EU and ESA.

On the European level the Drafting of a European Space Nuclear Safety Framework (ENSaF) process has been initiated. The US and Russian setup demonstrate the need to involve organizations which are not present during regular launch approval process. Space and nuclear safety experts from big ESA member states prepare a draft of a technically sound European framework that provides a predictable, efficient and workable process for ESA missions and addresses the main concerns of participating member states. The safety framework takes advantage of the existing European nuclear safety expertise [R 11, 15, 16] and experience gained on the subject in US and Russia and provides a technically sound basis for an early decision on processes, roles and responsibilities.

A study was initiated under the general studies program in 2005. To share experience for ENSaF ESA and NASA cooperated in a letter during spring 2006. It is the goal to keep ENSaF in close alignment with the IAEA-STSC safety framework for NPS, which would allow the EU in the future to launch their own RPS [R 5, 11, 15, 16].

3.3 Heritage (USA)

The United States are using nuclear elements in space since over 40 years and had to develop an acceptable security framework to cover these elements.

UN/IAEA Safety Framework	United States Federal Law/Guidance
Governmental Guidance	<ul style="list-style-type: none"> - National Environmental Policy Act - White House Launch Nuclear Safety Approval Process - Code of Federal Regulations - NASA Procedural Requirements - National Response Framework
Management Guidance	<ul style="list-style-type: none"> - NASA Procedural Requirements - Department of Energy Orders - RPS Development Plans
Technical Guidance	<ul style="list-style-type: none"> - NASA Procedural Requirements - NASA Task Orders - RPS Development Requirements and Performance Specifications - National Response Framework

Table 1: Comparison UN/IAEA with NASA safety framework [R 4, 14]

There are three levels of guidance designated in the UN-COPUOS/IAEA safety framework including governmental, management and technical guidance all of which have congruent sections in the US rationale. Table 1 gives examples of US laws, orders and frameworks associated with each level.

The first level, Governmental Guidance, ensures that Governments that authorize or approve space nuclear power source missions receive sufficient information to take a proper decision. It is also necessary for the government to verify that the rationale for using the space nuclear power source application has been appropriately justified which is accomplished by an assessment of the risks and potential environmental impacts in the environmental impact statement (EIS) by NASA. In addition a detailed safety analysis of the actual system is required.

In case of disasters and emergencies a National Response Framework has been developed which includes accidents involving space NPS applications [R4]

The second level, Management Guidance, states that the prime responsibility for safety should rest with the organization that conducts the space nuclear power source mission, in this case NASA, which includes:

- Establishing and maintaining the necessary technical competencies
- Providing adequate training and information to all relevant participants
- Establishing procedures to promote safety under all reasonably foreseeable conditions
- Developing specific safety requirements, as appropriate, for missions that use space NPS
- Performing and documenting safety tests and analyses as input to the governmental mission launch authorization process
- Considering credible opposing views on safety matters
- Providing relevant, accurate and timely information to the public

Management Guidance should also establish effective leadership and management for safety and be sustained in the organization that conducts the space nuclear power source mission. [R 10]

The program executive is responsible that all the above efforts meet the specifications of the National Environment Protection Act (NEPA), the Presidential Launch Nuclear Safety Approval Process and the National Response Framework and has to inform the organizations about current developments [R 4, 12, 14].

The third level, technical guidance, affects the whole designing process, development and the mission phases by establishing and maintaining a nuclear safety design, test and analysis

Capability and applying it, e.g. by defining space NPS application accident scenarios, characterizing the physical conditions to which the space NPS and its components could be exposed in normal operations and identifying and assessing inherent and engineered safety features to reduce the risk of potential accidents to people and the environment.

Another element of the technical guidance is the assessing of radiation risk to people and the environment arising from potential accidents and ensuring that the risk is Acceptable and Low As Reasonably Achievable (ALARA in nuclear engineering terms) as well as taking action to manage the consequences of potential accidents, which means developing and implementing contingency plans to interrupt accident sequences that could lead to radiation hazards and being able to determining whether a release of radioactive material has occurred and if so, identify location of the release and areas contaminated by radioactive materials.

Additionally recommending protective measures for the population of affected areas and provide sufficient information for appropriate governments, organizations and the public [R 4, 10, 14].

