U.S. Department
of Transportation
Federal Aviation Administration

Advisory Circular

Subject: Launch and Reentry of Space Nuclear Systems

Date: 10/20/2023

Initiated By: AST-1

AC No: AC 450.45-1

This Advisory Circular (AC) guides applicants through the launch and reentry licensing process when space nuclear systems (SNS) are present on a launch or reentry vehicle. This AC provides a means of compliance and guidance for applicants proposing to launch or reenter SNS for meeting the requirements for a safety review under § 450.45. This AC also applies to applicants for a payload determination for SNS under 14 CFR § 450.43.

This AC provides an accepted means of compliance with the regulatory requirements of §§ 450.43 and 450.45 related to SNS. It presents one, but not the only, acceptable means of compliance with the associated regulatory requirements. The contents of this document do not have the force and effect of law and are not meant to bind the public in any way. The document is intended only to provide clarity to the public regarding existing requirements under the law or agency policies.

If you have suggestions for improving this AC, you may use the Advisory Circular Feedback form at the end of this AC.

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1 PURPOSE.

The purpose of this AC is to guide applicants through the launch and reentry licensing process when SNS are present on a launch or reentry vehicle. This AC provides a means of compliance and guidance for applicants proposing to launch or reenter SNS for meeting the requirements for a safety review under § 450.45. This AC also applies to applicants seeking a payload determination for SNS under 14 CFR § 450.43. In accordance with § 450.45(e)(6), the FAA will evaluate the launch or reentry of any radionuclide on a case-by-case basis and issue an approval if the FAA finds that the launch or reentry is consistent with public health and safety, safety of property, and national security and foreign policy interests of the United States. The guidance in this AC can also be used for reference by mission planners and operators in the commercial space industry, designers and manufacturers of launch vehicles or reentry vehicles that may transport SNS, and designers, manufacturers, and operators of SNS, to assist them in understanding the safety analysis and regulatory processes that the FAA will apply in reviewing applications for commercial launches or reentries involving SNS. Spaceports may also find portions of this AC useful for understanding the public safety and regulatory concerns with SNS.

1.1 Level of Imperatives.

This AC presents one, but not the only, acceptable means of compliance with the associated regulatory requirements. The FAA will consider other means of compliance that an applicant may elect to present. In addition, an operator may tailor the provisions of this AC to meet its unique needs, provided the changes are accepted as a means of compliance by the FAA. Throughout this document, the word “must” characterizes statements that directly follow from regulatory text and therefore reflect regulatory mandates. The word “should” describes an option that, if used would constitute a means to comply with the regulation; variation from the provisions of this AC is possible, but must satisfy the regulation to constitute a means of compliance. The word “may” describes variations or alternatives allowed within the accepted means of compliance set forth in this AC. The term “applicant” is used throughout this AC to describe any party seeking any approval, determination, or license from the FAA under 14 CFR Chapter III for commercial space operations involving an SNS.

2 APPLICABILITY.

2.1 The guidance in this AC is for launch and reentry vehicle applicants and operators required to comply with 14 CFR part 450. The guidance in this AC is for those seeking a launch or reentry vehicle operator license, licensed operators seeking to renew or modify an existing vehicle operator license, and FAA commercial space transportation evaluators.

2.2 The material in this AC is advisory in nature and does not constitute a regulation. This guidance is not legally binding in its own right and will not be relied upon by the FAA as a separate basis for affirmative enforcement action or other administrative penalty. Conformity with this guidance document (as distinct from existing statutes and regulations) is voluntary only, and nonconformity will not affect rights and obligations under existing statutes and regulations. This AC describes acceptable means, but not the only means, for demonstrating compliance with the applicable regulations.

2.3 The material in this AC does not change or create any additional regulatory requirements, nor does it authorize changes to, or deviations from, existing regulatory requirements.

3 APPLICABLE REGULATIONS AND RELATED DOCUMENTS.

The documents referenced in this chapter refer to the current revisions or regulatory authorities' accepted revisions.

3.1 Related United States Office of the President Documents.

- Executive Order 12114, *Environmental Effects Abroad of Major Federal Actions*, dated January 4, 1979. https://www.archives.gov/federal-register/codification/executive-order/12114.html.
- Executive Order 13972, *Promoting Small Modular Reactors for National Defense and Space Exploration*, dated January 5, 2021; https://www.federalregister.gov/documents/2021/01/14/2021-01013/promoting-small-modular-reactors-for-national-defense-and-space-exploration.
- Memorandum on Space Policy Directive -5, *Cybersecurity Principles for Space Systems*, dated September 4, 2020; https://trumpwhitehouse.archives.gov/presidential-actions/memorandum-space-policy-directive-5-cybersecurity-principles-space-systems/.
- Memorandum on Space Policy Directive -6, *Memorandum on the National Strategy for Space Nuclear Power and Propulsion*, dated December 16, 2020; https://trumpwhitehouse.archives.gov/presidential-actions/memorandum-national-strategy-space-nuclear-power-propulsion-space-policy-directive-6/.
- NSPM-20, *Presidential Memorandum on Launch of Spacecraft Containing Space Nuclear Systems*, dated August 20, 2019; https://trumpwhitehouse.archives.gov/presidential-actions/presidential-memorandum-launch-spacecraft-containing-space-nuclear-systems/.

3.2 Related Council on Environmental Quality Regulations.

- Title 40, Code of Federal Regulations (CFR) Chapter V, Subchapter A, *National Environmental Policy Act Implementing Regulations*, last amended May 20, 2022.

3.3 Related Department of Defense (DOD) Manual.

- Department of the Air Force Manual (DAFMAN) 91-110, Nuclear Safety Review and Launch Approval for Space or Missile Use of Radioactive Material, dated February 24, 2022.

3.4 Related Department of Energy Regulations.

- Title 10 CFR part 835, *Occupational Radiation Protection*, last amended October 11, 2022.

3.5 **Related Department of Transportation Orders and Regulations**.

- Department of Transportation (DOT) Order 5610.1C, *Procedures for Considering Environmental Impacts,* dated September 18, 1979. https://www.transportation.gov/sites/dot.gov/files/docs/Procedures_Considering_Environmental_Impacts_5610_1C.pdf.
- Transportation of Radioactive Materials; *Memorandum of Understanding Between the NRC and DOT*, (44 FR 38690, dated July 2, 1979). https://www.nrc.gov/about-nrc/regulatory/enforcement/moudot.pdf.
- Title 49 CFR part172, *Hazardous Materials Table, Special Provisions, Hazardous Materials Communications, Emergency Response Information, Training Requirements, And Security Plans*.
- Title 49 CFR 173 Subpart I – Class 7 (Radioactive) Materials.

3.6 **Related Environmental Protection Agency Regulations and Reports**.

- Environmental Protection Agency (EPA) Federal Guidance Report No. 11, EPA-520/1-88-020, *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion*, dated September 1988. https://www.epa.gov/radiation/federal-guidance-radiation-protection.
- EPA, Federal Guidance Report No. 15, EPA-402-R19-002, *External Exposure to Radionuclides in Air, Water and Soil*, revised August 2019. https://www.epa.gov/radiation/federal-guidance-radiation-protection.
- EPA, Revision to the PAG Manual: Protective Action Guide (PAG) for Drinking Water After a Radiological Incident, revised January 19, 2017. https://www.federalregister.gov/documents/2017/01/19/2017-01230/revision-to-the-pag-manual-protective-action-guide-pag-for-drinking-water-after-a-radiological
- EPA, Protective Action Questions & Answers for Radiological and Nuclear Emergencies: A companion document to the U.S. Environmental Protection Agency Protection Action Guide (PAG) Manual," EPA-402/K-22/002, January 2022. https://www.epa.gov/radiation/pag-public-communication-resources.

3.7 **Related FAA Order and Regulations**.

- FAA Order 1050.1F Environmental Impacts: Policies and Procedures, dated July 16, 2015.
- Title 14 CFR Chapter III, Commercial Space Transportation, Federal Aviation Administration, Department of Transportation.

3.8 **Related Federal Emergency Management Agency Programs**.

- Federal Emergency Management Agency (FEMA) National Incident Management System, dated October 10, 2017. https://www.fema.gov/sites/default/files/2020-07/fema_nims_doctrine-2017.pdf.

- FEMA National Response Framework, dated October 28, 2019. https://www.fema.gov/sites/default/files/2020-04/NRF_FINALApproved_2011028.pdf.
- FEMA Nuclear/Radiological Incident Annex to the Response and Recovery Federal Interagency Operational Plans, dated May 2023. https://www.fema.gov/sites/default/files/documents/fema_incident-annex_nuclear-radiological.pdf.
- FEMA Radiological Emergency Preparedness Program Manual, FEMA P-1028, dated December 23, 2019. https://www.fema.gov/sites/default/files/2020-06/FEMA_REP_Program_Manual_Dec_2019.pdf.

3.9 **Related NASA Standards and Documents**.

- National Aeronautics and Space Administration (NASA), Nuclear Safety, Procedural Requirements, NPR 8715.26, Nuclear Flight Safety, dated February 3, 2023.
- NASA Standard 8719.24B, NASA Payload Safety Requirements Table, https://standards.nasa.gov/sites/default/files/standards/NASA/B//NASA-STD-871924B-Annex.pdf.

3.10 **Related Nuclear Regulatory Commission (NRC) Definitions and Regulations**.

- Nuclear Regulatory Commission NRC Full Text Glossary. https://www.nrc.gov/reading-rm/basic-ref/glossary.html.
- Title 10 CFR, Chapter I. Nuclear Regulatory Commission.

3.10.1 **Related International Atomic Energy Agency Report and Regulations**.

- International Atomic Energy Agency (IAEA), *Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material*, 2018 Edition, SSG-26. Revision 1. https://www.iaea.org/publications/14685/advisory-material-for-the-iaea-regulations-for-the-safe-transport-of-radioactive-material-2018-edition.
- IAEA, *Convention on Early Notification of a Nuclear Accident and Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency*, updated 2002. https://www.iaea.org/sites/default/files/publications/documents/infcircs/1986/infcirc335a11-infcirc336a12.pdf.
- IAEA, *Regulations for the Safe Transport of Radioactive Material*, SSR-6 Rev.1. 2018 edition, https://www.iaea.org/publications/12288/regulations-for-the-safe-transport-of-radioactive-material.
- IAEA, *The Role of Nuclear Power and Nuclear Propulsion in the Peaceful Exploration of Space*, 2005. https://www-pub.iaea.org/MTCD/publications/PDF/Pub1197_web.pdf.

- IAEA, *Criteria for Use in Preparedness and Response for a Nuclear or Radiological Emergency*, GSG-2 General Safety Guide, 2011. https://www.iaea.org/publications/8506/criteria-for-use-in-preparedness-and-response-for-a-nuclear-or-radiological-emergency.
- IAEA, *Operational Intervention Levels for Reactor Emergencies and Methodology for their Derivation*, EPR-NPP-OILs, 2017, https://www.iaea.org/publications/11093/operational-intervention-levels-for-reactor-emergencies

3.10.2 **Related United Nations Conventions, Documents, Resolution and Treaties**.

- United Nations *Treaty on the Non-Proliferation of Nuclear Weapons;* https://www.un.org/disarmament/wmd/nuclear/npt/
- United Nations Treaty on *Principles Governing the Activities of States in the Exploration and Use of Outer Space*, including the Moon and Other Celestial Bodies, Resolution 222, dated 1966. https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html

3.11 **Related U.S. Department of Health and Human Services, Food and Drug Administration Program Alignment Recommendation**.

- United States Food and Drug Administration, *Accidental Radioactive Contamination of Human Food and Animal Feeds: Recommendations for State and Local Agencies*, dated August 13, 1998. https://www.fda.gov/about-fda/fda-organization/fda-program-alignment.

4 DEFINITION OF TERMS.

For this AC, the terms from 14 CFR § 401.7 and the following definitions apply:

4.1 Anticipated Operational Occurrences

Those conditions of normal operation, which are expected to occur one or more times during the life of an SNS, including single failures that can be anticipated to occur during its operational life.

4.2 Biosphere

Also known as the ecosphere, this is the worldwide sum of the earth's ecosystems including its hydrosphere, and lithosphere. It is the life-supporting stratum of the Earth's surface, extending from a few kilometers into the atmosphere to the deep-sea vents of the ocean. The biosphere is a global ecosystem composed of living organisms (biota) and the abiotic (nonliving) factors from which the organisms derive their energy and nutrients.

4.3 Collision

Physical contact between two objects at a relative speed greater than 1 kilometer per hour, or any physical contact between two objects that can cause physical damage to either object.

4.4 Critical or Criticality

The normal operating condition of a fission reactor, in which nuclear fuel sustains a fission chain reaction and each fission event releases enough neutrons to sustain an ongoing series of reactions.

4.5 Criticality Accident

The release of energy that is a result of accidentally producing a critical or supercritical fission chain reaction.

4.6 Decay Heat

The heat produced by the decay of radioactive fission products after a reactor has been shut down.

4.7 Delayed Critical

State of a reactor that is critical based on the contribution of delayed neutrons to the overall neutron flux, i.e., a reactor with a controllable fission chain reaction.

4.8 Delayed Neutrons

Neutrons from nuclei produced by beta decay following fission. They follow fission by intervals of seconds to minutes.

4.9 **Dose Equivalent**

A measure of the biological damage to living tissue because of radiation exposure. Calculated as the product of the absorbed dose in tissue multiplied by a quality factor and other necessary modifying factors.

4.10 **Exposure**

Absorption of ionizing radiation or ingestion of a radioisotope.

4.11 **Fission**

The splitting of an atom, which releases a considerable amount of energy, usually in the form of heat, radiation, at least two lighter elements, and neutrons. Fission may occur spontaneously but is commonly neutron-induced for nuclear reactors.

4.12 **High-fidelity Radiological Safety Analysis (HFRSA)**

A high-fidelity radiological safety analysis applies probabilistic risk assessment methods and calculates the risk to the public for all reasonably foreseeable events and failures of safety-critical systems during normal and malfunction operations in all mission phases.

4.13 **Low-Enriched Uranium (LEU)**

Uranium fuel in which the weight percent of U-235 in the uranium is less than 20%.

4.14 **Prompt Critical**

A fission reactor that is critical only due to the prompt neutrons and is therefore supercritical due to the additional presence of delayed neutrons.

4.15 **Prompt Neutrons**

Neutrons emitted immediately during the fission process.

4.16 **Shutdown Margin**

The instantaneous amount of reactivity by which a reactor is subcritical or would be subcritical from its present condition assuming the reactivity control system is fully activated to minimize reactivity, except the single reactivity control device of highest reactivity worth is fully maximizing reactivity.

4.17 **Single Failure**

An occurrence that results in the loss of capability of a component to perform its intended safety functions. Multiple failures resulting from a single occurrence are considered to be a single failure.

4.18 **Source Term**

The magnitude, composition, form (physical and chemical), and mode of release (puff, intermittent, or continuous) of radioactive elements (including source isotope, fission, and activation products) released during a reactor accident.

4.19 Space Nuclear System

A nuclear system intended to operate in space, including any radioactive fuel and associated structures, systems, and components that are required to operate the nuclear power system. Space nuclear systems would include radioisotope power systems (RPSs), such as radioisotope thermoelectric generators (RTGs) and radioisotope heater units (RHUs), and fission reactors used for power and propulsion.

4.20 Supercritical or Supercriticality

A state of a nuclear reactor core during which fission neutron production exceeds all neutron losses, causing an increase in the number of fissions occurring and resulting in rising power.

4.21 Uncontrolled Release

A release of any radioactive material that cannot be terminated on command by the operator. An example of uncontrolled release is a material fracture resulting in a direct pathway for nuclear fuel or fission products to reach the environment with no way for the operator to stop the release.

5 ACRONYMS AND SYMBOLS.

AC – Advisory Circular

ALARA – As Low as Reasonably Achievable

ANS – American Nuclear Society

ANSI – American National Standards Institute

APNSA – Assistant to the President for National Security Affairs

ASME – American Society of Mechanical Engineers

AST – FAA Office of Commercial Space Transportation

CEc – Conditional Expected Casualty

CFR – Code of Federal Regulations

d/dt – Differential Operator

DBTT – Ductile-to-Brittle Transition Temperature

DOD – Department of Defense

DOE – Department of Energy

DOT – Department of Transportation

EA – Environmental Assessment

Ec – Expected Casualty

EIS – Environmental Impact Statement

EOM – End of Mission

EPA – Environmental Protection Agency

EPZ – Emergency Planning Zone

ERP – Emergency Response Plan

FAA – Federal Aviation Administration

FCC – Federal Communications Commission

FEMA – Federal Emergency Management Agency

FGR – Federal Guidance Report

FHA – Functional Hazard Assessment

HALEU – High-Assay Low-Enriched Uranium

HEU – Highly Enriched Uranium

HFRSA – High-Fidelity Radiological Safety Analysis

IAEA – International Atomic Energy Agency

ICRP – International Commission on Radiological Protection

INSRB – Interagency Nuclear Safety Review Board

ISO – International Organization for Standardization

LEO – Low Earth Orbit

LEU – Low Enriched Uranium

MM – Mission Multiple

MPL – Maximum Probable Loss

NASA – National Aeronautics and Space Administration

NEPA – National Environmental Policy Act

NRC – U.S. Nuclear Regulatory Commission

NSPM-20 – Presidential Memorandum on the Launch of Spacecraft Containing Space Nuclear Systems, dated August 20, 2019

NUREG – U.S. Nuclear Regulatory Commission technical report designation

P – Linear Momentum

P_{ER} – Probability of Exposure to Radiation

PoC – Probability of Collision

REM – Roentgen Equivalent in Man (rem)

REP – Radiological Emergency Preparedness

RERP – Radiological Emergency Response Plan

RHA – Radiological Hazard Analysis

RHUs – Radioisotope Heater Units

RMR – Radioactive Materials On-Board Report

RPSs – Radioisotope Power Systems

RTGs – Radioisotope Thermoelectric Generators

SAR – Safety Analysis Report

SI – System International, i.e., meter, kilogram, second units

SNS – Space Nuclear System

SSG – Specific Safety Guide

SSR – Safety Series Requirement

TBq – Tera-Becquerel

TED – Total Effective Dose

U.S.C. – United States Code

U.S. – United States

USD – United States Dollars

6 PERTINENT REGULATIONS FOR SPACE NUCLEAR SYSTEMS.

6.1 Safety Challenges.

Commercial space activities involving SNS introduce unique public safety challenges. For example, various radionuclides carried on SNS emit radiation which can be harmful to human health. Some radionuclides are long-lived, emit high-energy radiation, or are difficult to decontaminate if released into the environment. Some radionuclides present all these characteristics simultaneously. Additionally, radioactive decay and nuclear fission inevitably change the isotopic composition of the nuclear fuel, producing isotopes which were not present at the start of the licensed activity, thereby changing the risk characteristics of the device. Appendix C provides an example of a past mishap involving an SNS. Due to the unique public health and safety hazards posed by the use of SNS in commercial space activities, the FAA will carefully review proposals to launch or reenter SNS for compliance with the following regulations.

