NASA/CR–2020-220569

Operational Considerations for Space Fission Power and Propulsion Platforms

A Report to the Nuclear Power & Propulsion Technical Discipline Team

Andrew C. Klein
Oregon State University, Corvallis, Oregon

Allen Camp
Consultant, Albuquerque, New Mexico

Patrick McClure
Los Alamos National Laboratory, Los Alamos, New Mexico

Susan Voss
Global Nuclear Network Analysis, LLC, Taos, New Mexico

Elan Borenstein
Jet Propulsion Laboratory, Pasadena, California

Paul VanDamme
Jet Propulsion Laboratory, Washington, D.C.

March 2020

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Jet Propulsion Laboratory, Pasadena, California

Paul VanDamme
Jet Propulsion Laboratory, Washington, D.C.

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

Prepared for Langley Research Center
under Contract 80LARC17C0003

March 2020

Acknowledgments

This study was chartered by NASA’s Nuclear Power & Propulsion Technical Discipline Team (TDT) led by Lee Mason and Mike Houts. The Nuclear Power & Propulsion TDT governance resides under the NASA Office of Chief Engineer with oversight by the NASA Engineering Safety Center (NESC) Power Technical Fellow (Chris Iannello) and Propulsion Technical Fellow (Daniel Dorney). The study team would like to thank them along with the other members of the TDT for their guidance and feedback during this effort.

Available from:

NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320
443-757-5802

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Acronyms

2D	Two-Dimensional
3D	Three-Dimensional
ALARA	As Low As (is) Reasonably Achievable
ARS	Acute Radiation Syndrome
BFO	Blood-Forming Organs
CNS	Central Nervous System
D&D	Decommissioning and Disposal
EVA	Extra-Vehicular Activity
FMEA	Failure modes and Effects Analysis
FSP	Fission Surface Power
GCR	Galactic Cosmic Radiation
INP	In-Space Nuclear Power
INPO	Institute for Nuclear Power Operations
ISRU	*In Situ* Resource Utilization
JSC	Johnson Space Center
KRUSTY	Kilopower Reactor Using Stirling TechnologY
kWe	Kilowatt Electrical
LEO	Low Earth Orbit
MeV	Mega Electron-Volt
mGy	Milligray
mGy-Eq	Milligray-Equivalent
MWe	Megawatt Electrical
MWt	Megawatt
NaK	Sodium-Potassium
NCRP	National Council on Radiation Protection & Measurements
NEP	Nuclear Electric Propulsion
NERVA	Nuclear Engine for Rocket Vehicle Application
NTP	Nuclear Thermal Propulsion
PEL	Permissible Exposure Limit
RBE	Relative Biological Effectiveness
REAG	Radiation Effects and Analysis Group
REID	Risk of Exposure-Induced Death
RORSAT	Radar Ocean Reconnaissance Satellite
RTG	Radioisotope Thermoelectric Generator
SNAP	Systems for Nuclear Auxiliary Power
SP	Space Reactor Prototype
SPE	Polar Particle Event
SPEL	Space-Permissible Exposure Limits
SRAG	Space Radiation Analysis Group
Sv	Sievert
U.S.	United States
UN	United Nations
WANO	World Association of Nuclear Operators

1.0 Introduction

This report is aimed at identifying the issues related to the operation of various space nuclear power and propulsion reactors. The foci of the report include the possible human radiation exposure issues that might occur during different types of missions and different operational stages within those missions, managing the approach to and working around space reactors, maintaining these reactors for long-duration operations, controlling these reactors and monitoring their availability and health, evaluating possible reactor accident scenarios, planning for planetary protection due to their operation, and post-operation decommissioning and disposal. This report does not intend to rehash the potential interactions and issues that could occur during any of these missions either pre-launch or during possible reentry scenarios as these have been extensively reviewed and researched elsewhere[1,2]. The risk and consequences to be incurred during the launch and reentry should be determined as part of the launch approval process.

The general applications of a nuclear reactor in space typically include Nuclear Electric Propulsion (NEP), Nuclear Thermal Propulsion (NTP), Fission Surface Power (FSP) and In-Space Nuclear Power (INP). The general mission categories that are considered in this report can initially be split into a few general categories as seen in Table 1-1. These possible mission categories can be further characterized depending upon the specific mission needs and profiles. Some of the variations that can be considered might include:

- whether the particular spacecraft includes a human crew or is a robotic mission that could interact with a crewed mission;
- whether the mission is a single deployment mission or can be considered an outpost or space station mission that could provide multiple opportunities for human interaction with the spacecraft or surface outpost that utilizes the nuclear reactor; or
- whether maintenance and repair activities could be considered for the nuclear reactor.

The expected power range for these general mission categories is included in Table 1-1. Due to the large amounts of power needed for electric propulsion, it is expected that the reactor power needs for these missions may be in excess of 1 MWe (megawatt electrical). Missions that utilize reactors for electrical power are potentially expected to demand lower power initially, but it is conceivable that some of these missions could require electrical power levels in excess of 100 kWe (kilowatt electrical), especially if *in situ* resource utilization applications are envisioned by mission planners. Mission length should also be a consideration when looking at the possible exposures of humans to the nuclear reactors on these missions. Some missions may only require electrical power or propulsion for relatively short periods of time or for only a limited number of opportunities.

Additionally, each of the applications for a space nuclear power or propulsion reactor needs to consider the possibilities of human interactions with the reactor after a postulated accident occurs. In these cases, it may be important to determine the extent and dimension of the distribution of released radioactive materials to enable the determination of the potential radiation doses that could be received by a spacecraft or outpost crew.

Table 1-1. General categories of space nuclear power and propulsion missions.

Mission Category	Brief General Description	Expected Power Range
NEP Transport Missions	Utilization of a nuclear reactor to produce and supply electrical power to electric propulsion technologies	Greater than 10 kWe
NTP Transport Missions	Utilization of a nuclear reactor to directly heat a propellant to provide a direct thermal propulsion capability	Greater than 100 MWt (megawatt-thermal)
INP for Electrical Power Missions	Utilization of a nuclear reactor to produce and supply electrical power for mission activities and housekeeping for an in-space or orbital mission	1 kWe to greater than 1 MWe
FSP for Electrical Power and Surface Outpost Missions	Utilization of a nuclear reactor to produce and supply electrical power for mission activities on the surface of a planet or other astronomical objects	1 kWe to greater than 1 MWe

This report covers many of the possible interactions between humans and space nuclear power and propulsion systems, but because there are no firm missions defined at this point that could utilize a nuclear reactor, it is impossible to cover all of the possible missions and applications for space nuclear power and propulsion that mission planners can envision. The issues and concerns for the different types of missions envisioned for nuclear reactors in space applications are discussed along with the potential efforts that can be made to reduce the possibilities for radiation exposure to humans for the different types of missions. Hopefully, this report captures the majority of expected missions into the near future.

Numerous operational factors must be considered during the design of both the nuclear power and propulsion system and any mission that could utilize these sources. These include dealing with radiation exposure to both humans and equipment; how the radiation exposure limits are established; managing how spacecraft could approach both the reactors on board or on site as well as the spacecraft themselves; handling the maintenance of the reactors, their power conversion systems, and their heat rejection systems; and designing the reactor controls and health monitoring systems to enable efficient and reliable reactor setup, startup and operation. Additional aspects to be addressed include consideration of the possible reactor accident scenarios, radioactive material transport, and potential accident consequences. Long-term planetary impacts and the development of particular planetary protection schemes for reactor operation, shutdown, decommissioning, and disposal must be considered. These will be discussed in the following sections of this report.

It has been recognized for decades that both humans and the equipment associated with space exploration and travel will be affected by the natural radiation fields in space, and by any radiation sources that might be carried aboard a spacecraft or included in a surface outpost operation, such as fission power and propulsion systems. The natural radiation fields in space come from various sources including the high energy charged primary particles of galactic cosmic rays and solar particle events (SPE) as well as any secondary protons and neutrons generated from interactions of these cosmic rays and particles with spacecraft materials.

Over the years, NASA has performed research and developed a set of radiation exposure standards for their astronauts, and it is likely that these will continue to be applied to future space missions including fission power and propulsion sources.[3] As electronic equipment for both experimental payloads and system controls have been developed they also have been tested against the radiation fields that they were likely to see and standards have been developed for radiation exposure for these sensitive instruments and equipment.[4] In general, however, the humans associated with space flight are much more sensitive to radiation exposure than the equipment required for space flight. Designs of fission power and propulsion systems have all included shielding to protect humans and equipment that might be planned for a mission.