The next paragraph outlines the resulting safety design and development requirements for Radioisotope Power System (RPS) mission applications when applying the US safety framework. It states that basic designs of vehicles, spacecraft, and systems utilizing radioactive materials have to provide protection to the public, the environment, and users such that radiation risk resulting from exposures to radioactive sources are as low as reasonably achievable.

Furthermore nuclear safety considerations are to be incorporated from the initial design stages throughout all project stages to ensure that overall mission radiological risk is acceptable and all space flight equipment (including medical and other experimental devices) that contain or use radioactive materials are identified and analyzed for radiological risk. All site-specific ground operations and radiological contingency plans have to be developed commensurate with the risk represented by the planned launch of nuclear materials which includes provisions for emergency response and support for source recovery efforts [R3].

The US safety framework is clearly focused on reducing any radiological risks on ground and in the spacecraft as early as possible in the design process but also includes planning for emergencies. Its focus is wide-ranged at the beginning and becomes more specific and more detailed once the development of specific RPS application begins (i.e. Spacecraft, launch system, mission design). [R 7] Over the years and with current testing and developments at hand the safety of RPS is enhanced and continuous. [R 4, 14].

3.3.1 Implementation of Nuclear Safety in NASA Space RPS Applications

NASA's implementation of nuclear safety spans all phases and all elements of an RPS application. Radioisotope Power System (RPS) development programs establish component and system level safety objectives, requirements and performance specifications such as:

- Radioisotope fuel element designs emphasize containment and immobilization under a wide range of normal and accident conditions (e.g. launch pad explosions, solid and liquid propellant fires, shrapnel impacts, ground impact, reentry). some tests intended to verify the design soundness are described in chapter 3.3.3.
- RPS designs include accident performance specifications that maximize the safety benefits of element containment/immobilization designs
- Safety testing and analysis programs verify safety designs

As a result of the RPS safety requirements system level safety objectives, requirements and specifications aiming at radioisotope fuel element containment and immobilization have been established [R 4, 14].

Table 2 on the next page depicts the safety considerations applied in the US during design / development, launch and mission operations phase. During the launch and mission operations

phase it is most important to prevent losing control of the spacecraft cause and counteract any uncontrolled reentry into atmosphere.

Phase	Nuclear Safety Considerations in Space RPS Applications
Design/Development Phase	<ul style="list-style-type: none"> - Assessing nuclear safety of launch, system, spacecraft and mission designs options - Considering spacecraft alternate RPS locations for reducing intact impact accident hazards
Launch Phase	<ul style="list-style-type: none"> - Enhancing visibility and telemetry for commanded destruct systems - Adding redundant and automated launch vehicle destruct system - Shortening response times for commanded launch destruct systems - Increasing likelihood of spacecraft control in on-orbit or post-injection anomalies - Deploying ground commanding resources for increasing likelihood of spacecraft in on-orbit anomalies
Mission Operations Phase	<ul style="list-style-type: none"> - Minimizing operations during critical manoeuvres - Biasing Earth swing-by trajectories away from Earth

Table 2: Safety considerations for space RPS [R 4]

3.3.2 Nuclear Safety Lessons Learned

The U.S. safety analysis begins with a thorough understanding of the launch vehicle, space craft, and mission design and launch rules and is followed by safety test campaigns. Furthermore finite element analysis models are used to understand how the RPS and nuclear fuels will respond to a variety of accident scenarios [R 8]. The following steps are taken while developing space RPS applications:

- Develop accident failure scenarios in partnership with the nuclear power source, spacecraft and launch vehicle developers
- Conduct coordinated rigorous nuclear launch safety analyses, reviews and evaluations with agencies involved in the launch authorization process
- Recognize that each spacecraft /launch vehicle configuration is unique
- Support a ‘safety culture’ by creating incentives to continually assess and consider implementation of safety enhancements
 - Include ‘nuclear safety’ elements in all major reviews
 - Establish and integrate a nuclear safety risk analysis team into the entire design and development process for an RPS application

- Independent evaluation of safety analyses coupled with the White House having responsibility for launch nuclear safety authorization creates a strong and sustained incentive to reduce nuclear risk

The above enumeration summarizes some of the most important safety aspects for space RPS applications. Especially creating a 'safety culture' is considered an important element to make everyone involved aware of the risks and how to prevent them.