6.2 FAA Launch and Reentry License Regulations.

This AC provides a means of compliance for assessing radionuclide safety within the context of 14 CFR part 450. Part 450 calls for a case-by-case approach to address hazards from SNS, as discussed in this section.

Note: The FAA has the authority to license the launch and reentry of commercial SNS, but it does not license possession of nuclear material in the U.S. Obtaining the appropriate licenses to legally possess nuclear material on the ground is an applicant responsibility and must be completed before the SNS launch or reentry can be licensed. Issuance of a part 450 license does not relieve a licensee of its obligation to comply with all applicable requirements of law or regulation (14 CFR § 450.13).

6.2.1 Safety Review and Approval.

6.2.1.1 In accordance with § 450.45, the FAA issues a safety approval to an applicant if it determines that an applicant can conduct a launch or reentry without jeopardizing public health and safety or the safety of property. The focus of the safety review is to ensure that an applicant can meet the safety requirements in subpart C, including the safety criteria in § 450.101. The safety criteria and other safety requirements in subpart C are primarily focused on three hazards: impacting inert and explosive debris, toxic release, and far field blast overpressure. The FAA included certain provisions in part 450 to cover other hazards such as radionuclides, as discussed below.

6.2.1.2 For nuclear hazards specifically, § 450.45(e)(6) states that the FAA will evaluate the launch or reentry of any radionuclide on a case-by-case basis and issue an approval if the FAA finds that the launch or reentry is consistent with public health and safety, safety of property, and national security and foreign policy interests of the United States. For any radionuclide on a launch or reentry vehicle, an applicant must:

- Identify the type and quantity of any radionuclide,
- Include a reference list of all documentation addressing the safety of its intended use, and
- Describe all approvals by the Nuclear Regulatory Commission for pre-flight ground operations.

6.2.1.3 Paragraphs 7.2 and 8.3 and Appendix A of this AC provide an acceptable means of compliance for § 450.45(e)(6) and will allow an applicant proposing to use SNS to demonstrate to the FAA that the launch or reentry is consistent with public health and safety. Use of the safety guidelines in paragraph 7.2, in addition to the analyses described in paragraph 8.3 and Appendix A, is one way to demonstrate that the launch or reentry of the SNS is consistent with public health and safety.

6.2.1.4 The means of compliance that the FAA sets forth in this AC generally follows the guidelines outlined in Presidential Memorandum on Launch of Spacecraft Containing Space Nuclear Systems (NSPM-20). NSPM-20 addresses the authorization process for government and commercial launches of spacecraft containing SNS, and categorizes launches of spacecraft containing SNS in three Tiers based upon the characteristics of the system, the level of potential hazards, and national security considerations.

6.2.1.5 During the safety review, the FAA will review the applicant's submitted information looking for ways that:

- The SNS might jeopardize the function or safety of the launch or reentry vehicle;
- The launch or reentry vehicle might jeopardize the function or safety of the SNS; and
- Interactions between the SNS and the launch or reentry vehicle that might have public safety implications.

6.2.2 Payload Review and Determination.

6.2.2.1 In accordance with § 450.43, the FAA issues a favorable payload determination for a launch or reentry to a license applicant or payload owner or operator if it has obtained all required licenses, authorizations, and permits (§ 450.43(a)(1)), and its launch or reentry would not jeopardize public health and safety, safety of property, U.S. national security or foreign policy interests, or international obligations of the United States (§ 450.43(a)(2)).

6.2.2.2 Under its payload review and determination authority, the FAA may prevent the launch or reentry of a payload that will conduct novel space activities if it determines that its launch or reentry would jeopardize the public health and safety, safety of property, or national security or foreign policy interests of the United States. In addition to a launch or reentry operator, a payload owner or payload operator may request a payload review and determination.

6.2.2.3 Similar to the safety review, paragraphs 7.2 and 8.3 and Appendix A of this AC provide an acceptable means of compliance for the safety aspects of § 450.43(a)(2) and will allow an applicant to demonstrate to the FAA that launch or reentry of a SNS will not jeopardize public health and safety. Use of the safety guidelines in paragraph 7.2, coupled with the analyses in paragraph 8.3 and Appendix A, will allow an applicant to show that the launch or reentry of the SNS is consistent with public health and safety.

6.2.2.4 Section 450.43(i) outlines specific application requirements, including paragraph (i)(1)(ii), which requires an applicant to describe the physical dimensions, weight, and composition of the payload for launch, paragraph (i)(1)(v), which requires an applicant to identify radioactive materials and their amount for launch, and paragraph (1)(2)(iv), which requires an applicant to identify the type, amount, and container of radioactive materials in the payload. Section 450.43(i)(1)(xi) requires an applicant to identify any other information necessary to make a determination based on public health and safety, safety of property, U.S. national security or foreign policy interests, or international obligations of the United States. For applicants using this AC as a means of compliance, Appendix A identifies other information unique to SNS.

6.2.3 Policy Review and Approval.

6.2.3.1 In accordance with § 450.41, the FAA issues a policy approval to an applicant unless the FAA determines that a proposed launch or reentry would jeopardize U.S. national security or foreign policy interests, or international obligations of the United States. The launch or reentry of SNS may very well implicate U.S. national security, foreign policy interests or international obligations due to the unique hazards posed by SNS and the potential for release of nuclear material outside the United States.

6.2.3.2 The interagency review is an important component of the policy and payload review process that provides other Federal agencies with the opportunity to examine the proposed activity from their unique perspectives. Table 1 of this AC indicates the FAA's primary partner agencies and their primary areas of responsibility. For applicants proposing to launch or reenter SNS, the FAA may also consult with other agencies as shown in Table 2 of this AC, as appropriate.

Table 1– Partner Agencies

Agency	Primary Area of Responsibility
Department of Defense	Issues related to US national security
Department of State	Issues related to US foreign policy
Federal Communications Commission	US commercially owned communications satellites and frequency issues involving FCC licensing of transmitters, including those on launch/reentry vehicles for telemetry
National Aeronautics and Space Administration	The effect of commercial space activities on NASA programs and Center operations
National Oceanic and Atmospheric Administration	US commercially owned remote sensing satellites
United States Coast Guard	Overflight of navigable waterways
Office of the Director of National Intelligence	Issues related to US national security

Table 2 – Additional Government Agencies Consulted for SNS Policy or Payload Review

Additional Government Agencies	Reason for Participation in the Policy Review
Department of Energy	Nuclear material sourced from the DOE
Department of Energy National Nuclear Security Administration	Material in the SNS poses a nuclear proliferation concern
Department of State Bureau of International Security and Nonproliferation	Material in the SNS poses a nuclear proliferation concern; NNSA provides critical capabilities to USG response in the case of a nuclear or radiological incident.
Federal Emergency Management Agency	National Response Framework, Nuclear/Radiological Incident Annex
Nuclear Regulatory Commission	Commercial use or possession of nuclear material
Office of the Director of National Intelligence	Radiation emissions from the space nuclear system have potential to interfere with national assets

6.2.4 Environmental Review.

The FAA is responsible for complying with the procedures and policies of the National Environmental Policy Act and other applicable environmental laws prior to issuing a launch or reentry license, and an applicant must provide the FAA with information needed to comply with such requirements. As specified in § 450.47, when directed by the FAA, an applicant must prepare an Environmental Assessment with FAA oversight; assume financial responsibility for preparation of an Environmental Impact Statement by an FAA-selected and managed consultant or contractor; or submit information to support a written re-evaluation of a previously submitted Environmental Assessment or Environmental Impact Statement.

6.2.5 Maximum Probable Loss (MPL) Determination.

6.2.5.1 In 14 CFR part 440, the FAA prescribes the amount of liability insurance required by the launch or reentry license applicant to compensate for the total of covered third-party claims for bodily injury or property damage, including Government personnel and property. This amount cannot exceed $500 million US dollars (USD), or the maximum liability insurance available on the world market at reasonable cost. Subject to Congressional appropriation, the Federal government indemnifies the launch or reentry operator for claims above the insured amount up to $1.5 billion USD, adjusted for inflation from January 1989.

6.2.5.2 MPL is the greatest dollar amount of loss for bodily injury or property damage that is reasonably expected to result from a licensed or permitted activity. Third parties are people, including government personnel, other than those involved in a licensed or permitted launch or reentry activity.

6.2.5.3 Property damage is the partial or total destruction, impairment, or loss of tangible property, real or personal. Radiological contamination can cause partial or total destruction of tangible property. Property damage includes the cost of radiological clean-up and remediation activities performed to limits required by the U.S. government, which can be substantial.

6.2.5.4 The FAA conducts a maximum probable loss analysis based on information provided by an applicant in accordance with § 450.31(a)(6), which refers to information requirements in part 440.

6.3 **Other Agency Regulations**.

6.3.1 Launch or reentry of SNS may be subject to regulation by other Federal agencies. The NRC is the terrestrial nuclear regulator, and the FAA expects that most commercial SNS missions will use commercial SNS devices that are under the regulatory authority of the NRC while on the ground. In some cases, the DOE or DOD may be the nuclear safety regulator. In these situations, the DOE or DOD will perform terrestrial nuclear safety regulation, while the FAA will remain responsible for protecting public safety during the launch and reentry. When ground transportation of the SNS occurs, the DOT PHMSA (Pipeline and Hazardous Materials Safety Administration) is involved as the nuclear material transportation safety regulator. Applicants should be aware of the appropriate terrestrial nuclear safety regulator for their SNS and operate in compliance with all applicable laws and regulations. Table 3 provides government agencies with roles in SNS licensing.

Table 3 – Government Agencies with Roles in SNS Licensing

Agency	Responsibilities
Department of Defense	Responsible for national security and critical asset protection, including federal launch ranges, launch sites, and national security missions (Department of the Air Force & FAA 2021).
Department of Energy	Produces certain nuclear materials and space nuclear systems, will be involved if the DOE is the source of the nuclear fuel (DOE 2021). DOE provides indemnification for nuclear mishaps.
Department of Energy, National Nuclear Security Administration	Works globally to prevent state and non-state actors from acquiring weapons-usable nuclear or radiological materials and technology (National Nuclear Security Administration 2021). NNSA Nuclear Emergency Response Teams (NEST) are the lead response teams when responding to accidents involving nuclear material."
Department of Homeland Security, Federal Emergency Management Agency	Planning for severe (worst-case credible) accident with release of radioactive material in populated areas (FEMA REP Program Manual 2019).
Department of State, Bureau of Oceans and International Environmental and Scientific Affairs	Prevents the spread of weapons of mass destruction, tracks, develops, and implements effective responses to proliferation threats (Department of State 2021)
Department of Transportation, Federal Motor Carrier Safety Administration	Regulates transportation using large trucks or busses, as described in Title 49 CFR parts 300-399 (Title 49 CFR Chapter I 2021).
Department of Transportation, Pipeline and Hazardous Materials Safety Administration	Transportation of hazardous (including radioactive) materials (Title 49 CFR Chapter I 2021).
Nuclear Regulatory Commission	Licenses the commercial possession and use of nuclear material (Title 10 CFR Chapter I 2021). Authorizes Type B and fissile material packages for its licensees, as well as for NRC agreement state licensees use.

7 TIER LEVELS AND SAFETY GUIDELINES.

7.1 NSPM-20 Tier Level Definitions.

7.1.1 NSPM-20 categorizes launches and reentries involving SNS into three Tiers of radiological risk based upon the P_{ER}, the level of total activity, and national security considerations of the SNS. NSPM-20 assigns SNS to the highest Tier for which they satisfy any criteria and, for commercial launches and reentries, directs the FAA to coordinate with other Federal agencies, based on the Tier. Because these tiers impact the FAA's level of government coordination, and so may impact the timing and depth of any review, the FAA provides the following descriptions from NSPM-20.

a. Tier I. Applies to launches of spacecraft containing radioactive sources of total quantities up to and including 100,000 times the A_2[1] value listed in Table 2 of the International Atomic Energy Agency's Specific Safety Requirements (SSR) No. SSR–6 (Rev. 1), Regulations for the Safe Transport of Radioactive Material, 2018 Edition.[2]

b. Tier II. Applies to:

(i) Launches of spacecraft containing radioactive sources in excess of 100,000 times the A_2 value referenced above;

(ii) Any Tier I launches where the associated safety analyses determine that the probability of an accident during launch or subsequent operation resulting in an exposure in the range of 5 rem to 25 rem TED to any member of the public is equal to or greater than 1 in 1,000,000; and

(iii) Any launches of spacecraft containing nuclear fission systems and other devices with a potential for criticality[3] when such systems utilize low-enriched uranium.[4]

c. Tier III. Applies to launches of any spacecraft containing a space nuclear system for which the associated safety analyses determine that the probability of an accident during launch or subsequent operation resulting in an exposure in excess of 25 rem TED to any member of the public is equal to or greater than 1 in 1,000,000. Due to potential national security considerations associated with nuclear nonproliferation, Tier III also applies to launches of spacecraft containing nuclear fission systems and other devices with a potential for criticality when such systems utilize any nuclear fuel other than low-enriched uranium.

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[1] A2 is an activity value, i.e., a level of radioactivity, in System International (SI) units of Tera-Becquerel (TBq) listed in the IAEA SSR-6 Regulations for the Safe Transport of Radioactive Material, 2018 Edition, Table 2. Note: 1 TBq is approximately = 27 Ci.

[2] Small amounts of nuclear materials such as those present in instrumentation may not necessarily result in an extensive review.

[3] The condition in which a nuclear fission chain reaction becomes self-sustaining.

[4] Less than 20 percent uranium-235 enrichment.

7.1.2 Tier II and Tier III can include low enriched Uranium (LEU) systems capable of criticality, as determined by the results of a probabilistic risk assessment. Only the Tier III definition includes SNS capable of criticality that employ other than LEU fuels, including highly enriched uranium, plutonium, and other fissile radionuclides.

7.1.3 Per NSPM-20, the FAA will consult with the heads of appropriate Federal agencies for commercial activities in Tier II or Tier III.

7.1.4 A flowchart to aid applicants in determining the Tier level of an SNS is provided in Figure 1 of this AC.

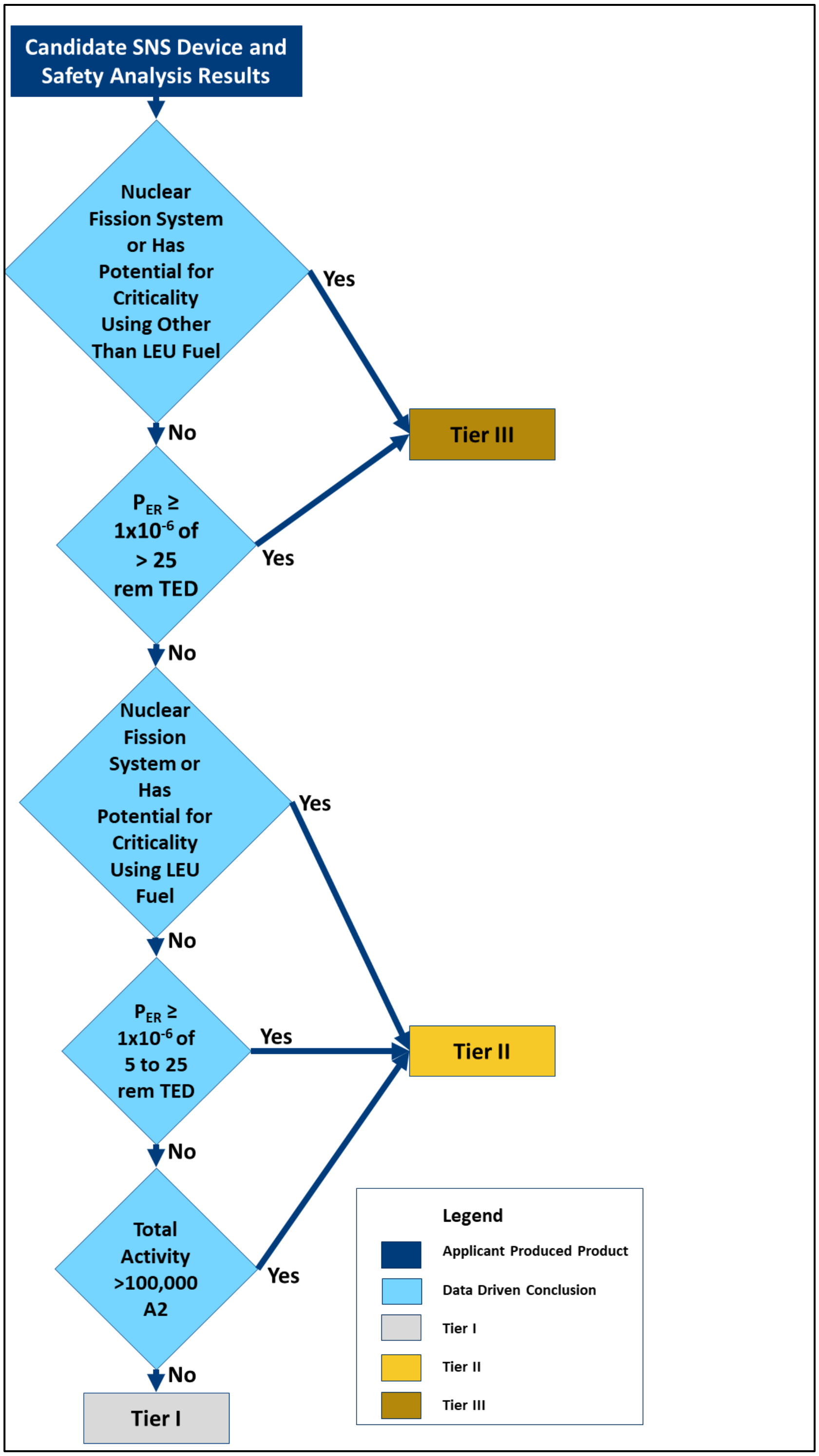

Figure 1– NSPM-20 Tier Level Determination Aid

7.2 **SNS Safety Guidelines**.