1.1 Missions and Applications for Nuclear Fission Technologies

There are a variety of missions and applications that can be conceived that could utilize the four general fission reactor power and propulsion types. The next, earliest missions to utilize fission power are likely to be robotic science missions on the lunar surface where the fission reactor is used to provide electrical power to operate the lander and/or the scientific package. In the past, Earth-orbiting missions were the primary utilization of fission power (Russian Radar Ocean Reconnaissance Satellites (RORSATs) and Systems for Nuclear Auxiliary Power (SNAP) 10A from the U.S.). Another potential nearer-term mission could be a fission reactor to provide electrical power for a demonstration mission with electric propulsion thrusters. Later-mission planners could utilize more advanced NEP or NTP reactors to provide propulsion to Mars or the outer planets or FSP reactors to provide surface power for long-duration crewed outposts on the Moon or Mars that include *in situ* resource utilization (ISRU).

To date, all applications of nuclear reactors on space missions have been for robotic applications where the reactors have been operated remotely from the ground/Earth and in near Earth orbit. These all have involved pretty straightforward reactor manipulations such as reactor startup, shutdown, and power level manipulations to provide electricity for spacecraft and mission operation. All of the reactor manipulations, except for those safety operations required for the emergency shutdown of the reactors, have been accomplished directly by operators on the ground/Earth or by automatic, pre-programmed controllers.

Foreseeable future robotic missions can include all four types of reactor configurations: NEP, NTP, INP, or FSP. Similar reactor manipulations would be reasonably expected to those that have already been accomplished; however, as the missions expand beyond low Earth orbit (LEO), it can be expected that more autonomous control and operation could be necessary because of the lengthier communications time frames required to these more distant locations. In these applications, the mission, system, and reactor designers may need to be cognizant of the needs of these more complicated operations. Additionally, consideration may need to be given to the designation of a designated ground/Earth “reactor operator” and whether this responsibility could be assumed by the broader mission operations team.

Crewed missions utilizing nuclear fission power sources could likely focus on the need for relatively large amounts of power needed to provide power for life support and experimentation involved in sending humans into space. Long-term space flight, outpost, and mining missions are enabled by the availability of very large amounts of electrical power. Additionally, since minimizing the trip time to Mars and other Solar System locations is critical to reducing galactic cosmic radiation (GCR) exposures by the crew, the high specific impulse attainable by NEP and

NTP may enable shorter trip times and reduced radiation exposures, which is contrary to the expectation for missions that carry space nuclear power and propulsion systems with them.

The remainder of this section describes the important features of the four basic nuclear fission reactor types that are usually considered: NEP, NTP, INP and FSP.

1.1.1 Nuclear Electric Propulsion

NEP is largely expected to be reserved for the transport of people and/or materials on long missions to distant locations. These mission types are characterized by the low thrust, high specific impulse capability of NEP systems[5] and could include reactors in the high-power capacity class (greater than 1 MWe). Typically, these reactors would operate at steady state power levels near the reactor capacity limit for long periods of time during the transport phase of the mission.

NEP transport mission profiles, following launch and Earth orbit establishment, typically include an initial startup and testing period followed by one, or more, long and slow steady state acceleration phases for roughly the first half of the transport trajectory followed by a long and slow steady state deceleration phase for roughly the second half of the transport trajectory as the spacecraft comes closer to reaching its objective. The reactors could then be placed in standby/shutdown mode or operated at close to zero power or low power for spacecraft maintenance applications while waiting for the next transport mission phase to begin. This mission pattern could be repeated.

It is often thought that NEP missions could be best utilized where multiple round trips from Earth orbit could be possible since the reactor’s useable lifetime could greatly exceed the time line for a single out-and-back trip. Multiple supply trips to the moon, Mars, and the outer planets are all possible for consideration using NEP. It is conceivable that NEP reactors could operate at steady-state power levels for extended periods of time from weeks to months or even years, depending upon the distance to be traveled, the power levels of the reactors and the capabilities of the electric propulsion engines. Crewed missions with NEP systems may require highly capable control systems and algorithms enabling largely autonomous reactor operation and control.

Transport spacecraft utilizing NEP could include multiple reactors to extend the mission’s power management capabilities and to enhance mission reliability. Issues that mission and reactor designers utilizing multiple reactors on a single spacecraft must assess could include spacecraft control and balance, autonomous or remote reactor control, health and lifetime monitoring, access to the various important spacecraft locations, the three-dimensional (3D) radiation fields that would be generated by multiple reactors, and more. Positive aspects of including more than one independent reactor system on NEP spacecraft may include an increase in the overall system reliability and safety that could be provided by utilizing independent and redundant reactor systems enabling a higher level of assurance for critical missions.

Issues that reactor and mission designers may need to assess and manage are likely to include multiple restarts and shutdowns of the reactor system, long dormancy or low power operation, long term steady state operation and reactor control, managing or avoiding return approaches to LEO in order to minimize the possibilities that the NEP reactors could reenter Earth’s atmosphere, management of multiple reactors, and the decommissioning and long-term disposition of the reactor systems.

1.1.2 Nuclear Thermal Propulsion

NTP is largely expected to be reserved for the transport of people and/or materials on long missions to distant locations. These reactors are characterized by the engines' high thrust, high specific impulse[6], and could include reactors in the high-power capacity class (greater than 100 MWt). The typical operation of an NTP engine could be for short periods of time (minutes to hours) at full capacity during the transport part of the mission. NTP transport mission profiles typically could include a short, high-acceleration ballistic phase at the beginning of the first half of the transport trajectory followed by a long coast towards the spacecraft's objective. As the spacecraft approaches its objective a short reverse, or deceleration phase could be used to bring the spacecraft into the vicinity and/or orbit around its objective. The reactors could then be placed in standby or maintenance mode until the end of the time at the objective and then the reactor could operate again in a pulse mode to return the spacecraft to Earth orbit. It is likely that early spacecraft adopting nuclear thermal propulsion could include multiple reactors for propulsion mode, with appropriate design and control coordination systems.

The possible missions for NTP likely will include both crewed and robotic supply missions. These could include single and multiple return/supply trips to the moon, Mars, and the outer planets. Such missions could enable the transport of considerable quantities of materials and people to distant locations throughout the Solar System. If these missions were to include humans, then there could be significant possible interactions between these reactors that could be considered during the mission and reactor designs.

Various issues may challenge mission and reactor designers utilizing NTP systems. These include the use of a single NTP engine versus multiple engines to increase reliability; approach to other crewed systems to minimize radiation exposures from the NTP systems; robotic versus crewed utilization of NTP systems; managing multiple startup, shutdown, and dormancy cycles (especially if the NTP system is used in a "space tug or bus" mode to transport crews, equipment and supplies to remote outposts); and those related to return approaches to LEO in order to minimize or avoid the possibilities that the NTP reactors could reenter Earth's atmosphere. Additionally, the decommissioning and long-term disposal of NTP systems needs to be carefully considered.

1.1.3 In-Space Nuclear Power

The INP generic fission reactor application type includes both free-space applications and orbital applications around planets or their moons. To date, all fission reactor applications of nuclear power in space have been on single, one-time missions in Earth orbit to test, demonstrate, or provide electrical power for a particular mission. These include both U.S. (1 reactor: SNAP-10A, on a technology demonstration mission[7]) and USSR (31 reactors in RORSATs[8]) applications. This generic class of mission applications could also include providing electrical power for a spacecraft orbiting another planet, or one of its moons, an outer planet flyby mission (such as the Voyager missions that were initiated in the 1970s)[9], or the recent Pluto New Horizons spacecraft[10].

Notionally, an ISP configuration could include a single reactor with a shadow shield and power conversion system separated from the science or mission platform by a boom or tether. The boom or tether could provide the necessary separation distance to protect the payload or crew from excessive radiation exposure and could be designed to meet the mission radiation exposure guidelines for the particular mission and payload. The system configuration could also include multiple individual reactors—including their shadow shielding and payload offsets. Such multiple reactor configurations could require significant design considerations to manage the collective radiation fields resulting from the individual reactors.

The considerations for INP systems include those already discussed for NEP and NTP systems, including startup, shutdown, and power-level changes. Since these systems could be used in Earth orbit, special consideration is needed to address reactor decommissioning and orbit management to minimize the possibility of the hot reactor system from reentering the Earth's atmosphere. These issues should not be considered to be important for INP systems that would be on interplanetary missions.