It is essential that the safety of space nuclear systems cannot be separated from integrated safety features of the launch vehicle, spacecraft and mission profile including a flight termination system. An extensive program to ensure reliability of launch vehicles and spacecraft is absolutely necessary when trying to improve the safety of space NPS. Additional important elements of this integrated approach to safety are a supporting range safety organization and related contingency planning activities prior to and during launch. [R 4, 14]

3.3.3 Examples for US safety features

Nuclear systems safety testing can consist of tests such as [R 6]:

- Explosive overpressure tests
- Fragment projectile test
- Drop tests
- Solid propellant fire tests
- Bare clad impact tests
- General Purpose Heat Source impact tests
- Large fragment tests
- Flyer plate tests
- Edge on flyer plate tests
- RTG End-on impact tests
- Iridium ductility testing
- Solid propellant fire characterization tests

Test /accidental situation relationship:

- Solid propellant fire tests: after a catastrophic launch failure (e; g; on launch pad), verification of the containment integrity in a solid propellant fire.
- RTG End-on impact tests : verification of the integrity of the RTG fuel element after an impact at terminal velocity speed (natural speed near sea level from aerodynamic drag after atmospheric reentry).

Nuclear safety analysis contains:

- Launch vehicle data book
- Safety analysis report
- Safety evaluation report

Computational safety analysis covers the areas shown in figure 3. The main issues for which specific code is required are:

- Blast and impact
- Fire and thermal analysis
- Re-entry analysis
- Source term analysis
- Consequence analysis

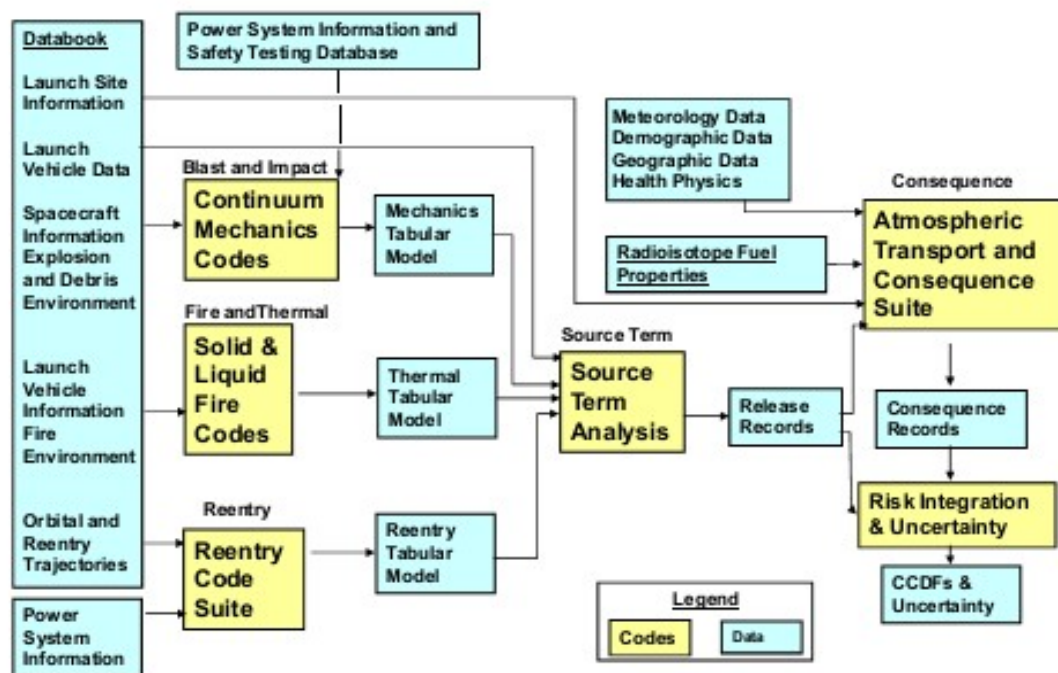


Figure 3: Computational safety analysis [R 6]

The re-entry analysis is especially relevant to the RTG case. The heat source shall survive re-entry heat flux while submitted also to the radioactive load. The carbon-carbon envelope is acting as a re-entry shield. The ballistic coefficient shall be moderate in order to limit the re-entry peak flux. In these conditions the carbon-carbon ablation is moderate and may be even inexistent.