7.2.1 As noted earlier, in accordance with § 450.45(e)(6), the FAA will evaluate the launch or reentry of any SNS on a case-by-case basis and issue an approval if the FAA finds that the launch or reentry is consistent with public health and safety, safety of property, and national security and foreign policy interests of the United States. Use of the following criteria (in terms of Probability of Exposure to Radiation (P_{ER})), in conjunction with the analyses set forth in paragraph 8.3 and Appendix A of this AC, is one way to demonstrate that the launch or reentry of the SNS is consistent with public health and safety:[5]

a. *An accident resulting in exposure in excess of 25 millirem but less than 5 rem Total Effective Dose (TED), as defined in 10 CFR § 835.2, to any member of the public is unlikely, such that the probability of such an event does not exceed 1 in 100;*

b. *An accident resulting in exposure in the range of 5 rem to 25 rem TED to any member of the public is extremely unlikely, such that the probability of such an event does not exceed 1 in 10,000; and*

c. *The probability of an accident resulting in exposure in excess of 25 rem TED to any member of the public does not exceed 1 in 100,000.*

7.2.2 Figure 2 of this AC was created to help applicants visualize potential P_{ER}s, the NSPM-20 Tier level based on P_{ER}, and the Safety Guidelines, and to identify any unique considerations based on the P_{ER}. Because Figure 2 of this AC considers only the P_{ER}, it does not capture the full scope of the Tier levels specified above, which can also be impacted by the quantity or type of nuclear material. The Tier levels are the grey, yellow, and gold boxes, while the black line capping the Tier boxes illustrates the SNS Safety Guidelines.

[5] These safety guidelines are stated in terms of probability of occurrence for a member of the public receiving ionizing radiation exposure—specifically, the probability of occurrence of a Total Effective Dose of threshold magnitudes. Radiation exposure within these criteria is not expected to cause death or serious injury. However, consistent with the linear no-threshold model of radiation exposure, any amount of radiation is assumed to increase the risk of stochastic radiation effects (e.g. cancer in the exposed individual). To distinguish that SNS radiation exposure is not normally expected to cause casualties, the FAA uses the term Probability of Exposure to Radiation, P_{ER}, to describe the probabilistic risks to the public associated with an SNS. The PER is a two-part term, specifying both the probability and magnitude of the dose to the most exposed member of the public.

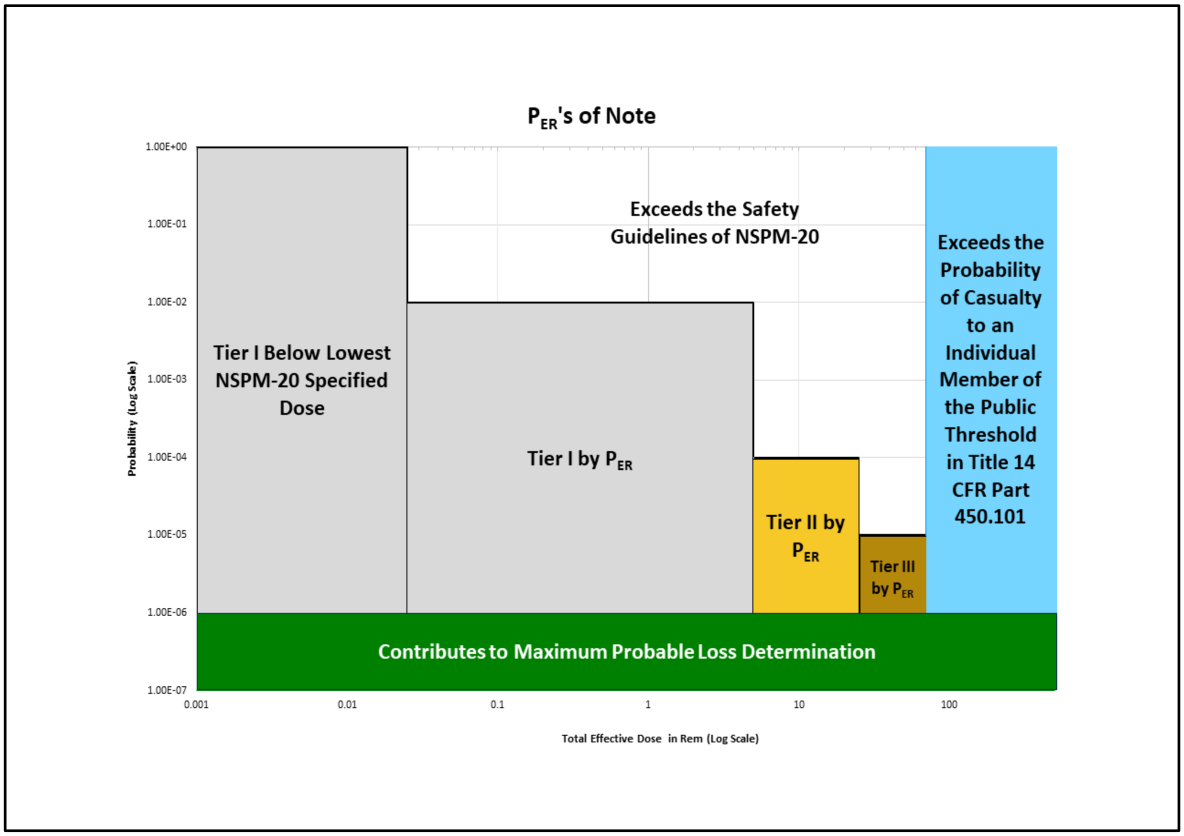

Figure 2 – Considerations Given to Various P_{ER}'s

7.2.3 To ensure the individual risk requirements of 14 CFR § 450.101(a)(2) are met, the applicant should select and justify to the FAA a TED value above which a casualty from their operation may occur. In situations where the P_{ER} exceeds 1×10^{-6} of a dose greater than this specified TED value, the FAA considers that the Pc exceeds the individual risk limit of § 450.101(a)(2). Figure 2 symbolizes this by the light blue box. The FAA considers exposure above that TED level a casualty for the purposes of evaluating the risk limit in § 450.101(a)(2). Therefore, such an exposure would violate the regulatory safety criteria defined in § 450.101(a)(2).

7.3 **Notes on the Tier Level Definitions.**

7.3.1 Subsequent Operation. Embedded in the definition for the various Tier levels is an important detail: the Tier level for an SNS is defined not only by the risk to the public during launch and reentry, but also by the risk to the public during subsequent operation, such as uncontrolled reentry.[6] Uncontrolled reentry can be initiated in a variety of ways, including malfunction, collision, hacking, deliberate signal

[6] Note that NSPM-20 uses the term "reentry" in a generic sense and is not limited to the reentry of a reentry vehicle as defined in 14 CFR § 401.7.

interference, operator error, etc. Applicants are encouraged to be mindful of how these initiation scenarios might result in inadvertent reentry, and the changes they might have on the SNS prior to, during, or after the uncontrolled reentry to create a robust assessment of potential consequences to a maximally exposed individual member of the public in accident scenarios.

7.3.2 Criticality. Criticality related to an SNS refers to an achievable state of sustained nuclear fission chain reactions (Paxton 1989). Radiological activity is greatly increased for radioactive materials during and after critical or supercritical chain reactions (American Nuclear Society 2018). Criticality depends upon several isotopic and physical or geometrical considerations related to neutron production, moderation, reflection, capture, and leakage. These factors can be changed by changing environmental conditions outside the SNS (Knief 2013). An applicant should consider the specifics of its SNS and all environments their SNS may encounter during normal and abnormal operating conditions to determine if the device is capable of criticality or unintended criticality. This is addressed further in Appendix A of this AC.

7.3.3 Quantities of Radioactive Material.

7.3.3.1 The amount of radioactive material is referenced to the A_2 activity level, a level of activity for a specific radionuclide in SI units of TBq, listed in Table 2 of the IAEA SSR-6. This comparison is analogous to the mission multiple (MM), which was used in historical government launches. Applicants choosing to use MM to describe the activity of their SNS should use the standard definition as shown in the following equation:

$$\boldsymbol{MM = \sum_{n} \frac{(\,Source\ Activity\ per\ Isotope)_n}{(Source\ Isotopic\ A2\ Value)_n}}$$

Mission Multiple Equation (NASA 2022)

7.3.3.2 MM is a dimensionless integer coefficient that scales a value of the activity level A_2. For example, if total activity equals 100,000 × A_2, MM equals 100,000. Additional information on specific A_2 values, their combination and derivation can be found in:

- IAEA Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material, IAEA Safety Standards Series No. SSG-26, Rev 1, (2018 Edition).
- IAEA, Regulations for the Safe transport of Radioactive Material, IAEA Safety Standards Series No. SSR-6 (Rev.1), 2018.

8 SPACE NUCLEAR SYSTEM LICENSING PROCESS.

8.1 Overview of Licensing Process

8.1.1 The launch and reentry license process is illustrated in Figure 3 of this AC. Any launch or reentry with an SNS will follow this process. As noted earlier, the FAA will address the unique safety aspects of SNS on a case-by-case basis during the licensing process.

8.1.2 Because of the unique public safety issues raised by use of SNS in commercial launch or reentry activity, the FAA encourages applicants to begin pre-application consultation for launches or reentries involving SNS as early as possible. The pre-application engagement with the FAA provides guidance for the applicant on developing an acceptable application, the roadmap to engaging with other government agencies, and the administrative and technical requirements for the application. This enables a timely and effective licensing evaluation and determination when the application package is complete enough for review.

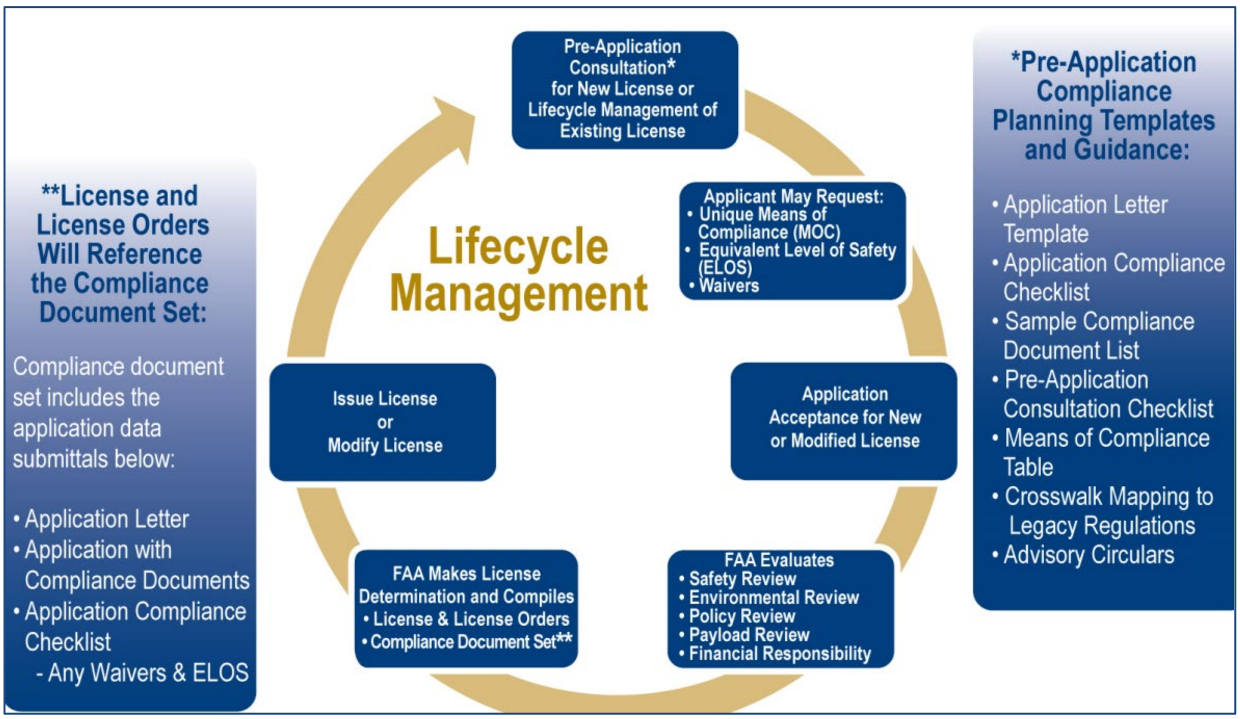

Figure 3 – License Evaluation Process

8.2 **Licensing Process for the Launch or Reentry of an SNS**.

8.2.1 The FAA issues a vehicle operator license if it determines that the launch or reentry operator can launch or reenter without jeopardizing public health and safety, the safety of property, or the national security or foreign policy interests of the United States. All the data requirements and licensing stages for a conventional launch or reentry, as described in 14 CFR part 450, apply for the launch or reentry of an SNS.

8.2.2 To show compliance with § 450.45(e)(6) specifically, an applicant can provide the information and conduct the analyses described in paragraph 8.3 below and Appendix A of this AC.

8.3 **Nuclear Safety Analyses to Demonstrate Acceptable Public Health and Safety**.

8.3.1 The scope and content of the nuclear safety analyses demonstrating compliance with the public health and safety criteria should be commensurate with the level of mission radiological risk incurred. Figure 4 provides applicants a way to determine which nuclear safety analyses could be used to demonstrate acceptable level of public health and safety for various SNS, and Appendix A provides details on the scope and intent of the various analyses.

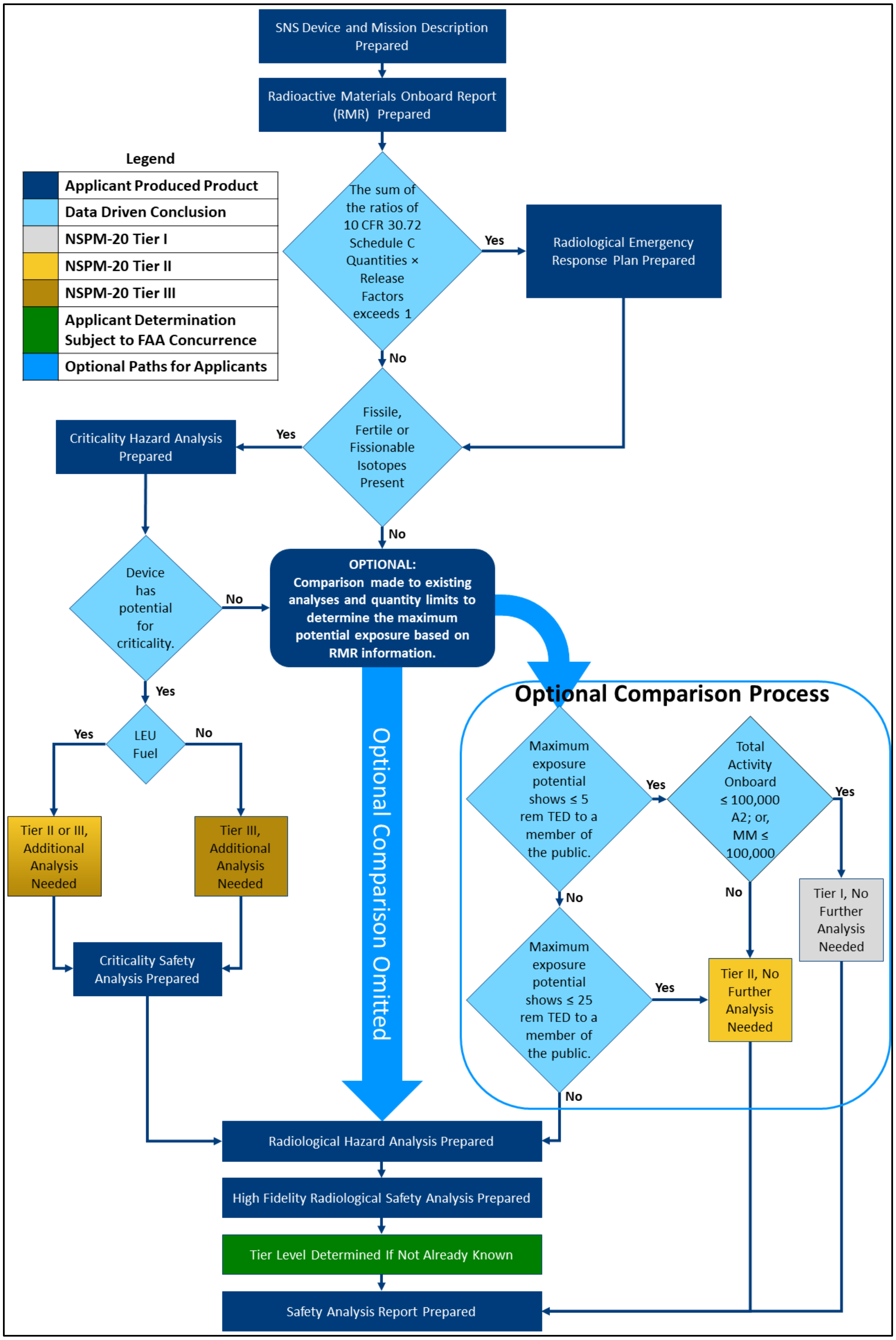

Figure 4 – Nuclear Safety Analysis Flow Chart

8.3.2 All applicant-developed nuclear safety analyses for payloads should consider the entire mission lifetime. Depending on mission specifics, the mission lifetime may include:

- Pre-Launch;
- Launch;
- Ascent, Early and Late;
- Suborbital, including staging;
- Orbital, including temporary on-orbit operations;
- Earth escape;
- Earth return, including flyby;
- Reentry; and
- End of Mission (EOM), including disposal.

8.3.3 The mission phases for nuclear space launch should cover all launch vehicle or payload potential for any planned or accidental Earth reentry of nuclear material. For example, Earth return scenarios would include considerations for nuclear material launched to:

- Other planetary bodies capable of a free return trajectory to Earth;
- Earth gravity assist fly-by trajectory; or
- Earth orbit intersecting trajectories where planned or accidental Earth reentry of nuclear material is possible.

8.3.4 If reasonably foreseeable scenarios exist that would pose a safety hazard to the public and environment, the nuclear safety analyses performed for licensing should quantify the radiological risk to the public from that scenario and include it in determining the overall mission risk.