1.1.4 Fission Surface Power

FSP reactor systems could generically supply electrical power for a mission on the surface of a planet or moon.[11,12] It could also supply thermal energy or heat to accomplish mission tasks and objectives. There are various configurations that might be possible for FSP operations including, but certainly not limited to a single reactor, multiple reactors, reactors residing directly on a lander, a reactor on a mobile platform, reactors partially or fully buried under the surface of a planet or moon, and reactors placed within an existing crater or surrounded by piled up surface material to provide *in situ* radiation shielding.

Missions for FSP reactors could include providing electrical power for landers, surface robots, crewed transport vehicles, mining and mineral extraction facilities, habitats, exploration, and other surface activities. The reactors themselves are likely to be fixed at a point on the surface from where they provide power to other surface assets; however, it might also be possible to include a small electrical power reactor on a movable utility cart. Reactor operational aspects could include mechanical deployment, reactor startup, long steady state power operation, power level changes, both upward as well as downward, both normal and emergency shutdown, reactor restart, maneuvers to cold shutdown, hot shutdown and many others. Consideration must also be given to extended dormancy periods and reactor restart after long pauses in operation.

Special design considerations appropriate for FSP reactors include the necessity to separate the reactor from a human-tended outpost or lander, providing sufficient radiation shielding to protect equipment and personnel, providing sufficient heat dissipation during the surface day-night cycle, and provisions for final disposition. FSP reactors might also enable planning to allow for limited maintenance to enable long-term operations. One particular aspect on some planetary surfaces could be considerations for managing wind-blown dust on heat rejection radiator surfaces. Cleaning and other regular maintenance activities might be possible for some reactor applications, but they must be considered during the system design phase. Another consideration for some FSP reactor applications might include interactions with the local atmosphere, including water and other vapor ice formation. Reactors may be designed to allow for significant capabilities for load following and autonomous control and operation. The Kilopower program recently demonstrated[13] self-regulation and load-following for the 1-kWe version of Kilopower in the KRUSTY (Kilopower Reactor Using Stirling TechnologY) test.

Human occupied outposts on the surface of the Moon, Mars or other Solar System bodies may demand high-power, long-duration operations and high reliability, especially if the crew must depend on *in situ* resource utilization for survival. Meeting these demands with one or more FSP systems can be the most effective means of delivering reliable power for surface outpost operations, *in situ* resource utilization, local propellant production, and life-support.

Once a surface outpost is established it is also likely that the outpost could be in operation for many years. Multiple FSP systems could be used to provide redundant power sources to enable highly reliable long-term operation. Operating an outpost with multiple reactors may require on-site reactor operations personnel or automated control as the communication delays with Earth may preclude efficient operations without local outpost control.

The electrical power needs of outpost missions have been extensively studied previously. Generically, NASA/TM—2005-213600[14] described the needs as follows:

> *"For the exploration missions, power production requirements can range from milliwatts for some robotic exploration components, to watts for human-portable energy storage devices, to kilowatts for surface mobility, to hundreds of kilowatts for surface habitats and operations, and up to multi-megawatts for Nuclear Electric Propulsion (NEP) dependent architectures. Other advanced power requirements will include low specific mass power production, high capacity/low mass energy storage, advanced materials and components, and flexible and intelligent power management. Advanced power systems must also address operational environment issues for space and surface applications."*

Many studies have been performed to estimate the power requirements for surface outposts and outposts on the moon and Mars. A generic FSP mission is expected to deliver power to stationary equipment (e.g., habitats), mobile equipment (e.g., rechargeable rovers), and deployed equipment (e.g., remote ISRU plants or science stations). A typical initial Mars surface mission indicated that a maximum capacity of approximately 34 kWe is needed throughout the various stages of the mission that includes a 500-day stay for six crew members, or about 6 kWe per crew member[15]. In the far term, Mars surface outposts that could be permanently inhabited may require as much as 90 kWe per occupant for an early stage outpost of around 12 people[16]. The economy of scale for larger outposts is expected to reduce the power capacity needed. An entirely solar powered Mars outpost has also been estimated to require approximately 45 kWe per occupant for an intermediate sized outpost of 150 people with the electrical power capacity required dropping to 20 kWe per occupant for more advanced projects.

2.0 Radiation Exposure Considerations

One of the responsibilities of the mission and reactor designers, as well as the mission operations team, will be to keep both human and equipment acceptably below the radiation exposure limits for humans and equipment. Consideration may need to be given to the possible pathways through which humans and equipment could be exposed to radiation and radioactive material during transit, operation, shutdown, and disposal operations.

2.1 Radiation Exposure Limits

It has been recognized for decades that both humans and the equipment associated with space exploration and travel will be affected by the natural radiation fields in space, and by any radiation sources that might be carried aboard a spacecraft or included in an outpost operation, such as fission power and propulsion systems. The natural radiation fields in space come from various sources including the high-energy charged primary particles of galactic cosmic rays and SPE as well as any secondary protons and neutrons generated from interactions of these cosmic rays and particles with spacecraft materials.

Over the years NASA has performed research and developed a set of radiation exposure standards for their astronauts, and it is likely that these may continue to be applied to future space missions including fission power and propulsion sources. As electronic equipment for both experimental payloads and system control have been developed they also have been tested against the radiation fields that they were likely to see and standards have been developed for radiation exposure for these sensitive instruments and equipment. In general, however, humans are much more sensitive to radiation exposure than the equipment required for space flight. Designs of fission power and propulsion systems have all included shielding to protect humans and equipment that might be planned for a mission.

2.1.1 Human Radiation Exposure Limits

The radiation exposures received by astronauts as they participate in the missions might come from a variety of sources, including GCR, solar flares, *in situ* natural radioactive materials inherent to the landing zones, and any manmade reactors or radioisotope heaters or electric generators that may be sent along on the crew's mission.

The dominant naturally occurring radiation in a spacecraft will include high-energy protons, helium ions, heavier ions, neutrons, and gamma rays. The composition and magnitude of these various radiations interacting with a spacecraft crew will be highly dependent upon a variety of factors including location (in space vs. at a landing site), the materials that make up the spacecraft, the local magnetic and electric fields, the amount and kinds of shielding materials used to protect the crew, and more.

Over the years, NASA has enlisted the National Council on Radiation Protection & Measurements (NCRP) to help understand the impact of the natural radiation sources in space on astronauts.[17] The NCRP has issued numerous reports on the nature of the radiation fields, radiation protection guidelines for astronauts, standards and ethics principles for long duration space flight, and others.

NASA also maintains a Space Radiation Analysis Group (SRAG) at Johnson Space Center (JSC). According to the Group's website[18] (https://srag.jsc.nasa.gov):

> *"Space Radiation Analysis Group (SRAG) at the Johnson Space Center is responsible for ensuring that the radiation exposure received by astronauts remains below established safety limits. To fulfill this responsibility, the group provides:*
>
> - *Radiological support during missions.*
> - *Pre-flight and extra-vehicular activity (EVA) crew exposure projections.*
> - *Evaluation of radiological safety with respect to exposure to isotopes and radiation producing equipment carried on the spacecraft.*
> - *Comprehensive crew exposure modeling capability.*
> - *Radiation instruments to characterize and quantify the radiation environment inside and outside the spacecraft."*

Additionally, NASA maintains an important two-volume Space Flight Technical Standard titled "NASA Space Flight Human-System Standard Volume 1: Crew Health"[19], NASA-STD-3001, Volume 1 and "NASA Space Flight Human-System Standard Volume 2: Human Factors, Habitibility, and Environmental Health",[20] NASA-STD-3001, Volume 2 that detail "NASA's policy is to establish requirements for providing a healthy and safe environment for crewmembers", including radiation protection.

Specifically, Section 4.2.10 of this standard delineates the "Space Permissible Exposure Limit for Space Flight Radiation Exposure Standard." The basis for the standard is related to the planned career exposure for any astronaut that "shall not exceed 3 percent Risk of Exposure-Induced Death (REID) for cancer mortality at a 95-percent confidence level to limit the cumulative effective dose (in units of Sievert (Sv)) received by an astronaut throughout his or her career." The resulting dose limits depend upon the mission's length, astronaut's age, sex, and other considerations. For example, the effective dose limit for a 1-year mission for a never-smoking, 40- to 60-year-old male astronaut would range from 0.88 Sv to 1.17 Sv. The effective dose limit for similarly aged female astronauts would be approximately 20 percent lower. The Standard also includes non-cancer radiation exposure limits, which are expressed in terms of dose and dose equivalent through two tables (Tables 2-1 and 2-2) contained within the standard.