In the case of nuclear reactors, two main re-entry approaches are considered:

- A shield covering the whole reactor vessel and protecting the reactor during re-entry.
- A re-entry guaranteed at nuclear fuel level, e. g. fuel formed of carbon – carbon tiles containing BISO or TRISO pellets. In that case, the reactor pressure vessel may burn during re-entry without risk of fission products release.

4. Lessons learned from the Fukushima Nuclear Accident

The Fukushima Daiichi Accident is at the date of the present report the most recent case of a nuclear incident raising questions on nuclear safety. The event was perceived by the public in several countries as an ultimate proof that nuclear safety cannot be achieved in an ethically sustainable manner and thus demanding to abandon the technology [R 17]. Consequently, it also raises the question of how the safety system failed and if the responsible failure mode can be avoided in space nuclear power and propulsion. The present chapter concentrates the failure analysis in “The official report of The Fukushima Nuclear Accident Independent Investigation Commission” [R F] presented to the National Japanese Diet¹ and compares the findings with the aspects covered in the safety considerations discussed above.

4.1. Succession of events

On March 11, 2011, the so called *Great East Japan Earthquake* caused an average of Level 7 (“Severe Accident”) on the International Nuclear Event Scale (INES) at the Fukushima Daiichi Nuclear Plant. Initially, while the Earthquake did not break the reactor blocks, it severely damaged the cooling system's external electricity supply at the Shin-Fukushima transformer station. Following that, the cooling systems were maintained by the plant's Diesel generators until they were flooded and thus halted by the subsequent Tsunami. Then, all power was lost because also the back-up line was not operable due to mismatched sockets. The consequence was a station black-out and failure of the cooling systems yielding at least a partial core melt down. It can be said that in practice there was neither a sufficient diversity nor a mutual independence of earthquake-resistant external power supply systems. It is also possible that the earth-quake led to a small-scale Lack Of Coolant Accident. However, this cannot be confirmed so far as the reactor blocks are inaccessible and will remain so for many years. The heat discharge and generation of Hydrogen led to an explosion releasing radioactive material [R 18].

Considering the failure of the systems, the cause of this severe accident is not only to be identified in the natural catastrophe but also in the omissions of the operating company, TEPCO.

Responding to the accident was very difficult for the staff on site since there were no suitable means of mitigation in place since and they were not sufficiently trained for such situations. The plans never considered a station wide accident scenario, i.e. encompassing all the blocks. For example, the operation of the Isolation Condenser (IC) could not be confirmed promptly because no manual or appropriate equipment was available or sections of were missing. Consequently, all activity was time-consuming, while a rapid response was necessary.

But this was only one of the safety failures on TEPCO's account. Although the risks of both earthquakes and tsunamis were known to TEPCO and to the regulating agency (NISA), no respective regulation was enacted. Above that, international safety standards were neglected and revisions of security measures, though conducted, failed to improve the public safety because nuclear power companies in Japan did not implement any of the recommended measures.

¹ i.e. the Japanese body of legislation or parliament.

4.2. Organizational problems regarding public safety

4.2.1. Regulations

The report [R 18] indicates that the lack of security measures to prevent nuclear disasters of this scale was due to organizational and regulating failures. The primary goal of a regulating body should be the public safety. Therefore, respective safety regulations on nuclear power plants must be even imposed if the operators opposed such measures. This is however not what happened. During an assessment of the nuclear plants it became obvious for NISA, the regulating agency, that safety reinforcements had to be made. But while some of the respective rules were already just voluntary, the remaining were postponed by the operators, and so eventually none of the reinforcements were realized, as NISA failed to take a strong position on behalf of the public.

This could happen because NISA was neither independent from the stately bodies promoting nuclear power, nor from the operators. Hence, enforcing relevant safety reinforcements came out to be effectively impossible being expensive for the operators and NISA being not strong enough. On a personal scale, the responsible in the operating companies overestimated the current nuclear safety situation and underestimated the probability of a natural disaster causing a nuclear average, while external experts were well aware of a need of retrofitting.

4.2.2. Evacuation process

Another problem occurred during the evacuation of contaminated areas surrounding the Fukushima Daiichi Nuclear Plant. The crisis management of the government, the regulators and TEPCO did not work.