8.3.5 The EOM should include safe disposal of the radionuclide. The long-term storage of spent nuclear fuel on Earth has been a problem since the advent of the nuclear industry (GAO 2021). SNS have disposal options at EOM not available to terrestrial nuclear devices, as summarized in Table 4 of this AC, with varying levels of government review required.[7] For example, a disposal option for an on-orbit nuclear reactor that has reached criticality might be to boost it into a high disposal orbit to allow sufficient time for radioactive decay of fission products, which could take hundreds or thousands of years (SPD-6 2020). Failure of the vehicle to boost itself or to eject the hot core into a safe disposal orbit could result in an inadvertent public safety reentry hazard (Gummer, et al. 1980). Alternately, if the core were boosted to escape velocity for disposal, it

[7] Because spent nuclear fuel is a significant hazard, the disposal plan is evaluated before licensing the launch of the system, even though the ultimate disposal may be years out. Terrestrial disposal will be high risk for systems that have operated critically.

might pose a reentry risk to future public generations should third-body orbital forces cause an eventual inadvertent return. Nuclear safety analyses take into consideration all of these potential scenarios and calculate the P_{ER} for each.

Table 4 – Nuclear Material Disposal Options

Disposal Location	Possibility of Return to Earth
Interplanetary Space, No Free-Return Trajectory to Earth	None or Extremely Low
Lagrange Point	L1, L2 and L3 Extremely Low; L4 and L5 None
A Sufficiently High Altitude in Earth Orbit	Low within the period of concern for radiation exposure to the public
On Earth	Will happen

8.4 **Space Nuclear System Design**.

Whether or not an applicant uses the means of compliance outlined in paragraph 8.3 and Appendix A of this AC, the design and any safety analyses conducted by an applicant will be evaluated by the FAA during the license evaluation process to assess public health and safety. SNS designs satisfy a variety of unique, competing design constraints. The performance guidelines in Appendix B give guidance on space specific performance characteristics the FAA has identified to reduce the baseline risk of the SNS.

8.5 **Interagency Nuclear Safety Review Board**.

8.5.1 When an applicant prepares a SAR, as detailed in Appendix A of this AC, to show compliance with § 450.45(e)(6), applicants should be aware that SARs prepared for commercial launches are distinctly different than those prepared for government launches in that SARs for a Tier II or Tier III government launch must go through an Interagency Nuclear Safety Review Board (INSRB) evaluation, while a SAR for a commercial launch of any Tier may, at the Secretary of Transportation's discretion, be evaluated by the INSRB. This distinction is important and streamlines the FAA's ability to license commercial SNS launch and reentry.

8.5.2 Under NSPM-20, the Secretary of Transportation can request no review, a partial review, or a full INSRB evaluation of the SAR. In these cases, the role of the INSRB will be to review the SAR and supporting nuclear safety analyses, to evaluate the quality of the analyses, and to identify specific gaps. This evaluation is then documented in a safety evaluation report, which may include recommendations for how to improve the analyses. The INSRB recommends approvals, and the FAA issues approvals.

8.5.3 The INSRB information is available at https://sma.nasa.gov/sma-disciplines/nuclear-flight-safety. Applicants may consider reviewing the INSRB guidance provided to government agencies seeking to launch SNS and other reports related to nuclear technology and safety.

8.6 **Application Determination**.

8.6.1 If applying for a license, after accepting the application and performing the policy review, safety review, payload review, environmental review, and financial responsibility determination, the FAA makes a licensing determination on the SNS on a case-by-case basis, per §450.45(e)(6). If applying for a payload determination, the FAA issues a favorable payload determination if the applicant has obtained all required licenses, authorizations, and permits and its launch or reentry would not jeopardize public health and safety, safety of property, U.S. national security or foreign policy interests, or international obligations of the United States.

Appendix A. Nuclear Safety Information and Analyses

A.1 SCOPE.

An applicant using this AC as a means of compliance to § 450.45(e)(6) or § 450.43(a)(2) should provide to the FAA the information and conduct the analyses in this appendix.

A.2 SNS DEVICE AND MISSION DESCRIPTION.

A.2.1 The following information is foundational to the nuclear safety analyses and ultimately the public safety risks of the SNS mission. The applicant should provide the following information to the FAA such as:

- SNS owner and operator;
- SNS type;
- SNS purpose;
- SNS physical dimensions and weight;
- Structural design of SNS components;
- SNS physical barriers to radioactive release;
- SNS instrumentation, monitoring, and control system characteristics;
- SNS fuel design;
- SNS orbital parameters for parking, transfer, and final orbits;
- Hazardous material quantities, including the radioactive material via the RMR;
- Mission stages for the SNS;
- Intended SNS operations during the entire mission;
- Delivery point in flight at which the SNS will no longer be under the launch licensee's control;
- Methods to prevent and terminate criticality during launch and reentry, as applicable;
- Shielding design and materials used;
- Decay heat generation rates expected during launch or reentry, as applicable;
- Decay heat removal methods, as applicable;
- Decay heat removal capability, as applicable;
- Signal paths from SNS to the operator;
- SNS control system design and operational parameters; and
- SNS and host spacecraft software design, configuration control, and performance.

A.2.2 The purpose of the SNS device and mission description is for applicants to communicate to the FAA what the SNS mission is and how the SNS will be operated. This information enables the FAA to determine the completeness of subsequent nuclear safety analyses. If the applicant considers other information relevant to the overall SNS design or mission, that information may also be included in the SNS device and mission description. There is no need to include nuclear safety analyses or public safety calculations in the SNS design and mission description, as this information is included in subsequent nuclear safety analysis reports.

A.3 RADIOLOGICAL MATERIAL REPORT.

A.3.1 All applications for SNS should include a RMR, as the type and quantity of radioactive material onboard is the foundation for determining the public safety risk of the SNS and the Tier level of the SNS. For every radionuclide on a launch or reentry vehicle, the RMR:

- Identifies the specific isotope, quantity, total activity and A_2 value;[8]
- Specifies the moment in time at which the activity was measured for each source;
- Describes any NRC or agreement state approval for pre-flight ground testing involving that isotope;

[8] Applicants may choose to use MM to describe the activity of the isotope.

Table 5 – Sample Radiological Material Report

Source Description	Element Symbol $^{A}_{Z}E$	Half- Life (Years) (IAEA 2021)	Activity per Source (Ci) as Measured on (date)	Number of Sources	Total Activity (Ci)	IAEA A2 (Ci) (IAEA 2018)	Mission Multiple MM	Material Supplier
General purpose heat source fuel clads (Contained in 3 Spacecraft Radioisotope Thermoelectric Generators)	$^{238}_{94}Pu$ as $^{238}_{94}PuO_2$	87.7	1,908 As measured on 8-20-2019	216	412,128	0.027	$1.53x10^7$	DOE
Radioisotope Heater Unit Fuel Clads (Onboard Payload)	$^{238}_{94}Pu$ as $^{238}_{94}PuO_2$	87.7	33.6 As measured on 12-16-2020	129	4,334	0.027	$1.61x10^5$	DOE
Instrument Calibration Source (Encapsulated)	$^{60}_{27}Co$	5.27	$6x10^{-6}$ As measured on 2-15-2021	2	1.2x10-5	10.8	$1.1x10^{-6}$	Commercial Source
	Total				416,462		$1.53x10^7$	

A.3.2 NSPM-20 specifies that the Tier level determination considers both launch and "subsequent stages when accidents may result in radiological effects to the public or environment" (NSPM-20 2019), which drives the potential need for RMR addendums to determine the Tier level of the SNS. For example, a fission reactor may meet Tier II criteria at launch, but after operation the resulting risk of the SNS and mission may meet the Tier III criteria, making it a Tier III system. Robust computer codes exist to model the burnup of nuclear fuel and aid in developing the RMR addendums (Argonne National Laboratory 2016), (Nuclear Regulatory Commission 2018). Table 5 of this AC shows a sample RMR for a mission using multiple radioactive devices, applicants may develop their own format that displays the essential information in a clear manner.

- Includes a RMR addendum addressing the safe terrestrial handling, use, and storage of all the isotopes in the SNS;
- Includes a RMR addendum showing the isotopic makeup of the SNS at the following times:
  a. Launch;
  b. During all planned flybys;
  c. During planned reentry, as applicable for the mission.
- If the SNS can over time develop an isotopic composition more harmful than that at launch, the RMR also includes an addendum for the worst time in life that the SNS will have potential to return to Earth.

A.4 CRITICALITY HAZARD ANALYSIS.

A.4.1 From the RMR, applicants will be able to quickly identify whether their SNS contains fertile material, fissionable material, or fissile material, as defined by the NRC or the IAEA (IAEA 2002), (Nuclear Regulatory Commission 2020). If these isotopes are present, or will become present as the SNS operates, then a criticality hazard analysis is needed to determine if the SNS has potential for criticality during normal SNS operations or off-nominal events in all mission phases (NSPM-20 2019). The criticality hazard analysis step is included even for an SNS with small amounts of fertile, fissionable, or fissile material because critical mass limits have not been established for space environments, since fission can dramatically change the public safety profile of the SNS, including nuclear proliferation concerns and ionizing radiation exposure potential (Connell and Trost 1994).

A.4.2 If a criticality hazard analysis is required, the analysis is conducted by first identifying all reasonably foreseeable hazards which may contribute to fission occurring in the SNS, using valid scientific principles and statistical methods. Examples of relevant information for completing a criticality hazard analysis include:

- The mass of material relative to the theoretical minimum mass limits for criticality emergencies on Earth, as discussed in various standards including American National Standards Institute (ANSI)/ANS-8.1-2014;
- Moderators and reflectors that are inherent to the SNS or spacecraft;
- Deliberate design features of the SNS to control form, shape, or collocation;
- Spacecraft operation, including launch, staging, and release;
- System, subsystem, and component failures or faults;
- Severe physical deformation of the SNS and spacecraft;
- Software operations or malfunctions;
- External environmental changes for all anticipated operational or malfunction environments;
- Interactions with space radiation;
- Proximity to other sources of radioactivity;
- Procedure deficiencies;
- Design inadequacies;
- Human factors;
- Functional and physical interfaces between subsystems; and
- Interactions of any of the above.

A.4.3 There are two possible outcomes for the criticality hazard analysis:

1. Criticality is not possible for the SNS under any reasonably foreseeable criticality hazard scenarios, or;
2. Criticality is possible within reasonably foreseeable criticality hazard scenarios, including deliberately designed capabilities for fission reactors.

A.4.4 When the criticality hazard analysis shows that criticality is possible, the analysis catalogs the scenarios and conditions necessary for criticality. The analysis also identifies and describes the criticality risk mitigation measures used to preclude unintended criticality. Much like a flight hazard analysis, criticality hazard analyses are continually updated throughout the lifecycle of the SNS to ensure the potential for the SNS to achieve criticality is known at all times under all foreseeable operating conditions.

A.5 CRITICALITY SAFETY ANALYSIS.

A.5.1 If the criticality hazard analysis finds that criticality is possible within foreseeable criticality hazard scenarios in any mission phase, a criticality safety analysis is performed to calculate the likelihood and effects of fission in the SNS under each of the foreseeable criticality hazard scenarios that can result in fission. The criticality safety analysis considers scenarios where the SNS is intact, as well as the scenarios that result in uncontrolled radioactive release to the environment. The criticality safety analysis is performed with sufficient fidelity to:

- Determine the conditions and associated probability factors impacting the prompt neutron population and the ability of the SNS to become prompt critical;
- Determine the conditions and associated probability factors impacting the delayed neutron population and the ability of the SNS to become delayed critical;
- Determine the extent to which the SNS can remain subcritical in all reasonably foreseeable environments, including malfunction environments, i.e., the shutdown margin of the device;
- Quantify the performance of the system and radiation emissions for the criticality accidents that could occur;
- Quantify the performance of the system and radiation emissions for various power excursions, including short duration dramatic power excursions and long duration marginal power excursions;
- Quantify the risk of ionizing radiation exposure to the public if criticality were to occur within the Earth's biosphere;
- Quantify the probability of criticality occurring;
- Quantify the expected rate of energy release and duration of criticality;
- Quantify the maximum possible activity in the SNS;

- Quantify the length of time for the fission products to decay to a level of radioactivity comparable to that of U-235 by the time it reenters the Earth's atmosphere (per Sec. 3(a)(iii) of SPD-6).
- Quantify the radiation types and exposure pathways if the intact SNS were in proximity to a member of the public with the maximum SNS activity.
- Quantify the expected radiation dose rate at various points and distances around the intact SNS, from on-contact to the distance at which the dose rate is 25 mrem per hour TED for various scenarios, including:
  a. During fission;
  b. Immediately after shutdown;
  c. At the time of maximum SNS activity;
  d. Hourly for the first 24 hours after shutdown;
  e. Daily for the first 7 days after shutdown;
  f. Weekly for the first month after shutdown;
  g. Monthly for the first year after shutdown;
  h. If deliberate reentry is planned:
     i. Hourly for the first 24 hours after reentry;
     ii. Daily for the first 7 days after reentry;
     iii. Weekly for the first month after reentry;
     iv. Monthly for the first year after reentry;
- Quantify how the temperature of the SNS would behave over time if the SNS returned to Earth after fission, considering fission product decay heat; and
- Quantify how containing a critical chain reaction in the space operating environment will alter the material properties of the physical barriers to radioactive release.

A.5.2 Criticality safety analysis may require applicants to apply a combination of computer models from the NRC or DOE national labs and analytical techniques described by various standards setting organizations, as applicable to the specific technologies and isotopes present in the SNS. As commercial SNS use increases and the technology matures, the FAA anticipates that standards will be developed that are uniquely applicable to commercial SNS, however those do not exist at the time of this AC. Until then, applicants should take care to use analysis methods with sound underlying scientific principles and valid statistical methods.

A.6 OPTIONAL COMPARISON TO EXISTING NUCLEAR ANALYSES.

A.6.1 Quantifying the ionizing radiation dose from various isotopes has been an ongoing field of research for decades, and practices continue to evolve and adapt. Some analyses have shown long-standing acceptance and may be suitable for SNS applicants to leverage to shorten their own nuclear safety analysis efforts. Some of these analyses have reached final conclusions on the mass or activity of an isotope required for certain dose thresholds to be met, a particularly useful conclusion for assessing the radiation exposure risk of an SNS. For a small SNS, it may be possible to compare the mass or activity of the isotopes to these pre-established values to establish the public safety risk of the SNS. Applicants have the option to compare their SNS and mission to these existing analyses, or to perform the more comprehensive analysis, which still may be required even if the comparison method is attempted.

A.6.2 If this route is utilized, care should be taken to ensure that rigorous analysis without biases that may prove to be non-conservative are used, as the release, exposure, or inhalation fractions used in the existing analyses may not be appropriate for the accident environments an SNS might experience. To meet or exceed the maximum quantity of radioactive material allowed in the existing analyses, evidence is needed that the release and exposure fractions for the SNS in any hazardous scenario will be equivalent to or less than the release and exposure fractions used in the existing analyses. If evidence is not provided, then FAA conservatively assumes the release and exposure fractions for an SNS accident are 1.0, this effectively reduces the threshold quantities of radioactive material to achieve a given maximum dose listed in the established analyses.

A.6.3 References that may be useful for SNS applicants include but are not limited to:

- DOE publications. The DOE may cancel, revise, or publish a new document at any time, when this AC was written the following series were germane to an SNS safety analysis:
  a. DOE-HDBK-3010(series), *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities.*
  b. DOE-STD-1196(series), *Derived Concentration Technical Standard.*
  c. DOE-STD-1027(series), *Hazard Categorization of DOE Nuclear Facilities*.
- EPA publications. The EPA may cancel, revise, or publish a new publication at any time. When this AC was written, the following publications were germane to SNS safety analysis:
  a. FGR No. 11: *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion*, September 1988.
  b. FGR No. 15, *External Exposure to Radionuclides in Air, Water and Soil*, revised August 2019.

- IAEA Publications. Because NSPM-20 is linked to a specific IAEA document, these references will remain valid unless national policy is updated:
  a. IAEA Specific Safety Requirements No. SSR-6 (Rev.1), *Regulations for the Safe Transport of Radioactive Material,* (2018 edition).
  b. IAEA Specific Safety Guide No. SSG-26, *Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (2012 Edition).*
- International Commission on Radiological Protection (ICRP) publications. The ICRP may cancel, revise, or publish a new publication at any time. When this AC was written, the following publications were germane to an SNS safety analysis:
  a. ICRP Publication 60, *1990 Recommendations of the International Commission on Radiological Protection*, 1990.
  b. ICRP Publication 103, *The 2007 Recommendations of the International Commission on Radiological Protection,* 2007.
  c. ICRP Publication 107, *Nuclear Decay Data for Dosimetric Calculations*, 2008.
  d. ICRP Publication 119, *Compendium of Dose Coefficients based on ICRP Publication 60*, 2012.
  e. ICRP Publication 133, *The ICRP Computational Framework for Internal Dose Assessment for Reference Adults: Specific Absorbed Fractions*, 2016.
- NRC Regulatory Guides (RG) and Technical Reports (NUREG), including:
  a. NUREG-1140, January 1988, *A Regulatory Analysis on Emergency Preparedness for Fuel Cycle and Other Radioactive Material Licensees*, reprinted August 1991.
  b. NRC Regulatory Guide 7.9, Revision 2, *Standard Format and Content of Part 71 Applications for Approval of Packages for Radioactive Material*.
- United Nations Scientific Committee on the Effects of Atomic Radiation, annual report to the General Assembly *Sources and Effects of Ionizing Radiation* series. At the time of this AC, the following reports were of particular interest for SNS:
  a. 2016 Report Annex A – Methodology for estimating public exposures due to radioactive discharges.
  b. 2008 Report Volume II Annex C – Radiation exposure in accidents.
  c. 2000 Report Volume I Annex A – Dose assessment methodologies.

A.6.4 Based on the RMR and comparison to the existing analyses mentioned above, it may be possible for applicants to quickly establish that their SNS is Tier I or Tier II without performing an elaborate nuclear safety analysis. The FAA expects that trace amounts of nuclear materials such as that which is typically used in instrumentation may not require any additional analyses.

A.7 RADIOLOGICAL HAZARD ANALYSIS.