Table 2-1. Dose limits for short-term or career non-cancer effects (in mGy-Eq. or mGy). Directly from NASA-STD-3001, Volume 1, page 22[19,20].

Organ	**30-day limit**	**1-Year Limit**	**Career**
Lens*	1,000 mGy-Eq (milligray-equivalent)	2,000 mGy-Eq	4,000 mGy-Eq
Skin	1,500	3,000	6,000
BFO	250	500	Not applicable
Circulatory System**	250	500	1000
CNS***	500 mGy	1,000 mGy	1,500 mGy
CNS*** **($Z \geq 10$)**	-	100 mGy	250 mGy

Note: RBEs for specific risks are distinct as described in Table 2.

[*] Lens limits are intended to prevent early (<5 yr) severe cataracts, e.g., from a solar particle event. An additional cataract risk exists at lower doses from cosmic rays for sub-clinical cataracts, which may progress to severe types after long latency (>5 yr) and are not preventable by existing mitigation measures; however, they are deemed an acceptable risk to the program.

[**] Circulatory system doses calculated as average over heart muscle and adjacent arteries.

[***] CNS limits should be calculated at the hippocampus.

Table 2-2. RBE for non-cancer effects[a] of the lens, skin, BFO, and circulatory systems[19,20].

Radiation Type	**Recommended RBE[b]**	**Range**
1 to 5 MeV neutrons	6.0	(4-8)
5 to 50 MeV neutrons	3.5	(2-5)
Heavy ions	2.5[c]	(1-4)
Proton > 2 MeV	1.5	-

[a] RBE values for late deterministic effects are higher than for early effects in some tissues and are influenced by the doses used to determine the RBE.

[b] There are not sufficient data on which to base RBE values for early or late effects by neutrons of energies <1 MeV (mega electron-volt) or greater than about 25 MeV.

[c] There are few data for the tissue effects of ions with a $Z > 18$, but the RBE values for iron ions ($Z = 26$) are comparable to those of argon ($Z = 18$). One possible exception is cataract of the lens of the eye because high RBE values for cataracts in mice have been reported.

As taken directly from the standard [which references NCRP Report 132[21]] Table 2-1 defines the organ dose limits for both short-term (30-day and 1-year) and career non-cancer radiation effects. Table 2-2 contains Relative Biological Effectiveness (RBE) values for non-cancer radiation effects for the lens, skin, Blood Forming Organs (BFOs) and circulatory systems. While the Gray Equivalent quantity is used to limit these non-cancer effects in Table 1, the RBE for the Central Nervous System (CNS) non-cancer effects is largely unknown and, therefore, a physical dose limit (mGy) is used, with an additional Permissible Exposure Limit (PEL) requirement for particles with charge Z > 10 (Table 2-1).

The objective of NCRP Report 132 is to: "(1) examine the new information about radiation environments in space, especially the radiation environment within vehicles in low-earth orbit (LEO), (2) to assess the risks to both women and men of various ages exposed to radiation in the light of the current risk estimates of excess cancer and other radiation effects, and (3) update the radiation protection recommendations given in NCRP Report No. 98[22]."

Additionally, the NASA standard (specifically NASA-STD-3001, Volume 1 Appendix F9) addresses and defines the rationale for setting total dose limits for astronauts. This is accomplished by establishing Space-Permissible Exposure Limits (SPEL) and the Cancer Risk-to-Dose Relationship for astronauts. According to the standard,

> *"SPEL for radiation have the primary functions of preventing in-flight risks that jeopardize mission success and of limiting chronic risks to acceptable levels based on legal, ethical or moral, and financial considerations. Both short-term and career exposure limits are applied using assessments of the uncertainties in projection models with the space radiation environment defined by the program. Uncertainties are related to gaps in knowledge of biological effects of GCR, heavy ions, and the nature of SPEs. Although specific exposure limits are identified based on mortality risk, in all cases, decisions concerning vehicle, habitat, and mission design are made such that resulting crew radiation exposures are As Low As Reasonably Achievable (ALARA). As an operating practice, ALARA is a recognized NASA requirement. However, at the current time, the large uncertainties in GCR risk projections prevent an effective ALARA strategy for shielding approaches to be developed. For Solar Particle Events (SPEs), uncertainties are smaller, acute risks are a concern, and ALARA is possible."*

The standard also recognizes that the "relationship between radiation exposure and risk is age- and sex-specific related to latency effects and differences in tissue types, sensitivities, and life-spans between sexes" and utilizes a 95th percentile confidence level approach when considering the uncertainties in risk projections when applied to the values.

Finally, it is important to note that there are many missions that are envisioned which may result in significant radiation doses to astronauts. Some of these doses may challenge or even exceed the limits discussed above, especially at the 95th percentile confidence level. Management approval of such missions and acceptance of increased risk should occur early in the mission and reactor design processes.

2.1.2 Equipment, Payload and Instrument Radiation Exposure Limits

The situation regarding radiation exposure limits to any equipment, payloads, or instruments is much more diffuse and likely will be driven mostly by mission requirements and exposure to GCR and other naturally occurring space radiation rather than by exposure to radiation coming from a space nuclear reactor, except for instrumentation required to operate and control the reactors themselves. In these cases, any equipment or instrumentation required for reactor control and operation will be specifically evaluated for that particular use and placed within the shadow shield of the reactor.

In all likelihood, the equipment and instruments that may be most susceptible to radiation damage and upset will be electronic components. While electronic components are considerably more resistant to radiation than human tissues, they can be vulnerable to radiation damage and failure. There have been significant efforts made to enhance the operability of electronic components over the years, especially for exposure to GCR and other naturally occurring radiation in space.

Because of the importance of understanding the effects of radiation on electronics and photonics, NASA maintains a Radiation Effects and Analysis Group (REAG) at Goddard Space Flight Center[23]. The REAG website (https://radhome.gsfc.nasa.gov) includes a wealth of up-to-date testing and research data on all types of electronic and photonic hardware relevant to space flight activities. The reader is referred to this extraordinarily complete and comprehensive set of reports on testing and analysis investigations related to radiation damage and its effects on electronic and photonic devices as well as the techniques and research on hardening these devices.

2.2 Potential Human and Equipment Radiation Exposure Pathways

Each particular utilization of space fission power may bring its own specific potential ways to expose humans and equipment to the radiation coming from the reactor. This section discusses the general pathways for human and equipment radiation exposure from NTP, NEP, INP and FSP systems. Clearly, as particular missions and utilizations of space fission power are envisioned, much more specific detail can be applied to those spacecraft and outpost designs.

The primary and most expected radiation path for radiation exposure from a space fission power reactor would come from the direct shine of neutrons, betas, and photons coming from the reactor during operation. All of these come directly or indirectly from the fission processes themselves and can be readily shielded to reduce the exposures to manageable levels. This is a standard part of the design process for any space fission power platform.

A secondary pathway for radiation exposure during reactor operation comes from the scattered neutrons and gamma rays that originate in the core. Scattering can occur off of any material that sees either a direct or a shielded path to the reactor core. Examples include neutrons and photons that would be scattered outside of the reactor's protective shadow off of a heat rejection radiator or other structures for an ISP, NEP or NTP system or off of the ground surrounding an FSP system. The level of radiation exposure from scattered radiation could be significantly less than the unscattered radiation emanating directly from the reactor core, but could still be a significant contributor to an astronaut's radiation dose.

Neutrons from the reactor core can interact with many materials and cause the formation of radioactive activation products. When these activation products decay, their radiations, predominantly gamma and beta rays, can be transported to the locations where they could cause an increase in the human radiation dose. Anything that can see these neutrons can become activated and become a potential secondary radiation source of primarily gamma rays. With neutron exposure, these components, including the soil surrounding the reactor, the reactor's shield, reflectors, and even equipment behind the reactor's shadow shield, all become increasingly radioactive over time. This buildup of radioactive material will tend to saturate over time, depending upon the half-life of the specific radioactive materials being formed and the components will remain radioactive for some time (months and years) after the reactor is decommissioned.

After shutdown of the reactor, the materials in the core may remain radioactive for years to come, predominantly coming from the fission and activation products in the core. The radiation coming from these radioactive materials will typically be energetic gamma rays and beta particles. For these reasons, the core itself must remain shielded and largely inaccessible for many years after shutdown. However, with shielding, and depending upon the power level and length of time at power, it may be possible to approach the reactor system in less time. Thus, it will be important to estimate the radiation fields surrounding the reactor system from the time it initially achieves criticality until well after the reactor is finally shut down.