A clear definition of the roles and responsibilities did not exist, making many of the means to prevent or limit consequential damages ineffective. Since the communications between the operators, NISA, the Kantei² and regional authorities did not work either, the chain of command was interrupted. The Kantei intervened directly in decisions at the plant thus causing confusion and delays. Regional authorities and nuclear response teams were informed slowly and insufficiently.

During the evacuation of contaminated areas radiation monitoring information was not provided, partially because systems failed without being replaced. Also the severity of the situation was not disseminated. This caused one part of the affected population being exposed to high levels of radiation while the other part was hastily escaped with only the barest necessities. Some individuals experienced this chaotic procedure several times. Many of the locals were informed about the accident very late and no accurate information about health implications and counter measures could be given.

Eventually the trust in the operators and the stately responsible was lost.

² i.e. the Japanese prime minister's office

4.2.3. Recommendations for the future

The *Fukushima Nuclear Accident Independent Investigation Commission* prepared recommendations [R 18] to prevent the encountered failure modes. For the future it is vitally important that nuclear power plants underlie strict regulations which will have to be imposed by a truly independent regulation agency which sets the safety of the public as its first priority. The regulations should be decided based on recent developments and international standards and be made transparent to the public. Especially information considering long-term health consequences should be disclosed to everyone in a comprehensive way. Moreover, it is important to clearly define all actions and responsibilities by operators and government agencies in case of a nuclear emergency.

4.3. Comparison to safety regulations concerning Nuclear Power Sources in space applications

The UN/IAEA Safety Framework and especially the US Federal Law/Guidance is very detailed about the development of an RPS. Many of the problems which occurred in Fukushima are much more unlikely to happen.

First of all it is not possible for an agency, in this case NASA, developing the RPS to avoid safety regulations, because they are controlled not only by a single body but also by the government. They have to assure that national and international safety aspects are given at any time during the operation of the RPS. Furthermore the use of an RPS has to be justified and other methods have to be discussed. If the decision is clear and RPS is the most suitable solution, an assessment of risks and potential of the environmental impacts has to be made, as well as a detailed safety analysis. During the on-going development, safety is the priority at all times and has to be assured throughout the process. In the unlikely event of an emergency there is a National Response framework to respond to the accident.

The technical guidance gives even more regulations on that, so that possible accident scenarios have to be assessed, identifying risks and counteractions and safety measures for each scenario. By the Management Guidance, it is assured that people working on the project are qualified to do so, safety is promoted and the public is informed. The management is also required to hear and cite credible opposing views on the project, so that better and safer solutions can be considered. During each step of development, safety measures become more detailed and specific for the application and phase of operation. The risk is always kept to the lowest achievable level.

Of course it is not possible to eliminate the risk completely, but there are countermeasures in place if the case of emergency occurs and radioactive material cannot be contained any further. As long as these measures are taken seriously and regulations are adhered to and the control mechanism are functioning, then the risk is kept to a minimum and the use of RPS in space can be accounted for.

4. Observations

The high level developments concerning UN/IAEA are congruent with the US safety rationale that has a heritage of some 40 years [R 13]. The mid level ENSaF draft is in alignment with IAEA/STSC Safety Framework which in turn is congruent with the US approach [R 11, 15, 16]. On working level the US approach has been well reported during the UN-COPUOS NPS workshops [R 5].

Argentina is currently working on establishing NPS on EO satellites of which the Nuclear Regulatory Authority is in charge to warrant that the design and use of NPS will be fully compatible with the UN-IAEA Safety Framework [R 9].

5. Conclusion

The usage of NPS in outer space is well justifiable and the review shows well aligning progress for an NPS safety approach development including implementation plans for ESA and their realization. It is shown that the congruency of UN/IAEA safety framework and the US nuclear safety implementation is due to the well established and qualified safety approach by the US and their strong involvement in the development process of the IAEA/UN safety framework. The ENSaF process is based on the IAEA/UN safety framework and also happens in cooperation with the US which explains its congruency to the US approach.

Concerning safety and sustainability data base and experiences gathered in the United States have been evaluated [R 4, 6]. A respective accident-mode analysis including relevant safety test campaigns, analysis and justifications has been preemptively outlined.

The assessment of sustainable mission scenarios and goals is still pending. For this purpose the respective requirements for the needed energy system will be taken into account.