A.7.1 When the comparison of existing analysis is unable to establish the public safety risk of the SNS, when fission is possible in the SNS, or for applicants who opt not to compare to existing nuclear safety analyses, a radiological hazard analysis (RHA) is needed. The purpose of the RHA is to identify all reasonably foreseeable hazards to public safety resulting from the launch, operation, or reentry of an SNS in all mission phases. Like a flight hazard analysis, the RHA is updated continually throughout the lifecycle of the SNS, as events may occur that change the performance of the SNS. Functionally, the RHA provides applicants an opportunity to identify hazards and develop hazard control strategies to minimize the public safety risk of the SNS. The FAA does not mandate the specific type of analysis used to perform the RHA so long as the method:

- Considers all mission phases;
- Identifies all reasonably foreseeable hazards, and the corresponding failure mode for each hazard associated with the launch or reentry of the SNS relevant to public safety, including those relevant from:
  a. Ionizing radiation;
  b. SNS operation;
  c. Scenarios where the boundaries to radioactive release remain intact;
  d. Scenarios where the boundaries to radioactive release fail;
  e. System, subsystem, and component failures or faults; including launch and reentry vehicle failures, flight abort system failure or activation, etc.;
  f. Software operations;
  g. Environmental conditions;
  h. Human factors;
  i. Design inadequacies;
  j. Procedure deficiencies;
  k. Functional and physical interfaces between subsystems, including SNS interaction with the launch or reentry vehicle and other payloads, if applicable; and
  l. Interactions of any of the above.
- Includes known failure modes, such as those addressed in Advisory Circular (AC) 450.101-1 *High Consequence Event Protection*; and,
- Has sound underlying scientific principles and statistical validity.

A.8 HIGH FIDELITY RADIOLOGICAL SAFETY ANALYSIS.

A.8.1 The high-fidelity radiological safety analysis (HFRSA) process involves applying probabilistic risk assessment methods and calculating the risk to the public for all reasonably foreseeable events and failures of safety-critical systems during normal and malfunction operations in all mission phases. The HFRSA should be complete enough for the FAA to validate the accuracy and findings of the HFRSA to make a licensing decision. For SNS, it is the consequence analysis side that introduces the greatest challenges and highest uncertainty in the HFRSA because of the complexities of radiation transport, exposure, biokinetics, and dosimetry. The end conclusions of the HFRSA are the P_{ER} for the most exposed individual for each event and failure.

A.8.2 The guidance provided in ACs 450.115-1 and -1A, High Fidelity Flight Safety Analysis provide applicants a good starting point for performing the HFRSA, but lacks the specific information needed to calculate the ionizing radiation exposure risks. To compute this additional information, applicants are encouraged to utilize computer codes developed by the NRC, the DOE national labs, or the computational methods underpinning the existing nuclear safety analyses. If none of these options are viable, applicants could make bounding assumptions without biases that may prove to be conservative using the worst-case radioactivity characteristics of the SNS, as identified in the RMR addendums. For all HFRSA, applicants should clearly demonstrate the accuracy of the fundamental scientific principles and statistical validity underpinning the analysis.

A.8.3 The purpose of HFRSA is to calculate the P_{ER} for all reasonably foreseeable events the SNS could experience, so the SNS risks can be accurately assessed. Doing this will necessitate determining the probability, location, accident type, radioactive material composition, dispersion, exposure pathways, and exposure magnitudes for ionizing radiation exposure to members of the public. This includes scenarios where the SNS remains intact, and those that result in uncontrolled radioactive release to the environment at some point. The HFRSA is a significant undertaking and will be more involved than the flight safety analysis for a non-SNS mission.

A.8.4 Specific accident environments that may need to be considered when performing the HFRSA include but are not limited to those shown in Table 6 of this AC.

Table 6 – Accident Environments for HFRSA Consideration

Accident Environment	Physical Mechanisms
Dynamic	Acceleration, Shock, Vibration
Explosive	Overpressure
Kinetic	ΔP, dP/dt
Thermal	T, ΔT, ∇T, dT/dt
Nuclear	Radiation Fluence
Chemical	Chemical Reactivity

A.8.5 Where P is Linear Momentum, T is the Temperature, t is the Time, Δ is the Difference Operator, ∇ is the Gradient Operator, d/dt is the Differential Operator.

A.8.6 Accident environments include fireball temperatures, explosive debris fragment velocities, and speeds for ground impact. Other accident environments include pressure gradient, atmospheric lapse rate, wind, and precipitation, which can affect the transport of released radioisotopes on the ground and in the atmosphere. Break-up state vectors – position (location and altitude), velocity, and acceleration are important initial conditions for the transport equations of motion.

A.8.7 These accident scenarios may, in and of themselves, pose hazards to people and property. They are addressed in non-nuclear portions of launch and reentry licensing. From a nuclear safety perspective, they also impose hazards to the physical barriers to radioactive release that can result in radiological release and dispersal resulting in a P_{ER} that must be determined by the HFRSA to satisfy acceptable levels of risk in Chapter 7 of this AC. When complete, the HFRSA provides the information shown in Table 7 of this AC. An iterative process may be beneficial to develop this information by considering the results of safety analyses required for non-nuclear and nuclear missions. In some cases, the results of the HFRSA may inform decisions regarding the performance of safety mitigations employed by the launch or reentry vehicle. Like all nuclear safety analyses, the HFRSA should be based on sound underlying scientific principles and valid statistical methods.

Table 7 – Information Produced by a HFRSA

Information Produced by a HFRSA	Rationale
Normal operational occurrences analysis for each stage of the mission, including launch, ascent, on orbit, departure from orbit, reentry, and end of mission (EOM).	*This information quantifies the baseline risk of the SNS and is used to develop the environmental review.*
The P_{ER} to the most exposed member of the public during normal operations.	*This information quantifies the baseline risk of the SNS and is used to develop the environmental review.*
Histograms showing the number of people expected to receive various TEDs above background radiation levels up to the highest dose for normal operations.	*This information quantifies the baseline risk of the SNS and is used to develop the environmental review.*
Normal operations analysis for return to orbit, on orbit, and EOM disposal, if applicable.	*This information is used to assess whether a commercial SNS might impact national assets with radiation detection capabilities. It is also used during the safety and payload reviews, and potentially to develop the environmental review.*
A radiation emission heatmap showing the maximum expected radiation from the SNS out to 100 km from the vehicle when operating in space.	*This information is used to assess whether a commercial SNS might impact national assets with radiation detection capabilities. It is also used during the safety and payload reviews, and potentially to develop the environmental review.*
Accident analysis for each stage of the mission, including launch, ascent, on orbit, departure from orbit, reentry, uncontrolled reentry, and EOM disposal.	*This information is used to validate the calculated SNS Tier level, to develop the environmental review, and to calculate the maximum probable loss (MPL).*
The P_{ER} to the most exposed member of the public for each failure chain with a probability greater than 1×10^{-7}.	*This information is used to validate the calculated SNS Tier level, to develop the environmental review, and to calculate the MPL.*

Information Produced by a HFRSA	Rationale
Histograms showing the number of people expected to receive various TEDs above background up to the highest dose for each scenario with a probability greater than $1x10^{-7}$.	*This information is used during the safety and payload reviews, and potentially to develop the environmental review.*
Severe accident analysis for each stage of the mission, including launch, ascent, on orbit, departure from orbit, reentry, uncontrolled reentry, and EOM disposal.	*This information is used to determine the risk to the public and to assist in the development of the environmental review.*
The P_{ER} to members of the public for the failure chain that produces the highest P_{ER} to a member of the public, and the probability of that failure.	*This information is used to determine the risk to the public and to assist in the development of the environmental review.*
A histogram showing the number of people expected to receive various TEDs for the failure chain with the highest P_{ER} to a member of the public, for various TEDs from background up to the highest dose.	*This information is used to determine the risk to the public and to assist in the development of the environmental review..*

A.8.8 Additional information on performing probabilistic risk assessment and public exposure calculations for nuclear systems is also available from various nuclear agencies and organizations. Some of these documents are listed in chapter 3 of this AC, but more specific probabilistic risk assessment guidance and standards are available elsewhere. This information may be very useful to applicants where the SNS merits an RHA or HFRSA. The following is a brief list of some, but not all, of the references available at the time of this AC which may aid applicants in performing their nuclear safety analyses:

A.8.8.1 American Nuclear Society (ANS).

- ANS RA-S-1.4-2021, Probabilistic Risk Assessment for Advanced Non-Light Water Reactor Nuclear Power Plants.
- ANS 6.1.1-2020, Photon and Neutron Fluence-to-Dose Conversion Coefficients.
- ANS 8.23-2019 Nuclear Criticality Accident Emergency Planning and Response.
- ASME/ANS RA-S-1.3-202x, “Standard for Radiological Accident Offsite Consequence Analysis (Level 3 PRA) to Support Nuclear Installation Application” (revision of trial-use standard ASME/ANS RA-S-1.3-2017)

A.8.8.2 American Society of Mechanical Engineers (ASME).

- ASME RA-S-2008, Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications.

Note: ASME/ANS RA-S-1.3-202x, "Standard for Radiological Accident Offsite Consequence Analysis (Level 3 PRA) to Support Nuclear Installation Application" (revision of trial-use standard ASME/ANS RA-S-1.3-2017) ANS RA-S-1.3-2017 and ASME/ANS RA-S-1.3-2017 refer to a joint standard under trial use development by ASME and ANS. It has not been made a final standard.

A.8.8.3 Department of Energy

- DOE-STD-1628(series), *Development of Probabilistic Risk Assessments for Nuclear Safety Applications*.

A.8.8.4 Nuclear Regulatory Commission

- NUREG-1513, *Integrated Safety Analysis Guidance Document*.
- NUREG-2201, *Probabilistic Risk Assessment and Regulatory Decision-making: Some Frequently Asked Questions*.
- NUREG-2199, *An Integrated Human Event Analysis System (IDHEAS) for Nuclear Power Plant Internal Events At-Power Application*.
- Regulatory Guide 1.200, *Acceptability of Probabilistic Risk Assessment Results for Risk-Informed Activities*.
- Regulatory Guide 1.233, *Guidance for a Technology-Inclusive, Risk Informed, and Performance-Based Methodology to Inform the Licensing Basis and Content of Applications for Licenses, Certifications, and Approvals for Non-Light Water Reactors.*
- Regulatory Guide 1.247, *Acceptability of Probabilistic Risk Assessment Results for Non-Light Water Reactor Risk-Informed Activities*.

Note: This regulatory guide was issued for trial use at the time of this AC publication. A final version may now be available.

A.9 RADIOLOGICAL EMERGENCY RESPONSE PLAN.

A.9.1 Consistent with DOE and NRC practices, a radiological emergency response plan (RERP) is needed when an SNS contains sufficient material to have off-site safety implications (Title 10 CFR Chapter I 2021). This determination is made when the amount of radioactive material, as indicated in the RMR, exceeds the thresholds of Title 10 CFR 30.72 Schedule C (Title 10 CFR Chapter I 2021). For the accident environments the SNS may experience, the release fractions stated in Title 10 CFR 30.72 Schedule C may not be appropriate. To avoid making a non-conservative assumption, the FAA uses a default assumption that the SNS release fraction is 1.0, unless evidence is presented to show that the release fraction is lower. This has the net effect of reducing the threshold quantities listed in Title 10 CFR part 30.72 Schedule C unless evidence is provided.

A.9.2 In cases where there are multiple isotopes present, an RERP is required when the sum of all the ratios on any RMR or RMR addendum between SNS isotopes and Title 10 CFR 30.72 Schedule C thresholds exceeds 1.0 (Title 10 CFR Chapter I 2021). For example: consider an SNS with only two isotopes, A and B, where the release fractions of Title 10 CFR 30.72 Schedule C are shown to be correct:

$$\frac{(SNS\ Activity)_A}{(10\ CFR\ 30.72\ Schedule\ C\ Threshold)_A} = 0.55$$

And

$$\frac{(SNS\ Activity)_B}{(10\ CFR\ 30.72\ Schedule\ C\ Threshold)_B} = 0.9$$

A.9.3 The combined value of all isotopes on this SNS would be:

$$0.55 + 0.9 = 1.45$$

A.9.4 Because the combined value 1.45 is greater than 1.0, an RERP would be required for this SNS.

A.9.5 RERP’s can be created by applying the principles and process of NUREG 0654/FEMA (Radiological Emergency Preparedness) REP-1 Rev. 2 Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness dated December 2019. The RERP is not itself an analysis, but rather a response plan that provides the FAA assurance that the applicant and involved government entities are prepared to respond in the event of a radiological emergency. RERPs contain contingencies to address scenarios addressing fixed facilities where a member of the public may be exposed to ionizing radiation, as identified in the RHA, HFRSA and criticality safety analysis if applicable. Thus, while the RMR determines whether an RERP is needed, the subsequent analyses may need to be completed before the RERP can be completed.

A.9.6 RERPs for SNS that will operate or linger in Earth orbit include how the radiological risks have been discussed with other nations, and the procedures and governmental collaboration that will be used to recover, mitigate, and decontaminate the area if a SNS has an uncontrolled reentry in another nation.

A.9.7 RERPs can be incorporated in an applicant's overall mishap plan as required by § 450.173.

A.10 TIER LEVEL DETERMINATION.

After the HFRSA process is complete, the final Tier level of the SNS can be determined, unless it was previously determined due to satisfying automatic criteria. The applicant will utilize the results of their HFRSA to determine the Tier level, and the FAA will evaluate both the analysis and the final Tier level conclusion.

A.11 SAFETY ANALYSIS REPORT.

An application for launch or reentry of an SNS requires a SAR (NSPM-20 2019). The SAR provides sufficiently detailed and complete enough documentation to support the FAA's evaluation of the applicant's safety analysis as applicable for that SNS. The SAR documents the detailed and complete results of all analysis performed to assess the safety of the SNS and elaborates on the comparison to existing analyses for the SNS that are assessed using this method. Additional information might be warranted in the SAR as determined by SNS mission parameters on a case-by-case basis. Creating the SAR provides the applicant an opportunity to communicate to the FAA how the risks of the SNS are being properly assessed and addressed to protect public health and safety and the national security and foreign policy interests of the United States. A SAR should include the following:

- Evidence of technical peer review for all hazard analyses and safety analyses;
- A concise, high-level summary of key risk information:
  a. The likelihood of an accident resulting in an exposure more than 5 rem TED to any member of the public;
  b. The number of individuals who might receive exposure more than 5 rem TED in an accident scenario;
  c. Comparisons of the potential exposure levels to other meaningful measures:
     i. Space nuclear system launch safety guidelines;
     ii. Average public exposure from natural and human made sources; and
     iii. Other relevant public safety standards.

A.11.1 In some cases, it may be appropriate to include a system-specific SAR within a mission SAR. This could be advantageous when multiple launches of the same space nuclear system are planned, as the first system-specific SAR could specify the safety basis envelope for the system. The safety basis envelope would set the conditions under which the nuclear safety analyses are valid and provide assurance of safe operation of the SNS. This would limit the scope of the applicant produced nuclear safety analysis for future missions with the same SNS. If a system-specific SAR is used, the mission SAR either:

1. Demonstrates that the mission is within the safety basis envelope established in the system-specific SAR.
    a. No additional safety analysis is required for the space nuclear system in this case because the safety of the system has already been established within the safety basis envelope.
2. Includes supplemental safety analysis for deviations outside the established safety basis envelope where safety has not yet been demonstrated.
    a. Additional analysis is required to ensure public safety is not adversely impacted by the planned operations outside the initial safety basis envelope.

Appendix B. Guideline Safety Recommendations

B.1 SCOPE.

This appendix provides recommendations for an applicant to consider to minimize the public safety risk of an SNS. This appendix also provides recommendations to applicants that, if incorporated, will increase the likelihood that the FAA will be able to issue a safety approval or a favorable payload determination.

B.2 NUCLEAR SAFETY THEMES.

B.2.1.1 From the comprehensive reviews performed to develop this AC, several overarching themes emerged for commercial SNS safety including but not limited to:

- Sustained successful use of nuclear technology requires a license applicant to have a strong safety culture developed in their organization;
- Preventing failure of an SNS does more to protect the public than responding to failures;
- The risk to the public increases if the radioactive material escapes from the SNS;
- The larger the ionizing radiation potential from an SNS, the less likely failures must be to achieve an acceptable overall risk to the public;
- The initial design of the SNS determines the baseline radiation exposure risk that an SNS can pose to the public;
- SNS may increase the risk to the public above the baseline radiation exposure risk any time there is potential for an SNS to return to Earth, including launch, orbit, reentry, and Earth flyby.
- Spacecraft maneuvers can change the risk of the SNS to the public relative to the baseline radiation exposure risk;
- Operation of the SNS can increase the risk to the public from the baseline radiation exposure risk, sometimes significantly;
- The risk to the public increases as the operating time increases for a fission based SNS;
- The risk to the public for any SNS is much higher when a critical chain reaction is in progress than when the chain reaction is sub-critical;
- The uncontrolled reentry of a fission reactor with a critical chain reaction in progress poses a significant risk to the public;
- The risk to the public increases the closer the SNS operates to Earth; and
- EOM disposal decisions can change the risk of the SNS to the public.

B.2.1.2 From reviewing the designs, licensing requirements, and standards that were in place for terrestrial nuclear reactors, it became clear that SNS have unique characteristics that will require additional consideration beyond what has been developed to this point. For example, the sophisticated computer models for analyzing terrestrial nuclear accidents currently lack the flexibility to analyze a radioactive release that begins in orbit and results in an uncontrolled reentry, which will make reactor accident analysis for on-orbit SNS challenging (Nuclear Regulatory Commission 2017), (Sandia National Laboratories 2021). The guidelines in this appendix were developed to help bridge those gaps.

B.2.1.3 These guidelines are intended to reduce the public safety risk of all SNS. The guidelines outlined in this appendix use an engineering approach without biases, and a narrow focus for each guideline, which can lead to apparent redundancy for mission concepts that include multiple guideline categories. Collectively, the guidelines in this appendix provide useful direction for a wide variety of nuclear technologies. In some instances, specific guidelines are applicable only to a specific technology or operational concept to address specific identified vulnerabilities. Applicants should use their judgement to identify the guidelines that do not apply to their SNS or mission. Applicants should also use sound engineering judgement and risk mitigation for their mission and implement these guidelines in a manner that reduces the overall public safety risk of the SNS mission.

B.2.2 **Minimizing Public Safety Risks**.