As with the radiation coming from the reactor core during operation, there will be scattered radiation from the system's equipment and radiators, predominantly gamma rays, to be concerned about during shutdown. The magnitude of this radiation field will be greatly reduced and is probably minimal, but may limit human approach near the shutdown reactor to provide maintenance or repairs.

Reactor accidents may open additional pathways to radiation exposure to both humans and equipment. Reasonable consideration will need to be given to the possible accident scenarios and mechanisms, the driving forces and available distribution energies for radioactive materials and material transport phenomena. Determination of the magnitude of the possible radioactive material releases and how might they impact access, rescue, cleanup, and disposal may all be important considerations for determining the possible radiation exposure to crew and equipment from reactor accidents.

2.3 Means to Minimize Crew Exposures

The primary means to minimize crew radiation exposures are the same as those for terrestrial reactors: time, distance, and shielding. Techniques to identify and declare high-radiation areas, severely restricting access time to these areas, separating any highly radioactive materials from crew access, and establishing decontamination areas may all need to be used on spacecraft, as well as placing shielding materials between the sources and the areas that will require access. Because of the importance of understanding the radiation fields surrounding all space reactors, mapping the likely radiation fields surrounding operating space fission reactor designs, whether they be for NTP, NEP, ISP or FSP, has typically been a part of the design considerations for all past reactor designs. As each planned usage of a nuclear reactor will likely be different from other applications, a detailed analysis of the radiation fields will need to be performed for each mission proposing to use any fission power or propulsion platform.

Ultimately, the combination of the reactor design, radiation field design, mission design, and operational practices design may result in a very complex optimization problem with mission design objectives strongly bounded by standards, regulations, safety, and management constraints. In other words, the inclusion of one or more nuclear reactors on a particular mission might result in more radiation coming from the reactors, but a significant reduction in the total radiation exposures to the astronauts resulting from the reduced travel times and radiation exposures coming from the other cosmic and galactic radiation sources. Reactors can be enabling or enhancing to many missions while also reducing the radiation exposure to astronauts on those missions.

2.4 Provisioning for Crew Radiation Exposures

As radiation exposure could be a concern under normal and accident conditions on a spacecraft whether or not it includes a nuclear reactor, astronauts will need to be provided and trained in the use of advanced radiation dosimetry. In the event that one or more crew members receive a radiation exposure in excess of the human exposure limits from GCR, SPE, radioisotope, or reactor systems, the operational spacecraft and crew must have been provisioned and trained to be able to respond and treat radiation exposure patients. Radiation exposures up to and including those required to cause Acute Radiation Syndrome (ARS) are possible under emergency and accident conditions.[24] As the symptoms of ARS can be quite devastating, system design and mission provisioning should include the management of the consequences of ARS for potentially everyone on the crew. Potential treatment methods include symptom and pain management, the administration of antibiotics, blood products, and stem cell transplants. Unfortunately, given the current state of medical advances, the last two methods require major equipment, techniques, and facilities and thus it is unlikely that the full range of ARS treatment options will be available to astronaut crews, except for those individuals who suffered the lowest of radiation exposures.

3.0 Managing Approach to Spacecraft and Reactors

One special design consideration for space reactors may be accessibility to the cargo or outpost area while avoiding any high-radiation areas. Each space reactor configuration will be designed to provide sufficient shadow shielding in order to protect their human habitation areas or equipment and payload areas. Putting multiple reactors on either a space platform or on a surface outpost may require radiation field challenges to be addressed by the designers.

There may be many reasons to approach a spacecraft containing a fission reactor or a surface power system, including cargo or personnel transfer, maintenance, or other operations near the reactor. One special design consideration for space reactors may be managing the radiation fields such that necessary approaches and operations may be carried out safely. Separate consideration may be necessary for personnel and equipment.

3.1 Three-Dimensional Radiation Mapping and Control

For surface fission power, radiation control for an approach to the reactor is largely two-dimensional (2D). The control will become more 3D close-in to the reactor and will need to allow for radiation scattering. For operations in space near a fission reactor, whether a docking or extra-vehicular activity (EVA), radiation control is 3D. In order to plan and manage activities near a reactor, mapping of radiation fields is warranted. Mapping may allow establishment of appropriate exclusion and hazard zones as well as managing necessary activities near the reactors. Initial planning and mapping may be done with models and analyses, but measurements are recommended for validating the expected radiation fields. Measurements can discover damage to shielding or unanticipated scattering paths.

Fission reactor radiation fields should be mapped for different radiation types relevant to personnel and equipment, primarily neutron and gamma radiation. If there is any potential for contamination that could adhere to equipment or space suits, additional planning and precautions may be necessary. If equipment is to be placed in a significant neutron flux, then activation of materials contained in the equipment must be considered. Before undertaking actual operations, radiation maps should be updated to account for changes to physical configurations, activation products, and contaminated areas. During an operation, dosimetry should be employed to verify the anticipated radiation fields and implement appropriate radiation worker protection.

3.2 Docking Avenues

Docking operations may occur to transfer cargo or personnel to/from the spacecraft containing one or more fission reactors. If the on-board reactors are cold, then there is little hazard to either personnel or equipment. If the reactors are hot, then operations need to be controlled to avoid direct shine once the docking spacecraft comes into close range. Most designs separate the reactor from the rest of the spacecraft using a long boom. Then, shadow shielding is provided on one side to protect the spacecraft, thus yielding a safe cone shape that envelops the spacecraft. The shadow shield may need to be enlarged to accommodate docking spacecraft within the safe cone. Docking spacecraft may need to approach within the safe cone, except perhaps for very brief periods or at long distances. For example, the docking port might be located at the far end of the spacecraft away from the reactor.

Docking spacecraft may need to be designed to tolerate the radiation fields that may still exist within the safe cone. If the reactor is shut down prior to docking, the radiation fields will be greatly reduced, depending on how long the reactor has been shut down. Robotic docking spacecraft are likely to be able to tolerate much higher radiation levels than crewed spacecraft. In any case the shield design, docking spacecraft design, location of docking ports, and physical approach profile need to all be developed with radiation fields in mind if a hot reactor is present. The commonly used ALARA (As Low As (is) Reasonably Achievable) principle is appropriate for developing docking strategies that minimize radiation exposure from on-board reactors.[25]

3.3 EVA Approach to Space Reactors

For the most part, space reactors for on-board power or propulsion should be designed to avoid the need for maintenance or other activities near the reactor. Should the need for such an EVA occur, then the ALARA principle applies. Much as for a docking operation, astronauts need to remain within the safe cone and at a maximum possible distance from the reactor. EVA considerations should factor into selecting the radius of the shadow shield. The reactor should be shut down as long as possible before the EVA. As with any EVA, planning to simplify the procedures and minimize the exposure time is important. NASA’s Human Integration Design Handbook[26] provides guidance on design of EVA translation paths and the need to avoid exposing astronauts to unnecessary hazards. Radiation needs to be included along with other hazards that could adversely impact the astronauts. Physical constraints that prevent movement into high radiation zones should be considered, e.g., limits to tether length. Radiation should be continuously monitored during the EVA. Precautions should be taken to make sure that no contamination is transported back inside the spacecraft. These precautions may include procedures for decontamination.

3.4 Approach to Surface Power Reactors

Surface power systems should be developed to minimize or avoid the need to approach the reactors. Should the need arise, then ALARA principles apply. The reactor should be shut down as long as possible prior to the approach. If maintenance or repairs are anticipated, then the subject components should be designed and located to facilitate access with minimal radiation exposure, e.g., outside the primary shielding. Robotic maintenance may also minimize the need for personnel exposure. Based on prior radiation mapping and surveying, paths of ingress and egress can be determined. Portable shielding or even mounding of surface materials can be employed if necessary. As with EVAs, dosimetry and radiation monitoring are important, and caution should be taken to avoid transporting contaminated materials back to the habitat area.

3.5 Multiple Reactors

If multiple hot reactors are present on a spacecraft, then the shielding becomes more complex. There may be multiple shadow shields, or one larger shield, that must account for both direct shine and scattering. Any EVAs or docking approaches must account for the combined effects. Generally, it would be expected that multiple reactors might all reside on the same side of the spacecraft so that the docking and EVA activities could be managed in a manner similar to spacecraft with a single reactor, i.e., within a designed safety cone.

For reactors on a surface, the exclusion/hazard zones need to be defined to consider the combined effects. There may be cases where it is necessary to approach a surface reactor for maintenance or other activities in the area. If the multiple reactors are collocated, it may be necessary to shut all of them down if problems occur, as opposed to just the single reactor that needs attention. Thus, it is advisable to provide separation among the reactors, although this may lead to larger exclusion areas and additional cables. Because maintenance operations are temporary, separation distances can be much less than between the reactors and a habitat. Previous work has suggested separation distances between the reactors and a habitat of 500 m to 1 km, depending on the reactor power[14]. This separation distance keeps the dose rate at the habitat less than 3 mR/hr, which is much lower than required for temporary maintenance operations. If separation proves to be too expensive in terms of mass and operational penalties, then portable shielding can be employed.

In all cases with multiple reactors, approaches need to consider the real-time radiation fields, based on which reactors are operating, which ones are shut down (and for how long), and the potential vulnerability of personnel and equipment.

3.6 Design Considerations and Positive Controls

In general, the need to approach a hot reactor by either personnel or robotic systems should be minimized. As discussed in Section 4, the need for regular maintenance should be minimized or eliminated entirely. However, if the need arises to approach a reactor for docking or other activities, then the design should facilitate safe operations. Key factors to consider include:

- Minimize the time needed to carry out planned operations, e.g., simplify tools and procedures
- Physical controls and barriers to prevent inadvertent entry into a hot zone, e.g., restrict tether lengths during an EVA
- Means to construct temporary shielding using *in situ* materials
- Simple dosimetry and warning systems
- Establish safe paths for ingress and egress
- Create decontamination zones.

3.7 Radiation Monitoring

Despite careful design and planning, radiation fields may change over time. Reasons for changes can include:

- Changes in the operating characteristics of the reactor, e.g., power level and flux profile

- Buildup of activation products in surrounding structures and materials
- Changes or degradation in the shielding configuration
- Changes to surrounding structures influencing the scattered radiation

While such changes are likely to have a minor impact on radiation fields, they warrant the need for periodic radiation surveys to confirm the stability of the fields. If changes occur, then procedures and exclusion areas should be adapted appropriately. Radiation monitoring is a normal part of nuclear operations, and it is anticipated that radiation monitors will remain in place around reactors to provide warnings of possible problems. In addition, portable monitoring equipment and personnel dosimetry may be required whenever humans approach a reactor for maintenance or other purposes.

4.0 Managing Reactor Maintenance

Ideally, manual maintenance requirements for reactors and associated systems should be minimized. To date there have been no crewed space missions involving a nuclear reactor, and un-crewed missions have not allowed for maintenance. Manual maintenance activities may incur a number of risks to astronauts either in space or on a surface. There is increased potential for radiation exposure, along with the normal risks of astronauts performing activities outside a spacecraft or habitat.

The amount of maintenance required, if any, will be very design and mission specific. Both the reactor and the power conversion system, including heat rejection, must be considered. Small, simple designs with few moving parts, such as KiloPower tend to require less maintenance than a large reactor with a complex power conversion system. Similarly, un-crewed missions to deep space will likely not allow for significant maintenance of the reactor. In the discussions below, it is assumed that all components are properly designed for the loads and environments associated with launch and other phases of the particular mission. The focus here is on the nuclear aspects of operation and maintenance.

4.1 Maintenance Options for Reactor Systems

4.1.1 General Maintenance Considerations in Design for Human-Rated Systems

There will be a number of components in a fission reactor system that are not amenable to maintenance, either due to radiation levels or practical considerations. In some cases, this limitation can be addressed through redundancy and diversity of system components that mitigate single failures. According to NASA requirements for human ratings, systems should be single failure tolerant.[27] Certain items are excepted from this requirement:

> "a. Failure of primary structure, structural failure of pressure vessel walls, and structural failure of pressurized lines are exempted from the failure tolerance requirement provided the potentially catastrophic failures are controlled through a defined process in which approved standards and margins are implemented that account for the absence of failure tolerance.
>
> b. Other potentially catastrophic hazards that cannot be controlled using failure tolerance are exempted from the failure tolerance requirements with mandatory concurrence from the Technical Authorities and the Director, JSC (for crew risk acceptance) provided the hazards are controlled through a defined process in which

> approved standards and margins are implemented that account for the absence of failure tolerance."

Certain reactor system components, such as the fuel, reactor internals, and primary cooling system, are likely to be potential single failures and also not amenable to maintenance activities. Therefore, the quality control and design margins may be particularly important for these components.

For cases where maintenance is possible, it is important to distinguish between planned maintenance and capability for maintenance. The former is generally to be avoided, as the goal is to design systems requiring little or no intervention by astronauts during normal activity. On the other hand, the capability to perform maintenance when necessary is consistent with human rating requirements that the crew be able to intervene when necessary to execute the mission or prevent a catastrophic event.[27] As with most design issues, this may lead to trade-offs. Providing the capability for maintenance may add complexity to the design, e.g., by designing for access, and adds mass through the need for tools and spare parts. Additionally, specific system maintenance training and procedures would need to be developed and delivered in order to ensure that all maintenance and operations outcomes are maximized.

4.1.2 Fuel and Passive Reactor Core Components

Refueling or maintenance on reactor core components is unlikely to be feasible in any space mission due to radiation levels and inaccessibility. These components include core support structures, reactor vessels, internal piping, instrumentation, and other passive items in or near the reactor core. Sufficient fuel must be provided for the entire mission. The fuel itself must be designed to deal with the effects of nuclear operation—including swelling and cracking. For NTP systems, erosion of the fuel and cladding materials must also be considered. All materials in and around the reactor must be designed for anticipated radiation effects and thermal loads assuming that maintenance may not be possible. Instrumentation should provide sufficient redundancy to allow for failed sensors. The design should also allow for expected impacts of meteoroids.

4.1.3 Passive Components in the Primary Cooling System

Piping, vessels, and instrumentation associated with the primary loop of a reactor should be designed such that no maintenance is necessary. The design must allow for expected radiation levels, thermal loads and possible meteoroid strikes.

4.1.4 Active Components in the Reactor Core or Primary Cooling System

Active components can include reactivity control systems and various types of pumps and valves. Maintenance on the active neutron absorbing part of a control system, such as a control rod or drum, is unlikely to be practical. The reliability or redundancy of such components must be assured. Drive motors and pumps or valves outside the core region may be amenable to maintenance. In those cases, there may still be high radiation levels present, and risks to astronauts could be significant. Further, parts and tools must be available and safe procedures need to be developed. It is preferable to design with sufficient redundancy and reliability that maintenance may not be required on these components.

4.1.5 Power Conversion and Heat Rejection

This discussion applies to fission power and nuclear electric propulsion systems. There are many different designs for power conversion systems, from direct passive thermionic conversion to a variety of thermal cycles and engines. Designs with high reliability and redundancy may require less maintenance and are preferred. In some cases, components may be located in or near the reactor core, such as a heat pipe, and can be considered as primary system components discussed above. However, many components, including heat-rejection components, can be located at a significant distance from the reactor core, possibly allowing for maintenance.

4.2 Considerations for Different Types of Maintenance

Table 4.1 provides a high-level summary of maintenance possibilities for various missions. These possibilities are discussed further below.

Table 4.1. Maintenance possibilities by mission type.