B.2.2.1 SNS pose a radiological risk to the public any time there is potential for an SNS to return to Earth, this includes launch, orbit, reentry, and Earth flyby. During the development of this AC, the FAA identified topics that each had the ability to significantly increase the overall risk of the system. Summarized below are vulnerabilities in the form of guidelines, recommending selection of lower risk alternatives, with rationale in italics. Some of the guidelines focus on reducing the mission risk, while others focus on reducing the SNS risk.

B.2.2.2 When assessing the risk of an SNS, operators should consider the risks of the system itself, and how the risks of the overall mission impact the risk of the SNS. This is because the public safety impact of an SNS depends not only on the potential failures, but also on the potential locations and interactions of those failures.

B.2.2.3 The overall risk of radiation exposure to the public is a combination of both risks, taking into consideration that the failure of either the SNS or the spacecraft may induce a subsequent failure in the other component. To stay within public risk range requires using lower risk SNS for higher risk missions or performing lower risk missions for higher risk SNS. The guidelines in this appendix address both the mission risk and the SNS risk to aid applicants in staying below the maximum risk threshold regardless of whether the mission development process is started from the perspective of fulfilling a specific mission (fixed initial mission risk) or using a specific SNS (fixed initial SNS risk).

B.2.2.4 Figure 5 of this AC was developed to aid applicants in understanding the different risk drivers for both mission and SNS risk. The colors assigned to various options are indicators of relative risk within that column, and not indicators of absolute risk, or relative risk between columns. For example, the relative risk between disposal on Earth and a fission system operating close to material limits cannot be definitively stated without knowing additional information about the SNS and the mission. Likewise, the absolute risk for disposal on Earth and operating close to material limits cannot be quantified without additional information about the SNS and mission. What can be definitively stated is that disposal on Earth is riskier than disposal in interplanetary space with no free return trajectory to Earth, and that operating with significant margin to material limits reduces risk compared to operating at material limits.

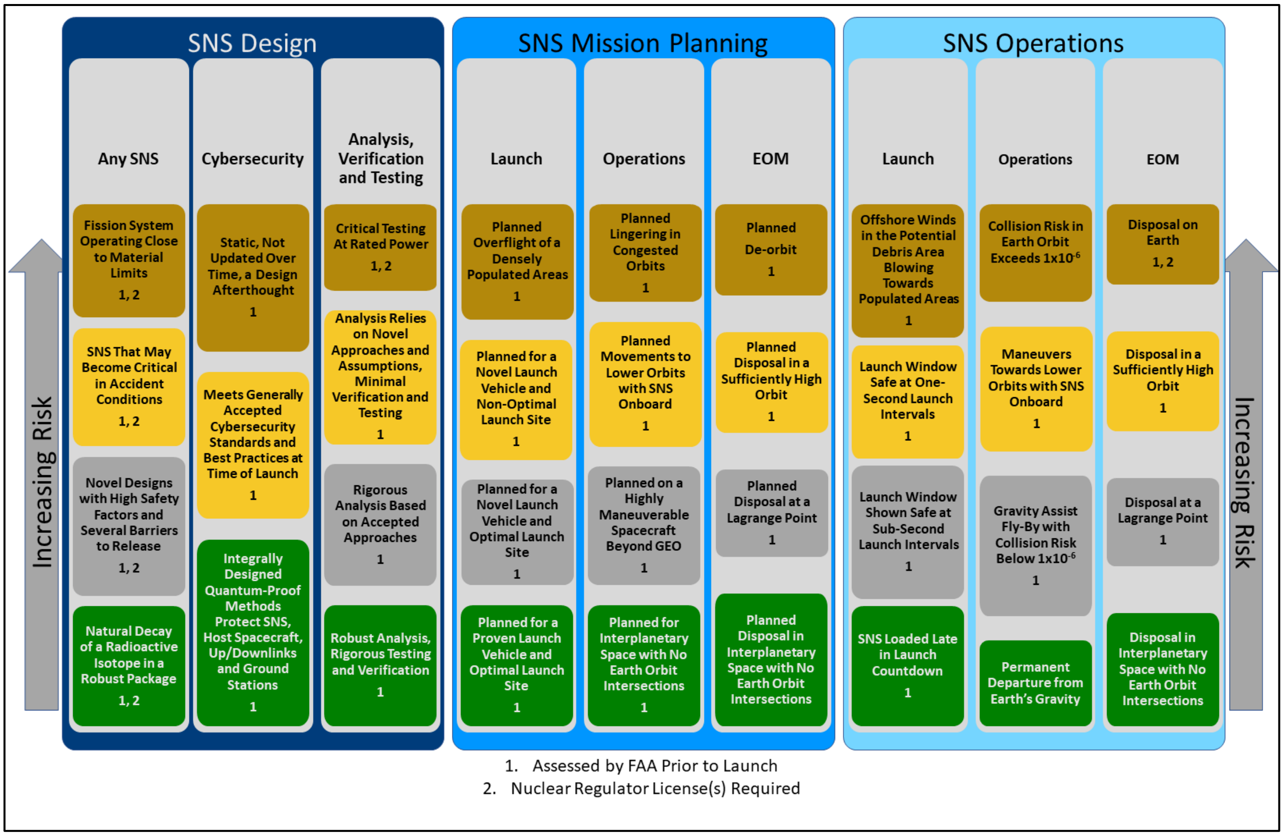

Figure 5 – SNS Mission Risk Drivers

B.2.2.5 The risk drivers, and guidelines to minimize risk, fall into these broad categories:

- SNS Design
  - Any SNS, appendix B.2.3;
  - SNS with Potential to Return to Earth, appendix B.2.4;
  - Fission-Based SNS, appendix B.2.5;
  - SNS Host Spacecraft, appendix B.2.6;

  - SNS Cybersecurity, appendix B.2.7;
  - SNS Analysis, appendix B.2.8; and
  - SNS Validation, Verification and Testing, appendix B.2.9.
- SNS Mission Planning
  - Launch and Launch Sites, appendix B.2.10;
  - Operations, appendix B.2.11; and
  - EOM, appendix B.2.12.
- SNS Operations
  - Launch, appendix B.2.13;
  - Operations, appendix B.2.14; and
  - EOM, appendix B.2.15.

B.2.2.6 These guidelines are not requirements or licensing criteria, as it may be possible to design a system that disregards one or more of these guidelines while still meeting an acceptable overall risk level for licensing. Rather, these guidelines give ways to minimize the overall risk to the public from any given SNS and aid applicants who are unfamiliar with either the risks of radioactive material, commercial space operations, or both.

B.2.3 **Guidelines Applicable to All SNS Designs**.

B.2.3.1 All SNS should be designed to survive the uniquely challenging space environment, including the conditions identified in Table 8 of this AC. SNS should be designed to have a low probability of releasing radionuclides in the event of a launch mishap, in space collision, or uncontrolled reentry impact. To meet this objective, designs should use materials that are able to withstand the operating environmental conditions without failure. Material failure can create a direct path for radioactive material release to the environment or lead to a subsequent SNS or space vehicle failure that results in a direct path for radioactive release to the environment. Of note, the FAA does not regulate SNS designs. Per the Atomic Energy Act of 1954 and the Energy Reorganization Act of 1974, the commercial use of nuclear material in the U.S. is regulated under the authority of the NRC (Atomic Energy Act of 1954, as amended 2021), (Energy Reorganization Act 1974).

Table 8 – Design Considerations for All SNS

Consideration	**Rationale**
SNS are designed with the ability to prevent uncontrolled release of radioactive material to the environment during anticipated operational occurrences.	*An uncontrolled release of radioactive material to the environment poses the greatest risk to the public. An uncontrolled release of radioactive material could expose the public to ionizing radiation and fission products that, in large enough doses, can cause human health effects, including death, to those exposed* (CDC 2018).
Design SNS to have negligible impact on probability of the launch vehicle experiencing a failure.	*The integration of an SNS with the launch vehicle is designed to have no effect on the risk of launch vehicle failure to minimize the risk to the public during an SNS launch.*
The use of radiation hardened electronics.	*Background space radiation and radiation from the SNS can induce single event upsets, which could cause safety critical components to malfunction* (LaBel 2004).
Ensuring systems and components maintain functionality during space weather events.	*Space weather conditions, including cosmic radiation and solar magnetic effects are an environmental factor that can influence the behavior of an SNS, potentially creating public safety hazards if inadequate designs are used.*
The behavior of fluid systems in a zero-gravity environment.	*Convection requires gravity and will be unavailable in space.* *Density changes due to temperature differences will not induce motion in the fluid due to insufficient gravitational force (NASA 2001).* *Saturated systems will not stratify based on phase (NASA 2001).* *Insufficient gravitational force will cause any systems to maintain a mixed quantity of liquid and vapor (NASA 2001). The density difference present between a substance's liquid and vapor phases will not cause a physical separation.*

Consideration	Rationale
Temperature extremes in space.	*Reactor designs derived from terrestrial systems consider increased stress due to temperature extremes and gradients; materials repurposed from reactors on Earth to be utilized within the space environment meet the performance requirements for this hostile environment (Wright 2014).* *Temperatures in space fluctuate hundreds of degrees in the matter of minutes* (Wright 2014). *The presence (or lack) of sunlight will substantially affect temperatures experienced on or near the exterior of the SNS* (Wright 2014).
High cyclic count, cyclic rate, and fatigue stress for components of a system in space that spin.	*Any moving or rotating equipment on the spacecraft will cause vibration, cyclic stress, and fatigue stress* (McPherson, et al. 2015).
Design SNS to include systems to ensure the safe disposal of the nuclear material after the EOM, in a manner that protects human, environmental and national security assets.	*Nuclear safety analyses and licensing criteria are based on the overall lifetime risk of the SNS, and the presence of long-lived fission products remains to this day a significant disposal challenge for spent fuel from terrestrial nuclear systems* (GAO 2021).

B.2.4 **Guidelines Applicable to Designing SNS that Have Potential to Return to Earth**.

When the mission plan calls for the SNS to linger in Earth orbit, operate in Earth orbit, or perform a fly-by, the following additional guidelines in Table 9 of this AC are relevant to reduce the risk to the public. SNS used in this way have potential to return to Earth and merit additional efforts to prevent exposing the public to ionizing radiation.

Table 9 – Guidelines for SNS Designed to Operate in Earth Orbit

Guideline	Rationale
SNS on missions with potential to return to Earth are designed with SNS monitoring signal paths that are at least single fault tolerant.	*When an SNS has the potential to return to Earth they present a risk of exposure to the public. Consequently, redundant monitoring signal paths are used to ensure the nuclear device parameters are known and understood by the owner/operators to quickly assess and intervene in the event of an anomaly* (IAEA 1999).
Design SNS that will be on missions with potential to return to Earth with the ability to maintain adequate decay heat removal capabilities at temperatures low enough to be handled (~140°F) to prevent physical damage during and after deliberate or uncontrolled reentry.	*Unlike the fission process, the heat produced by the decay of fission products does not stop when the reactor is shut down* (Nuclear Regulatory Commission 2020). *After shutdown, the heat produced by fission products is called decay heat, and decay heat generation continues for years after a reactor is shut down, with the overall rate of decay heat generation decreasing over a long time* (Nuclear Regulatory Commission 2020). *Applicants should consider decay heat generation in the design of any SNS, and during accident analysis. For public safety, a space nuclear reactor should adequately remove the decay heat during all times when the system could return to Earth to prevent overheating and damaging the nuclear fuel or posing a handling hazard to personnel.*
Design SNS to be operated in Earth orbit with the ability to monitor and report the structural integrity of its nuclear fuel and surrounding barriers.	*Monitoring of the structural integrity of nuclear fuel allows operators to recognize signs of failure before it occurs to prevent or minimize the consequences of the failure to minimize the risk to the public and environment.*

Guideline	**Rationale**
When the mission plan calls for terrestrial disposal of the SNS (in situations where this is a permissible strategy) they are designed so the physical barriers to radioactive release can survive the environmental conditions of controlled reentry and landing, as well as reentry and landing casualties, considering the neutron embrittlement and fatigue of the physical barriers that occurred while the nuclear system was operated.	*Physical barriers prevent the release of radiation and radioactive material to the environment, minimizing the risk to the public* (IAEA 1999). *The design of a physical barrier considers the unique operating conditions that the SNS will undergo and ensure a significant safety margin for all operating profiles and reentry casualties.*
Design physical barriers to radioactive release to remain intact during any space vehicle mishap where the debris could return to Earth.	*A physical barrier is intact if it retains sufficient integrity to keep radioactive fuel, solid fission products, and structures together collectively, preventing uncontrolled release of fission products to the environment* (IAEA 1999).
When SNS will have the potential to reenter Earth's atmosphere, they are designed with sufficient safety factors to survive reentry through recovery without experiencing fracture of the physical barriers designed to prevent radioactive material release.	*The intent of ensuring containment is to prevent radioactive material from the SNS escaping into the Earth's environment.*
For systems to be disposed in Earth orbit, design SNS having features such as mirrors and corner reflectors that aide in the orbital tracking of the passivated space system.	*These features enable the space traffic management agency to easily maintain current orbital parameters of the dead satellite, vital for predicting future collisions against other resident space objects* (18th Space Control Squadron 2020).
An SNS that will be disposed through controlled reentry to Earth will likely need more physical barriers to radioactive release.	*Physical barriers include design features that allow the spent nuclear material to survive the reentry forces and to be recovered on the ground before any malicious actors can retrieve them.*

B.2.5 **Guidelines Applicable to the Design of Fission-Based SNS**.

B.2.5.1 Fission can rapidly release massive amounts of energy. Controlling the critical fission chain reaction is of the utmost importance to protect public safety. Applicants should consider the following description, which relates to criticality accidents when handling fissionable or fissile material in situations where personnel are proximate to the material or system, from the *Lecture Notes for Criticality Safety* (Fullwood 1992):

> *A criticality accident is like an explosion or a fire or both in the sense that considerable energy is released. This energy can melt, boil, and vaporize apparatus, boil liquids, blow- apart structures, and produce hazardous missiles. Personnel can be killed or maimed by the energy release but the usual killer is radiation in the form of neutrons, and gammas. Betas and alphas can play a part, but their range is limited. To emphasize these points, a criticality accident may, depending on the severity:*
>
> • *Throw personnel down and about,*
>
> • *Rupture containers by steam pressure,*
>
> • *Fracture equipment and produce flying missiles,*
>
> • *Violently eject liquids,*
>
> • *Melt, and possibly ignite, uranium and plutonium metals,*
>
> • *Disperse radioactive particles,*
>
> • *Ignite and explode surrounding materials,*
>
> • *Emit lethal or incapacitating radiation.*
>
> *Typically, a criticality accident produces an initial pulse of energy and radiation. The only protection for this is to be as far away from, and behind as much shielding material as possible. However, as will be seen from the following accident descriptions, many criticality accidents are of considerable duration (Fullwood 1992).*

B.2.5.2 The operation of the fission based SNS significantly changes the radioactive isotope inventory, and thus changes the ionizing radiation exposure risks associated with the system. Fission based SNS are designed in a manner that balances meeting the mission requirements and minimizing the risk to the public, as explained in Table 10 of this AC.

Table 10 – Guidelines for Designing Fission Based SNS

Guidelines	Rationale
For space nuclear reactors that are normally controlled from Earth and are on missions that have the potential to return the reactor to Earth, design features are included to automatically shut down the reactor if communication is lost with the Earth control station.	*If all ability to remotely operate the reactor is lost, automatic shutdown occurs to prevent an uncontrolled reentry of a critical reactor and to prevent reactor power excursions while control is lost.*
For space nuclear reactors that are normally controlled from Earth and are on missions that have the potential to return the reactor to Earth, design features are included to ensure the reactor remains shut down until the Earth control station regains reliable communication with the reactor.	*If the control station can reestablish positive control of the reactor, and all other conditions for criticality are met, reactors may be started up and operated at power. Until that happens, keeping the reactor shutdown best protects public safety.*
Design SNS to prevent an inadvertent criticality event regardless of the orientation of the system during pre-flight and flight.	*The potential for an SNS to undergo abnormal orientations means that the nuclear system is designed so these orientation changes have no effect on the system.*
Design SNS to prevent an inadvertent criticality in challenging space weather environments.	*Cosmic radiation, along with solar magnetics and other space weather events may be able to change the neutron flux in a reactor. SNS designs consider these factors and ensure the SNS can maintain control of the critical chain reaction in the expected space weather environment.*
Design SNS to minimize the fission product yield during the dynamic conditions of collision in space or with the ground.	*The varying forces encountered by an SNS may cause shock and relative position changes of reactor components, changing the geometry of the SNS and potentially leading to criticality* (Dabrowski, et al. 2020). *Minimizing the fission product yield in these scenarios is essential to minimizing the public safety risk, as history shows that fission yields exceeding* 1×10^{16} *fissions have a high probability of causing death if personnel are in close proximity* (Fullwood 1992).(Fullwood 1992).

Guidelines	**Rationale**
Design SNS to remain subcritical during planned reentries.	*Reentries present a risk of contamination and consequent risk to the public due to potential overflight of populated areas or deviation from planned reentry routes. Reentries also subject the SNS to temperature extremes and significant accelerations that could alter reactor parameters and physical systems* (Bluck 2006). *Ensuring the system can remain subcritical will minimize the design-basis accident source term by preventing the creation of fission products during the reentry.*
Design reactors to rely on delayed critical chain reactions and ensure proper design and operational mitigations are in place to minimize the possibility of prompt critical conditions occurring during times when the SNS may return to Earth.	*Prompt-critical reactions are typically unstoppable and typically result in reactors self-disassembling* (Fullwood 1992). *This could cause an uncontrolled radioactive release, posing a risk to the public.*
Design reactors to minimize the possibility of unintentional criticality occurring, regardless of the medium surrounding the nuclear system (i.e., when submerged in water, sand, dirt, air, in-space radiation, deformation during crashes, etc.) unless reactor startup is intentionally initiated.	*Because SNS move, the external environment cannot be assumed constant. External operating environments (i.e., in cold water vice warm air), or changes in system geometry (i.e. deformation during a crash) may affect the neutron flux in the system enough to cause criticality* (Corliss 1969). *This change to the neutron flux is accounted for in design such that the system can remain subcritical unless criticality is intentionally initiated.*
Design reactors so they are inherently stable, i.e., when operating they can adjust their output power based on the power demands of the supplied loads without the need for operator action.	*Active and passive safety measures incorporated into the SNS's design will ensure that any deviations from equilibrium can be sufficiently mitigated and reorient back towards equilibrium, preventing runaway power and damage to the device* (IAEA 1999).
When fission based SNS are designed to be controlled from Earth, the control paths between the operator and the SNS are designed with redundancy such that they are at least single failure tolerant.	*SNS have designed redundancy such that no single fault impedes the ability to safely operate or shutdown the reactor* (IAEA 1999). *Designing SNS with redundant control systems will lower the severity and probability of nuclear accidents, which will lower the risk to the public.*

B.2.6 **Guidelines Applicable to Design of SNS Host Spacecraft**.

The SNS host spacecraft plays a key role in ensuring the safe delivery, operation, and disposal of the SNS. The guidelines in Table 11 of this AC will aid designers in designing or selecting the appropriate spacecraft to host their SNS and minimize public safety risks.

Table 11 – Guidelines Applicable to Design of SNS Host Spacecraft

Guideline	Rationale
Design spacecraft hosting space nuclear reactors with adequate instrumentation and communication capabilities for the operator to determine the power level of the reactor and the integrity of the physical barriers to radioactive release at all times when there is potential for the SNS to return to Earth's surface.	*Monitoring the power level ensures the space nuclear reactor does not violate design specifications ensuring the reactor operates normally (as expected and modeled) preventing damage to the reactor core. The operator always knows the status of fission product physical barriers to release to understand if there is an uncontrolled radiation and fission product release to the environment. Systems with uncontrolled release in the space environment can then be moved further from Earth to minimize the risk to the public.*
Design spacecraft that will host SNS in Earth orbit with the capability to maneuver at any time until EOM.	*Maneuvers avoid collisions and close approaches to nuclear-sensitive spacecraft, counteract natural orbital decay, and permit disposal into safe locations.*
Design spacecraft hosting SNS having independently powered subsystems that give precise orbital position and velocity vector information to ground operators for use in collision avoidance against the on-orbit catalog.	*Despite the ability of the Space Surveillance Network's ability to track a spacecraft's position, the most accurate data comes in the form of ephemeris reported directly from the owner operator of a spacecraft* (18th Space Control Squadron 2020). *Hence, the most accurate collision avoidance predictions come from a combination of precise orbital position from the satellite and owner operator coupled with the orbital tracking capabilities of the Space Surveillance Network for the on-orbit catalog* (18th Space Control Squadron 2020).
Risk is minimized by using a launch vehicle design with successful operational history under similar conditions with payloads of similar size and weight.	*Proven successful operations reduce the uncertainty in the nuclear safety analyses and gives greater confidence that the launch will be safe.*

Guideline	Rationale
Risk is minimized using reentry vehicle designs with successful operational history under similar conditions with payloads of similar size and weight.	*Avoid failures during reentry as they are particularly harmful to the public because the radioactive material is returning to Earth. If reentry is desired, using a proven vehicle design reduces the risk and gives greater confidence that the reentry can be performed safely. Reentry of an SNS is still a risky mission operation, but the risk can be mitigated somewhat by using a proven design.*
SNS designs and operation plans minimize radioactive contamination or activation of launch vehicle components, which will return to Earth during normal launch operations.	*Since these components are known to return to Earth, any radioactivity added to them by the SNS poses a risk to the public. Minimizing the activation and contamination of these components minimizes the risk to the public.*
Spacecraft hosting SNS contain propulsion systems to maintain orbital control and prevent orbital decay into the atmosphere due to drag.	*The ability to maintain orbital control of any operational spacecraft is important but especially so when dealing with an SNS. Despite expectations that SNS avoid the highly congested low Earth orbital regime, situations may arise where the SNS ends up closer to Earth than intended. In these unintended circumstances, orbital control through propulsion is essential to avoid atmospheric drag and the possibility of an unintended reentry.*
Risk is minimized for on-orbit operations using spacecraft with proven propulsion and maneuverability device designs.	*Maneuverability on-orbit plays a significant role in reducing the likelihood of collision, which could result in uncontrolled reentry. Proven systems for propulsion and maneuverability give greater confidence that on-orbit operations will be safe.*
For SNS missions that plan de-orbits, utilize reentry vehicle designs having proven reliability.	*Planning a de-orbit with new unproven technology and low reliability is not an optimal means to ensure environmental or public safety. Hardened and proven reentry vehicle designs give the best chance of safely de-orbiting an SNS regardless of how long it has been on orbit.*

B.2.7 **Guidelines Applicable to SNS Cybersecurity**.

Cybersecurity threats and protection practices are evolving rapidly. Applicants are encouraged to seek out additional cybersecurity and cyber-physical security guidance, utilizing the most developed and suitable means to protect the SNS and its host spacecraft from hacking, and thus protect the public from ionizing radiation exposure. The National Institute of Standards and Technology has published many cybersecurity guidelines, including some specific to spacecraft, and is a reliable source for detailed cybersecurity information. Table 12 provides specific concerns applicants should endeavor to mitigate.

Table 12 – Guidelines for SNS Cybersecurity

Guideline	Rationale
Design SNS, host spacecraft, and supporting ground stations with the ability to prevent malicious actors from gaining control or executing commands on the system's power output and control systems.	*When the Slammer worm attacked the Davis-Besse nuclear power plant on January 25, 2003, it disabled the Safety Parameter Display System and the Plant Process Computer for several hours* (Markey 2003). *Proper design will ensure this type of disruption will not occur in an SNS.*
Design SNS, host spacecraft, and supporting ground stations with the ability to prevent malicious actors from gaining control or executing commands on the space vehicle control system.	*Satellite hacking is a legitimate threat, as evidenced by the 2020 "Hack-A Sat" DEF CON run by the US Department of the Air Force* (USDAF 2020). *Hacking resulting in physical movement of the SNS or host spacecraft could cause public safety impacts.*
Design SNS, host spacecraft, and supporting ground stations with the ability to prevent malicious actors from remotely directing action that could damage the nuclear system.	*In August 2006, plant operators at Browns Ferry Unit 3 in Athens, Alabama manually scrammed the reactor after two cooling water recirculation pumps failed due to a sharp spike in data traffic on the plant's control system network* (Case 2007). *A malfunctioning programmable logic controller may have caused the data storm, but the plant and the NRC could not determine whether the malfunction resulted from an external distributed denial-of-service cyberattack* (Case 2007). *This type of disruption could be avoided by designing the SNS to prevent it from occurring.*

Guideline	**Rationale**
Design SNS, host spacecraft, and supporting ground stations with the ability to prevent malicious actors from remotely directing action that could cause a collision or reentry.	*In February 1999, cyber hackers gained control of a United Kingdom SkyNet satellite, moved it on orbit, and then demanded ransom. This type of operation with an SNS has potential for significant negative outcomes, including deliberate malicious reentry into populated areas (dirty bomb from space), or controlled malicious reentry to gain control of nuclear material with the intent of developing a nuclear weapon.*
Design SNS, host spacecraft, and supporting ground stations to ensure malicious actors cannot prevent any space vehicle or SNS control command from being executed.	*This action against an SNS has potential to cause uncontrolled release of radioactive material to the environment if SNS or space vehicle safety commands are interfered with.*
Design SNS, host spacecraft, and supporting ground stations to ensure the intrusion of malicious actors into the control system can be detected.	*Cyber hackers breached the air gapped Kudankulam Nuclear Power Plant's administrative network in Tamil Nadu, India, in 2019* (C.C. Lamb, R.E. Fasano, T. Ortiz 2020). *Detection of air-gapped computer system malware infections may not occur until years after the initial attack, which is not acceptable for SNS due to the risks this intrusion poses to the public* (C.C. Lamb, R.E. Fasano, T. Ortiz 2020).
Design SNS, host spacecraft, and supporting ground stations to ensure that the nuclear power output will be reduced during a denial of service cyberattack.	*In the Browns Ferry Unit 3 example above, plant operators manually inserted control rods into the reactor core after the possible denial-of-service incident* (Case 2007). *This manual scram would not be possible in an autonomous SNS environment; thus, the system needs sufficient autonomy to detect the attack and place itself in a safe condition.*
Design SNS, host spacecraft, and supporting ground stations using cybersecurity methods that are quantum proof.	*Quantum computing has the potential to compromise traditional cybersecurity and encryption methods* (National Institute of Standards and Technology 2021). *Given the long hazard potential for SNS, it is vital that the cybersecurity methods utilized are as forward looking as possible to prevent a malicious actor from causing harm to the public using an SNS.*

B.2.8 **Guidelines Applicable to SNS Analysis**.

Performing the safety analysis for an SNS is a key step prior to licensing. Table 13 below provides guidelines to aid applicants in developing a robust, reliable analysis for their SNS.

Table 12 – SNS Analysis Guidelines

Guideline	Rationale
When assessing the risk of the system, the worst-case scenario is assessed (IAEA 1999).	*Applicants assessing the worst-case scenario for their system and mission concept, might consider:* • *Source term;* • *Time of failure;* • *Population;* • *Location;* • *Spread of contamination* • *Maximum dose to members of the public; and* • *Extent of the damage.*
SNS have well analyzed characteristics for their design-basis accidents.	*Expected SNS conditions during the design-basis accident are thoroughly understood to ensure SNS can be accurately characterized during all phases of operation (from normal operations to credible accident scenarios) to quantify the risk the system poses to the public* (NSPM-20 2019), (IAEA 1999).
SNS which will operate in Earth orbit give adequate data on the expected and unexpected radiation emissions and orbital location to enable assessment of potential interference with national assets.	*All terrestrial based or space-based nuclear systems emit low levels of acceptable radiation non-harmful to life or physical assets. With space becoming a contested environment, it is crucial to have the ability to quickly assess if a national space asset was affected by an SNS or an adversary based on location and the level of radiation emissions and the emission parameters of the SNS.*

Guideline	**Rationale**
Planned movements to lower orbits after operating fission systems at power are identified and analyzed during the nuclear safety analysis.	*Intentionally moving an SNS closer to Earth shortens the natural orbital decay period; in the event of a failure this would minimize the time for the SNS to return to Earth, resulting in more fission products onboard when an uncontrolled reentry occurs. These risks are quantified and analyzed to ensure that an accurate assessment of the overall risk to the public is understood at the time the mission is licensed.*
SNS are analyzed for the effects of corrosion.	*Corrosion is a major concern for SNS, and materials science expertise is applied to determine the correct materials for each component to avoid premature or unexpected material failure. For example, in the case of a lithium heat-pipe fast reactor SNS at elevated operating temperatures, any contaminants within the lithium heat pipe can accelerate corrosion and heat pipe failure* (Obal 2011).
SNS are analyzed for the effects of material fatigue.	*In addition to possible low-cycle and high-cycle metal fatigue, in the case of a fission power reactor used in long transport missions, neutron embrittlement will raise the DBTT over time and may also contribute to metal fatigue* (Finckenor and de Groh 2020), (Obal 2011).
SNS are analyzed for the effects of outgassing.	*Outgassing can change the material properties or have undesirable effects on structural components. For example, when choosing refractory materials in an SNS, designers are aware of vacuum welding and contaminant outgassing* (Obal 2011).
SNS are analyzed for radiation effects on materials and electronics.	*In addition to DBTT, in the case of polymers, particulate radiation exposure can lead to chain scission or cross-linking, causing polymer embrittlement* (Finckenor and de Groh 2020). *In the case of electronics, radiation-induced single event upsets, latch-ups, and bit errors can occur* (Finckenor and de Groh 2020). *Once again, material science is applied to the design of the SNS to choose suitable materials for each component.*
SNS are analyzed for the effects of shock.	*The explosive force of a launch mishap can range from thousands of kilograms TNT-equivalent up to one thousand tons TNT-equivalent* (Camp, et al. 2019).

Guideline	Rationale
SNS are analyzed for the effects of thermal cycles.	*The cyclic stress from thermal cycles can contribute to material failures. Depending upon the mission orbit, as many as 16 spacecraft thermal cycles a day could take place* (Finckenor and de Groh 2020). *Material failure increases the risk to the public, as it can create a path for radioactive material to reach the environment.*
SNS are analyzed for the effects of vibration.	*Vibration can harm structural and internal components of SNS and may be caused by the spacecraft or the SNS. For instance, in the case of an SNS using fuel particles, the vibration analysis accounts for the possibility of damage to or shifting of the fuel particles, resulting in reactor plugging, or local coolant flow blockage* (Idaho National Laboratory 2015).

B.2.9 **Guidelines Applicable to SNS Validation, Verification and Testing**.

Validation, verification, and testing of the SNS are a key step to ensure the as-built device performs like the as-designed device. In this context, testing an actual nuclear system provides the ability to generate actual test data, but naturally presents greater risk to the surrounding people and property than a computer simulation or mathematical model, since the nuclear system is actually operating. During this process, applicants may discover that the actual performance differs significantly enough to impact the safety analysis conclusions. To aid applicants in developing a robust validation, verification, and testing program, the guidelines in Table 14 of this AC are provided.

Table 13 - Guidelines for SNS Validation, Verification, and Testing

Guideline	Rationale
Validate, verify, and test SNS to ensure the as-constructed system and its host spacecraft are within design specifications.	*Validating the constructed SNS meets the design requirements minimizes the probability of failure leading to the release of radioactive material to the environment under normal operating conditions and minimizes the probability of the physical barriers to radioactive release failing during abnormal or accident conditions, thus minimizing the risk to the public and environment (IAEA 1999).*

Guideline	**Rationale**
SNS have well understood operating characteristics for anticipated operational occurrences.	*Significant modeling, simulation, validation, verification and testing will be conducted prior to launch approval to ensure that SNS can be operated safely within expected operational parameters (NSPM-20 2019), (IAEA 1999).*
The verification and testing of SNS should demonstrate structural integrity for anticipated operational occurrences and design-basis accidents.	*Design-basis accidents ensure the SNS can withstand the most severe failures expected. For systems to be operated in Earth orbit, the design-basis accidents include uncontrolled reentry. The risk to the public can be minimized by proper design, informed by modeling, and testing of SNS.*
SNS to be operated in orbits that naturally decay to Earth before the activity of the system will decay to about the activity of uranium-235 have overall system reliabilities meeting or exceeding those of highly reliable flight safety systems, 0.999 at 95% confidence (SPD-6 2020), (Title 14 CFR Part 450 2022).	*SNS are designed and manufactured with the reliability standards of highly reliable flight safety systems to minimize the risk to the public if an SNS is not able to remain on orbit. Because SNS have significant public safety risks, they are designed to be as reliable as the most reliable systems on the spacecraft.*
To the maximum extent practical, minimize critical operations and testing for a fission based SNS before arriving at a safe orbital altitude (SPD-6 2020).	*Starting up a nuclear fission reactor increases the quantity and concentration of shorter lived, higher energy emitting radioactive isotopes and increases the potential source term and radiological risk to the public (Fullwood 1992). In general, fission products pose more exposure risk to the public than nuclear fuels, therefore the amount of fission products in the system is minimized to the extent practical prior to launch (IAEA 2021). Minimizing fission product generation will lessen radiation levels after shutdown and thus the risk to the public.*

B.2.10 **Guidelines Applicable to Mission Planning for SNS Launch**.

B.2.10.1 Launch is a time of particularly high risk to the SNS and the public. Applicants are encouraged to consider the full spectrum of design and operations concepts to identify the one that best minimizes the risk to the public. Guidance for planning SNS launch is provided in Table 15 of this AC. The areas overflown during launch determine the potential locations for the debris field impact during a launch mishap. The populations and land use of the overflown areas, as well as the nuclear proliferation concerns of the overflown areas drive the risk to the public from the SNS crashing during launch. Because NSPM-20 directs the nuclear safety analyses to consider any subsequent stages of SNS operation, which “may result in radiological effects on the public or the environment,” the overflight areas are relevant to determining the overall risk of the SNS (NSPM-20 2019).

B.2.10.2 The vehicles used for launch, operation, and reentry of an SNS directly affect the risk to the public, as a vehicle failure significantly increases the risk of a nuclear system failure. Additionally, overall vehicle reliability, vehicle control and contingency management capabilities can greatly influence the safety of a launch attempt, including if the launch is unsuccessful. For example, the controllability of a liquid-fueled vehicle might minimize the stress on an SNS payload, or a vehicle with a thrust termination system may mitigate safety risk more effectively than a vehicle with a destruct system.

Table 14 – Guidelines for SNS Launch Planning

Guideline	Rationale
Risk to the public is minimized when the SNS launch vehicle is highly reliable.	*Highly reliable launch vehicles are more likely to have launch success, and less likely to expose the public to ionizing radiation.*
Maximize overflight of oceans during launch.	*Crashing into the ocean versus onto land minimizes the risk to individuals and the cleanup costs of the event, due to the radiation shielding and contamination dilution effects of large bodies of water* (National Institute of Standards and Technology 2019).
For a given SNS and launch vehicle, the risk to the public can be changed through the selection of different launch sites and azimuths. Proper risk mitigation for SNS includes a comprehensive review to identify the right combination to best accomplish the mission objectives while minimizing risk.	*It is prudent for launch applicants to consider a variety of launch sites and azimuths for launches with SNS to make an informed, risk-based decision when planning missions.*

Guideline	**Rationale**
When considering alternative launch sites, it is best to include comparisons for nominal, off nominal, and flight abort system triggering flight profiles. Each profile will produce a unique probability of exposure to the public and contamination of land, which can aid applicants in determining the most appropriate launch site.	*It is possible that the risk to the public for a site might be lower for one specific flight profile, but the composite risk from all flight profiles is higher. For example, it would be inappropriate to select a launch site with the lowest risk for a nominal flight profile if that site also had the highest composite risk when all possible flight profiles are considered. Radiological risk is just one part of the overall risk of the mission, consideration is also given to:* • *Any hazard from a launch vehicle, vehicle component, payload or radioactive material that can reach any protected area at any time during flight.* • *A failure of the launch vehicle that would have a high consequence to the public.* • *Launch vehicle failures that could place severe stresses on an SNS, increasing the probability of a nuclear system failure.*
Evacuations are a method to reduce the radiation exposure risk to the public, but the practicality varies. If an applicant intends to evacuate an Emergency Planning Zone (EPZ) as determined during the NRC licensing or support for launch authorization to reduce risk during launch, the following information is relevant: • The amount of risk reduction gained by the evacuation; • The duration of the evacuation; • The impacted population; • The land use in the EPZ; • The local jurisdictional boundaries within the EPZ; • The willingness and ability of local authorities to enact an evacuation; and The economic impact of the evacuation.	*Evacuations are an effective way to reduce the radiological risk to individuals but can be costly and cumbersome to enact. Sheltering is often preferable to evacuations, and evacuating people also does nothing to reduce the hazard of ground contamination, and thus could have only a slight impact to the MPL. For evacuation to be a viable risk reduction strategy, evidence is needed that the evacuation tangibly reduces the risk to the public, and that the evacuation can be carried out at a cost commensurate to the risk reduction.*

B.2.11 **Guidelines Applicable to Mission Planning for SNS Operations in Space**.