	Reactor Core and Passive Reactor Components	Passive Primary System Components	Active Primary System Components	Power Conversion or Propulsion System
Deep Space (Un-crewed)	No	No	No	No
Orbital Missions (Un-crewed)	No	No	Unlikely, Possibly Robotic	Possible Robotic
Crewed Space Missions	No	No	Unlikely, Possibly Robotic or after delay	Possible
Surface Power (Robotic Missions)	No	No	Unlikely, Possible Robotic	Unlikely, Possible Robotic
Surface Power (Crewed Missions)	No	No	Possible after Delay	Possible

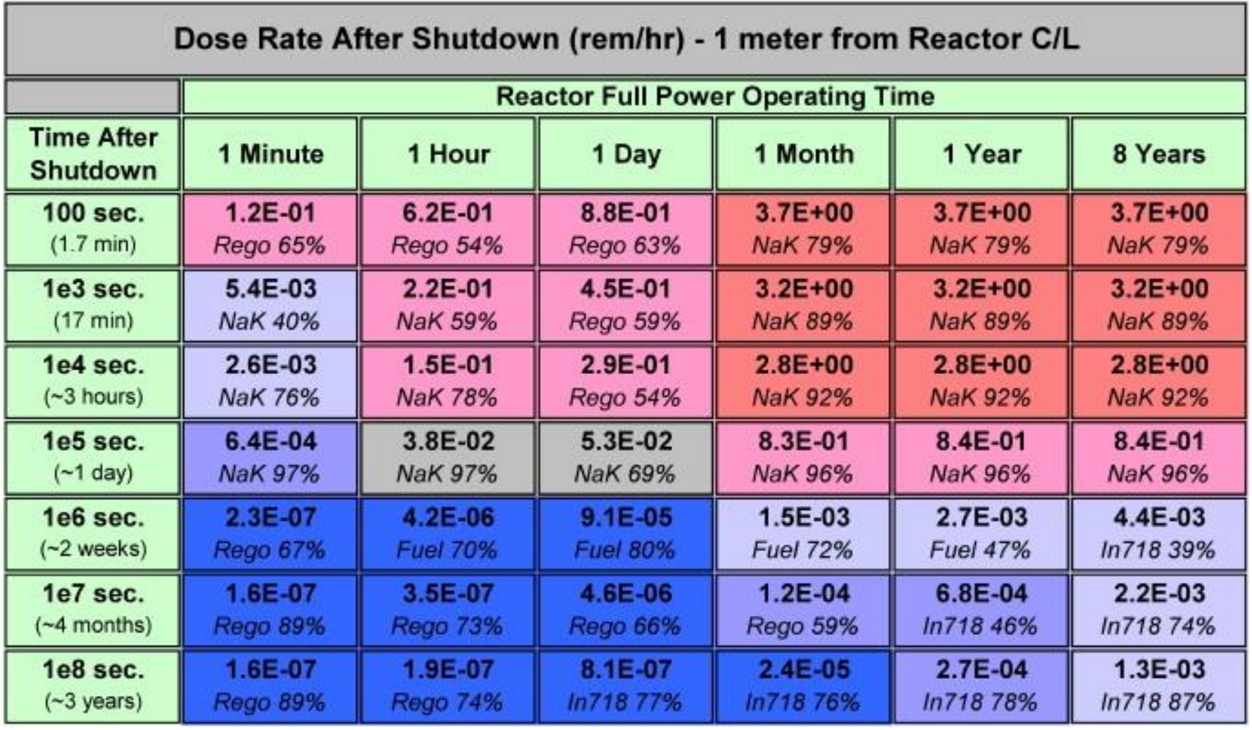
4.2.1 Robotic Maintenance

In theory, robotic maintenance could be performed for most missions. Robotic operations can be designed to withstand high-radiation environments, and eliminate risks involved in human activities. Remote operations performed by humans on a spacecraft or surface may be effective and reduce risks to astronauts associate with high radiation and space environments. Robotic capabilities can be sent with the mission at a cost of additional mass in robotics and spare parts. For near Earth operations, robotic maintenance capability can be sent to a failed spacecraft—at considerable cost. In any case, the reactor and associated systems should be designed for minimum maintenance and for simple operations should any maintenance be required. Replacement of a plug-in sensor is an example of a potentially simple operation. Replacing pumps and valves may be difficult in any situation.

4.2.2 Maintenance Performed by Astronauts in Space

Maintenance needs by astronauts should be minimized in all cases, particularly in space. Section 3.3 discussed some of the issues surrounding EVAs and reactors. If maintenance is required, it should be as simple as possible and require minimum time outside the spacecraft. Normally, it is preferable to wait a significant time after reactor shutdown before beginning maintenance operations. If maintenance can be delayed for a few weeks, the radiation doses to the astronauts from the reactor may be greatly reduced, see Table 4.2.[22] If maintenance cannot be delayed, then shielding may be necessary for any maintenance operations. The astronauts can approach the reactor from behind the shadow shield that is likely to be between the reactor and spacecraft. Additional, temporary shielding may be needed to support maintenance operations, and time near the reactor needs to be minimized, by simplifying the operations as much as possible. Procedures and training could be needed to optimize the operations to achieve minimum times and doses.

Table 4.2. Dose rate versus time after shutdown for an example 40-kW space reactor.



Dose Rate After Shutdown (rem/hr) - 1 meter from Reactor C/L

	Reactor Full Power Operating Time					
Time After Shutdown	**1 Minute**	**1 Hour**	**1 Day**	**1 Month**	**1 Year**	**8 Years**
100 sec. (1.7 min)	**1.2E-01** *Rego 65%*	**6.2E-01** *Rego 54%*	**8.8E-01** *Rego 63%*	**3.7E+00** *NaK 79%*	**3.7E+00** *NaK 79%*	**3.7E+00** *NaK 79%*
1e3 sec. (17 min)	**5.4E-03** *NaK 40%*	**2.2E-01** *NaK 59%*	**4.5E-01** *Rego 59%*	**3.2E+00** *NaK 89%*	**3.2E+00** *NaK 89%*	**3.2E+00** *NaK 89%*
1e4 sec. (~3 hours)	**2.6E-03** *NaK 76%*	**1.5E-01** *NaK 78%*	**2.9E-01** *Rego 54%*	**2.8E+00** *NaK 92%*	**2.8E+00** *NaK 92%*	**2.8E+00** *NaK 92%*
1e5 sec. (~1 day)	**6.4E-04** *NaK 97%*	**3.8E-02** *NaK 97%*	**5.3E-02** *NaK 69%*	**8.3E-01** *NaK 96%*	**8.4E-01** *NaK 96%*	**8.4E-01** *NaK 96%*
1e6 sec. (~2 weeks)	**2.3E-07** *Rego 67%*	**4.2E-06** *Fuel 70%*	**9.1E-05** *Fuel 80%*	**1.5E-03** *Fuel 72%*	**2.7E-03** *Fuel 47%*	**4.4E-03** *In718 39%*
1e7 sec. (~4 months)	**1.6E-07** *Rego 89%*	**3.5E-07** *Rego 73%*	**4.6E-06** *Rego 66%*	**1.2E-04** *Rego 59%*	**6.8E-04** *In718 46%*	**2.2E-03** *In718 74%*
1e8 sec. (~3 years)	**1.6E-07** *Rego 89%*	**1.9E-07** *Rego 74%*	**8.1E-07** *In718 77%*	**2.4E-05** *In718 76%*	**2.7E-04** *In718 78%*	**1.3E-03** *In718 87%*

4.2.3 Maintenance Performed by Astronauts on a Surface

Maintenance on a surface, such as the Moon or Mars, may be necessary for long-duration missions. As noted previously, maintenance on the reactor itself should be avoided. Maintenance on the power conversion system may occasionally be necessary. On Mars, dust storms may occasionally require cleaning of radiators, which might be done manually or remotely. As with repairs in space, a key to astronaut safety is to allow time after shutdown before carrying out operations near the reactor. Providing redundancy through multiple reactors could allow time for the failed system to cool off prior to beginning maintenance. This requires that the individual reactors are far enough apart that the radiation field of the operating reactors does not affect the astronauts working on the failed reactor system. Even in this situation, maintenance needs should be minimized, as transporting spare parts to a distant planet is undesired, and the efforts associated with training and procedures may be significant.

5.0 Reactor Control and Health Monitoring

All space reactors require constant monitoring and control prior to launch and initial operation, during pre-startup testing, during the various phases of operation including startup, ascent to power operation, steady-state power operation, during changes in power level, through shutdown (both hot and cold) and restart, and during the final shutdown and management of the disposal of the reactor system. All of these various phases of operation require a robust instrumentation and control system to constantly monitor the health and viability of the reactor to deliver power when it is requested. Additional considerations with respect to reactor control and health monitoring include the necessary extent of the utilization of autonomous and/or remote control of a space reactor, a determination of the need for a continuously occupied and managed control room either on Earth or close to the reactor, and control of multiple reactors on a spacecraft, space station or surface outpost.

5.1 Initial Reactor Setup and Startup

As with terrestrial reactors, the initial setup and startup of any space reactor will entail detailed procedures and testing to ensure the smooth and sustainable operation of the system. There may be both mechanical and procedural activities during the initial setup and startup of the systems that would need to be developed. It must also be determined how much autonomous and robotic setup and control will be utilized and how much human interaction will be needed to start up the reactors. These decisions may necessarily need to be mission and design specific and cannot be made without a real system and mission to consider. Additional considerations may need to be given should multiple reactors be included on a spacecraft or on an orbital or surface outpost.