Mission planning plays an outsized role in determining the risk of unintentional or uncontrolled reentry of an SNS. Reentry mechanisms vary, but the consequences of unsuccessful reentry can be severe, and are best avoided by mindful planning (Gummer, et al. 1980), (NSPM-20 2019). Guidelines for planning SNS destinations are found in Table 16 of this AC.

Table 15 – Guidelines for Planning SNS Operations in Space

Guideline	Rationale
The safest place for an SNS to operate is a location with no potential to return to Earth.	*If the system cannot return to Earth, the risk of radiation exposure to the public on the ground or ground contamination is eliminated.*
Plan missions with SNS to minimize the probability of nuclear material having an uncontrolled reentry.	*Mission planning helps determine the best operational orbits to minimize the possibility of the SNS returning to Earth in an uncontrolled reentry due to loss of operational control, collision with other space systems or orbital debris, or atmospheric drag.*
SNS missions are planned to operate above the highest altitude where the spatial density of objects exceeds 1×10^{-8} objects per km^3 at launch or is expected to exceed 1×10^{-8} objects per km^3 during the mission lifetime.	*In orbits where orbital density is high, the risk of collision and subsequent uncontrolled reentry is also high. In lower, more densely occupied altitudes, orbits also decay faster, providing less time for radioactive decay to reduce the radiation exposure hazard of the SNS. Consistent with national policy, these risks are minimized by operating SNS at sufficiently high altitudes in accordance with the principles in SPD-6 Section 3 to avoid space traffic and extend the uncontrolled reentry timeline* (SPD-6 2020).
Missions using SNS with a scheduled Earth flyby are planned to not approach Earth closer than the highest orbit where the spatial density exceeds 1×10^{-8} objects per km^3.	*Earth flybys in general present unique challenges in that they are not routinely tracked with an orbital Element Set the way orbital spacecraft are tracked as they continuously orbit the Earth* (18th Space Control Squadron 2020). *Spacecraft performing a flyby of Earth have a hyperbolic trajectory and depend primarily on the owner operator's assessment of position as it enters the Earth's gravitational pull. The possibility of collision with another orbiting object is always greater in congested regions. This can cause damage to the SNS worse yet, an unintended reentry into the Earth's atmosphere. The public safety risk during flybys is minimized when they are planned to avoid orbital altitudes with the heaviest concentrated satellites and debris.*

B.2.12 **Guidelines Applicable to Mission Planning for SNS EOM**.

Applicants should plan SNS missions with a cradle to grave philosophy that includes the long-term disposal plan for the nuclear system at the end of its useful life (IAEA 1999). This EOM plan informs the design of the overall system design and operation, and guidelines for developing the EOM plan are provided in Table 17 of this AC.

Table 16 – Guidelines for Planning SNS EOM

Guideline	Rationale
Intentional reentry for disposal on Earth is riskier than disposal in space.	*The chance of radiation exposure to the public is minimized when the disposal location has no possibility of natural decay while the activity of the fission products is greater than the activity of uranium-235* (SPD-6 2020).
SNS that utilize fission are not intentionally reentered after operation at power.	*Hundreds to thousands of years may be required for fission product decay to reduce the activity of a fission reactor to about the activity of uranium-235, as needed for reentry* (SPD-6 2020). *Planning on deorbiting this far in the future is unrealistic, impractical and neglects the long-term in-space storage that will need to occur.*
Preferably plan SNS disposal locations with no possibility of return to Earth to minimize the risk to the public.	*Disposal in a decaying Earth orbit is riskier than disposal in a location that has no likelihood of future return to Earth such as L4 and L5* (Cornish 2020).
Maximize overflight of oceans during reentry and target an oceanic landing point.	*Crashing into the ocean versus onto land minimizes the risk to individuals and the cleanup costs of the event, due to the radiation shielding and contamination dilution effects of large bodies of water* (National Institute of Standards and Technology 2019).
Evaluate planned de-orbits to minimize the risk that restricted or embargoed nations, as defined in 10 CFR §110.28, could acquire the nuclear material during or after de-orbit.	*Nuclear proliferation is a significant threat to global security and stability* (National Nuclear Security Administration 2021). *Careful measures are taken to minimize the probability of commercial space activity providing nuclear material to embargoed or restricted nations, and during the safety review the FAA reviews these measures to ensure the launch satisfies the legal requirements to protect the national security and foreign policy interests of the United States* (Title 14 CFR Part 450 2022).

Guideline	**Rationale**
SNS disposal for Tier I devices in Earth orbit may involve controlled reentries or raising maneuvers into disposal orbits.	*Mission planners account for disposal in spacecraft design and strive to place aging SNS in orbits of sufficient altitude to minimize the chance of orbital decay. Although less desirable, mission planners may also consider controlled reentries of the SNS to decommission and dispose of the system. Orbital decays present a risk to all resident space objects in the decay path.*
For planned de-orbits select reentry sites that minimize the risk of exposing the public to radiation if there is a reentry failure, consistent with ALARA (as low as reasonably achievable).	*Predetermined reentry sites (over water or land) are planned with a significant buffer on either side of the reentry location to allow for unintended reentry failures to protect the environment and population. If, in the event the de-orbit is conducted over a land mass for payload retrieval, considerations for radioactive environmental cleanup and remediation may become paramount if any radioactive material is released during the reentry or landing, and the MPL may be significant.*
Evaluate planned de-orbit sites to minimize the risk that restricted or embargoed nations, as defined in 10 CFR, could acquire the nuclear material during or after de-orbit.	*The U.S. Government updates and publishes a list of restricted or embargoed nations as necessary due to unfavorable economic or political circumstances between the two countries* (Title 10 CFR Chapter I 2021). *Hostile nations or groups gaining control of an SNS during or after reentry could harm the national security or foreign policy interests of the U.S. Minimize the risk by selecting sites well clear of restricted or embargoed nations.*

B.2.13 **Guidelines Applicable to SNS Launch Operations**.

Launch operations with SNS merit additional attention and steps to minimize the risk of the public being exposed to ionizing radiation, or the launch facility being contaminated with radioactive material. To aid applicants in identifying these additional steps, the guidelines of Table 18 of this AC are provided.

Table 17 – Guidelines for SNS Launch Operations

Guideline	Rationale
SNS are installed as late in the launch countdown as possible.	*The largest amount of propellant is present at spacecraft launch, presenting an explosion hazard. By delaying system installation until absolutely essential in the launch countdown, the time window for the SNS to be exposed to this explosion risk is minimized.* *Also, nuclear safety requirements for storage are proven effective for maintaining custody of nuclear material. Minimizing the time with modified security requirements and physical barriers gives the greatest assurance of the nuclear material remaining in custody of the licensed owner.*
Launch collision risks are fully evaluated and every effort is taken to minimize the risk of collision during launch.	*Collision during or shortly after launch could lead to damaged reentry of the SNS and subsequent public radiation exposure or radioactive contamination. Therefore, it is recommended that the most thorough launch collision risk calculation process possible is used for SNS launches. At the time of this AC, the most thorough approach utilizes multiple screening methods for launch time planning. Specifically, probability of collision screening should be done for all human spaceflight objects as well as active payloads. Debris objects should be screened for both probability of collision and standoff distance violations.*

Guideline	Rationale
Meteorological conditions from the time of launch through departure from Earth's atmosphere play a significant role in determining the spread of the debris field and radioactive debris, and ultimately in the radiological risk associated with the launch. Meteorological conditions vary with the launch site, and daily at the launch site, not all meteorological conditions at a given launch site may be appropriate for SNS launch.	*Considering the impact of meteorological conditions to nuclear risks may result in a different determination of acceptable meteorological conditions for a launch with a nuclear payload than an otherwise identical launch without a nuclear payload. The nuclear safety analyses are sufficiently detailed for operators to quantify how wind and weather impact the risk to the public, providing justification for the weather commit criteria for launch of the SNS.*

B.2.14 **Guidelines Applicable to SNS Operations in Space**.

SNS operations, and the operations of their host spacecraft mission can increase the likelihood of an uncontrolled reentry, particularly for maneuvers to lower orbits or returns to Earth's orbit from interplanetary orbits. Guidelines for planning in-flight maneuvers to minimize risks to the public are provided in Table 19 of this AC.

Table 18 – Guidelines for SNS Operations in Space

Guideline	**Rationale**
SNS that will linger in Earth orbit are on spacecraft with sufficient maneuverability that the space operator can keep the risk of collision less than $1x10^{-6}$ while in orbit.	*Earth orbits are becoming increasingly congested, necessitating in-flight maneuvers to avoid collision on an increasingly frequent basis. Consequently, SNS are designed with the capability to evade imminent collisions to minimize the risk of collision and radioactive material release*.
Earth gravity assist fly-bys are performed at sufficient distance that the risk of collision with a tracked space object remains below $1x10^{-6}$.	*Earth flybys in general present unique challenges in that they are not routinely tracked with an orbital Element Set the way orbital spacecraft are tracked as they continuously orbit the Earth* (18th Space Control Squadron 2020). *Spacecraft performing a flyby of Earth have a hyperbolic trajectory and depend primarily on the owner operator's assessment of position as it enters the Earth's gravitational pull. The possibility of collision with another orbiting object is always greater in congested regions. This can cause damage to the SNS worse yet, an unintended reentry into the Earth's atmosphere. The public safety risk during flybys is minimized by staying far enough from Earth to minimize the risk of collision.*

B.2.15 **Guidelines Applicable to SNS Operations at EOM**.

SNS disposal is non-trivial, and in the case of terrestrial disposal can significantly add to the public safety risk of the SNS. Specific guidelines for safely completing EOM disposal are provided in Table 19 of this AC.

Table 19 – Guidelines for EOM Disposal

Guideline	Rationale
Ensure SNS that are disposed in Earth orbit are passivated at EOM.	*Passivation minimizes the risk of on-orbit explosions and prevents any possible reactivation by malicious actors* (The United States Government 2019).
Perform planned de-orbits only if it can be proven that the nuclear fuel and physical barriers to radioactive release are intact.	*Having intact fuel and physical barriers to release of radioactive material before de-orbit are crucial to ensure the remaining radioactive material is not released to the environment and populated areas during reentry or on impact.*
Prior to reentry, perform analysis to ensure adequate heat removal while remaining safe to touch (~140°F) after landing.	*Reentering a system with a temperature too high to handle and move to a safe location is a significant health hazard and nuclear material security challenge, even if the system releases no radioactive material to the environment. Inadequate SNS heat removal can result in temperatures that are thousands of degrees* (Nuclear Regulatory Commission 1979). *Heat removal methods and rates will be significantly different between the space and Earth environments. Also, the space environment subjects any spacecraft to extreme temperature variations depending on whether the spacecraft is in direct sunlight or eclipse and is different on Earth. Proper design will give adequate heat removal capabilities regardless of the EOM disposal plan. Radiative cooling via high thermal flux, which may be effective in space, is generally not a viable heat removal option on Earth.*
Prior to reentry, verify heat removal systems that are at least single-fault tolerant if they rely on means other than convective and radiative losses to ambient to protect personnel and SNS integrity.	*A fault-tolerant design enables a system to continue its intended operation, rather than failing completely, when some part of the system fails, even if at a reduced level. SNS design includes the ability to remove heat even if a prescribed means of heat removal fails to prevent overheating the SNS and causing a radioactive release to the environment.*

Appendix C. Historical SNS Accident

C.1 COSMOS 954.

While SNS are novel technology for the U.S. commercial industry, governments have utilized SNS for decades (NASA 2021). One example that illustrates the risks of an uncontrolled SNS reentry occurred on January 24, 1978, when the Soviet Union Cosmos 954 satellite had a malfunction. Cosmos 954 contained a 3 kW BES 5 Buk fast neutron nuclear fission reactor employing 30 kg of highly enriched uranium (HEU) fuel as a 90% ($92U^{235}$) UMo alloy (IAEA 2005). Cosmos 954 failed to achieve proper orbital altitude, was unable to eject its reactor core, and made an inadvertent uncontrolled reentry (Connell and Trost 1994). The inadvertent reentry scattered tens of thousands of Curies (Ci) of radioactively hot nuclear reactor core debris including source fuel, toxic fission products, and activated materials over 124,000 square kilometers of Alberta and Saskatchewan regions of northwest Canada near the Great Slave Lake (Connell and Trost 1994), (Gummer, et al. 1980). The major axis of the dispersion ellipsoid for the radioactive debris field was 600 kilometers long in the downrange direction as depicted in Figure 6 of this AC (Gummer, et al. 1980).

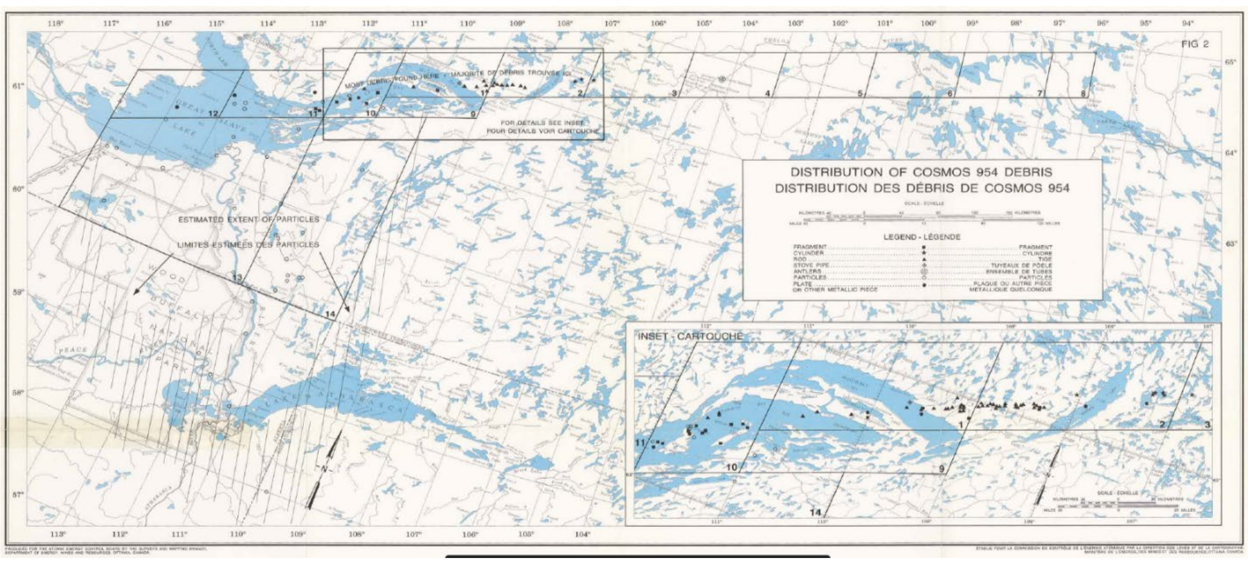

Figure 6 – Cosmos 954 Debris Map (Gummer, et al. 1980)

Most of the HEU fuel vaporized in the atmosphere over Canada upon reentry, however 500 roentgen per hour ground impact debris was located inside the dispersion ellipsoid (Gummer, et al. 1980). This is enough activity to be lethal for anyone in close proximity for one hour (CDC 2018). This historical context illustrates the potential for an SNS to cause events with significant public safety risk. To mitigate these risks, applicants need to rely on strong engineering principles, robust mission planning, and rigorous analysis without biases that may prove to be conservative (Title 14 CFR § 450.101 2022).

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Appendix E. Radiological Units

Per NSPM-20 and 10 CFR part 830 this AC employs the widely used U.S. radiological units – Curie (Ci), rad, Roentgen (R), rem, and their sub-units. The NRC full text glossary is available on the NRC's website and provides a comprehensive set of nuclear terminology definitions that are widely accepted. There is a difference between 10 CFR part 830 and the NRC glossary on the definition of Total Effective Dose (TED) that applicants should be mindful of.

Becquerel (Bq) – the system international (SI) unit of radioactivity. The Becquerel is one disintegration per second (Nuclear Regulatory Commission 2020). The Becquerel is a much smaller unit than the Curie. 1 Bq = 2.70×10^{-11} Ci.

Curie (Ci) – the amount of radioactive material that will undergo 3.7×10^{10} disintegrations per second, which is the amount of activity in 1 g of $^{226}_{88}Ra$ (226-Radium) (Nuclear Regulatory Commission 2020). The Ci is a US unit of radioactivity which has been used for more than a century and is widely employed worldwide. One Ci is a fairly large amount of radioactive material from a radiation health and safety perspective.

Gray (Gy) – An SI unit of absorbed dose of 1 Joule/kilogram (Nuclear Regulatory Commission 2020). 1 Gray is equal to 100 rads (Nuclear Regulatory Commission 2020).

Radiation Absorbed Dose (Rad) – A unit for absorbed dose, the amount of ionizing radiation that will deposit 0.01 Joule of energy per kilogram of absorbing material, which equals 100 ergs of radiation energy per gram of matter (Nuclear Regulatory Commission 2020). The rad is the US measure of absorbed dose and is widely used worldwide.

Roentgen Equivalent Man (Rem) – A unit of measure for dose equivalent or effective dose (Nuclear Regulatory Commission 2020). The rem is the U.S. measure and is widely used worldwide. The effective dose in rems can be calculated from the absorbed dose in rads by scaling the absorbed dose by a quality factor that accounts for the effectiveness of the specific type of radiation inducing damage in a biological tissue (Nuclear Regulatory Commission 2020). 100 rem is equivalent to 1 Sv (Nuclear Regulatory Commission 2020).

Roentgen (R) – the amount of ionizing radiation that will produce 0.000258 coulombs/kilogram of dry air at standard temperature and pressure (Nuclear Regulatory Commission 2020). The Roentgen (R) is the US unit of radiation exposure.

Sievert (SV) – the Sievert (Sv) is the SI unit of effective dose, equivalent to 1 Joule/kilogram (Nuclear Regulatory Commission 2020). 1 Sievert = 100 rem

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