Additionally, the initial setup and startup of the various platforms may be different from each other, depending upon the application. NTP, NEP, ISP and FSP systems will likely differ dramatically in their reactor, heat rejection, shielding, and other systems thus requiring individual and particular procedures for setup and startup. For different designs, the time required for startup may vary significantly due to the need to manage the temperature transients throughout the system and ensure a stable ascent to power.

5.2 Impact of Multiple Reactors on Spacecraft and Surface Outposts

The inclusion of multiple reactors on a mission could increase mission reliability, redundancy, enhance defense-in-depth strategies, and enable mission capabilities that a single unit might not be able to match. However, multiple reactors might also add complexity and complications when operating those reactors. Some examples of possible complications include the need to account for 3D radiation fields from each of the reactor systems, enhancing the difficulty of accessing habitat areas due to enhanced radiation fields, and affecting the balance, control, and dynamical loading for spacecraft employing multiple NTP or NEP reactors for propulsion. If one of the goals of multiple reactors is increased redundancy, then care must be taken in the design to make the reactors as independent as possible, e.g., though separation of cables and control systems and other factors that impact independence of the systems.

5.3 Dynamic Operations and Restarts

In cases where fission reactors are used for propulsion or critical life-support functions, the ability to rapidly change power level or even restart following an unplanned shutdown may be important. Naval submarines have important experiences in these issues. The USS Thresher was lost, in part, because of an inability to rapidly restart the reactor following a SCRAM, something that was later remedied by the U.S. Navy.[28] Reactor restarts can be affected by the need to control temperature transients throughout the cooling and power conversion systems and by the buildup of fission products, such as Xenon-135, which act as neutron absorbers and hamper restart operations for certain reactor designs.

5.4 Impact of Long Shutdown Between Restarts

Some space nuclear fission systems might experience long times of shutdown or minimal maintenance power levels such as NTP or NEP reactors used in tug or bus operational modes.

FSP reactors might also experience long shutdown times as outposts or spacecraft sit dormant for periods of time. Each of these systems might face risks and uncertainties if a long shutdown is needed. Some of these risks include an inability of the reactor to be restarted when called upon, long times required for restart, limited power levels during start up and others. Each system would also need to be examined to determine if an extended cold shutdown is possible or reasonable or a determination could be made whether a particular reactor could be put into and maintained in a hot shutdown mode. Mission and reactor designers would need to establish the applicable parameters for long shutdown for each mission and reactor.

5.5 Impact of Autonomous Control and Health Monitoring

Autonomous control may be needed for some, if not all, space missions that use nuclear reactors. This would be an imperative for any robotic missions. There is little current experience with autonomous control of terrestrial nuclear reactors as these systems always have a dedicated control room and reactor operators that are close enough to the reactors so that any electronic time delays would be minimal. However, previous orbital missions have been managed from a distance in both U.S. and former Soviet Union reactor applications.

Careful consideration by mission and reactor designers might need to be given to managing time delays and other reactor control and monitoring actions. Designing autonomous reactor control into most space nuclear reactor systems will likely be required to minimize crew and ground support interactions with the reactors. Even missions using FSP reactors could benefit from effective autonomous control of their reactors as this might eliminate the need for a dedicated "reactor operating crew member."

There is limited experience with the design of specific development of autonomous control systems for space reactor applications. Various researchers over the years have identified some of the considerations related to both power and propulsion reactor systems and provide a good set of starting points for future development[29,30,31,32,33,34,35,36,37].

Additional questions will need to be considered by mission and reactor designers including

- Where does the value of completely autonomous system operation fit in?
- How would autonomous operation be utilized on piloted missions?
- What will be the ability of the crew to override autonomous controls?
- Is autonomous control absolutely essential?
- Would someone still need to be functionally the "reactor operator?"
- Could this be a part-time local task, or could the operations be entirely controlled from Earth, as if it were a purely robotic mission activity?
- How would a fully autonomous or ground/Earth controlled nuclear power system be advantageous/disadvantageous?

6.0 Reactor Accident Scenarios

Reactors in space could have the same potential accidents as their terrestrial counterparts and therefore space reactor designs must account for these potential accidents. Examples of the types of accidents that can be postulated include:

- A reactor failure leading to the reactor not providing electricity to critical systems;
- An accident leading to the partial or full melting of the reactor core;

- A reactivity insertion accident leading to thermal shock of the core destroying all or part of the reactor;
- An accident leading to the release of fission products;
- A reactor providing a direct dose to personnel because of lack of shielding or violation of procedure; or
- Combinations of the above.

Some or all of these accident types may be of concern for the safety of astronauts or completion of a mission. For example, the loss of the reactor producing electricity may be the greatest hazard to astronauts since this may be the primary source of power for life support. The reactor design must therefore consider all issues for each specific mission, although the importance of each accident type may change based on the mission characteristics. Examples of mission specific attributes that might impact importance of accident consequences include:

- Robotic versus crewed missions;
- The presence of an atmosphere to transport aerosols versus a vacuum that lack a transportation mechanism;
- The reactor is a mission-critical system necessary for life support.

This section explores space reactor accidents in greater detail.

6.1 Failure Modes

Some failure modes might be common to all types of reactors. Other failure modes of reactors will vary by reactor type. Traditionally, space reactors fall into several broad categories such as:

- Gas-cooled reactors (including hydrogen cooled thermal nuclear rockets),
- Liquid-metal-cooled reactors, and
- Heat-pipe-cooled reactors.

In addition, these reactors may have either a fast neutron spectrum or a thermal neutron spectrum. Thermal reactors typically have some type of moderator such as Zirconium or Yttrium Hydride.

The common failure modes among the many types of reactors might include:

- Single-point failures in components such as a gas leak in a Brayton power conversion system.
- A controller failure for a control drum,
- Fuel failures such as fuel swelling,
- Cladding failure due to radiation damage,
- Loss of heat sink (radiator panels),
- Radiation damage to critical electrical components,
- Reactivity excursion caused by spurious control element movement, or
- Damage from outside forces such as meteoroids or fuel explosions.

Some failure modes more specific to a particular reactor design can include:

- Heat-pipe failure due to corrosion,
- Liquid-metal freezing causing phase change and inducing a stress failure, or
- Hydrogen disassociation, diffusion, and loss in a metal hydride moderator causing loss of reactivity.

A systematic study of initiating events and failure modes should be undertaken using standard methods such as Failure Modes and Effects Analysis (FMEA) or a probabilistic risk assessment using such tools as fault trees. This document is not prescribing the level of detail for determining failures, their probabilities and the uncertainties on the probabilities. This decision could be determined by the agency with approval authority and may be based upon how close the probabilities come to the acceptance criteria. Reference 27 discusses the requirements for managing risk for human-rated missions.

6.2 Accident Progression and End States of Failure Modes

After failure modes have been determined, the end state or accident progression needs to be calculated. The accident progression may involve complex phenomenological models including radiation transport, fluid mechanics, or heat transfer. The end state that results may be a fully functioning reactor, a partially functioning reactor, a dead reactor, or fission product release up to full core melt with fission product release.

The end state of a failure may not need further evaluation depending on the particular type of mission. Example, for most robotic missions for deep space, a failure mode may cause loss of mission, but given that no people are present, no evaluation for dose consequence could be required.

Phenomena that may be of importance to the design includes the environment of the reactor given a failure. For deep space and the lunar surface, the reactor is in a vacuum environment, so convection to an atmosphere is not available as it would be on Mars. If a reactor is buried, there may be issues with heat transfer, e.g., lunar regolith is very non-conductive. Typically, radiation is the only means of heat removal for these environments. So, in the case where the reactor loses it heat sink (e.g., ultimate heat removal is lost because fluid flow to the radiator panel malfunctions), radiation from the reactor core may be the only means to cool the core.

It is worth noting that for an NTP system the impact of a single failure may have a catastrophic effect on the system. This catastrophic effect is because NTP systems traditionally have much higher temperatures and far greater power densities than surface and NEP systems. This difference in temperature and power density is shown in Figure 6.1 from work done by Poston[38]. Note, that very small space reactors (like Kilopower) are down in the lower left corner while nuclear thermal rockets are in the upper right corner. This plot is also a log scale, so the difference in power density can be as high as 5 orders of magnitude. A failure mode such as a plugged flow hole is not typically a large issue for a surface power reactor, but in a nuclear thermal rocket a single plugged flow hole can cause melting of the whole core very rapidly. Conversely, low temperature, low power density systems (like Kilopower) that have a power density of a few watts per cm^3 can easily radiate the decay heat of the system away to the point that no postulated failures could cause core melt.

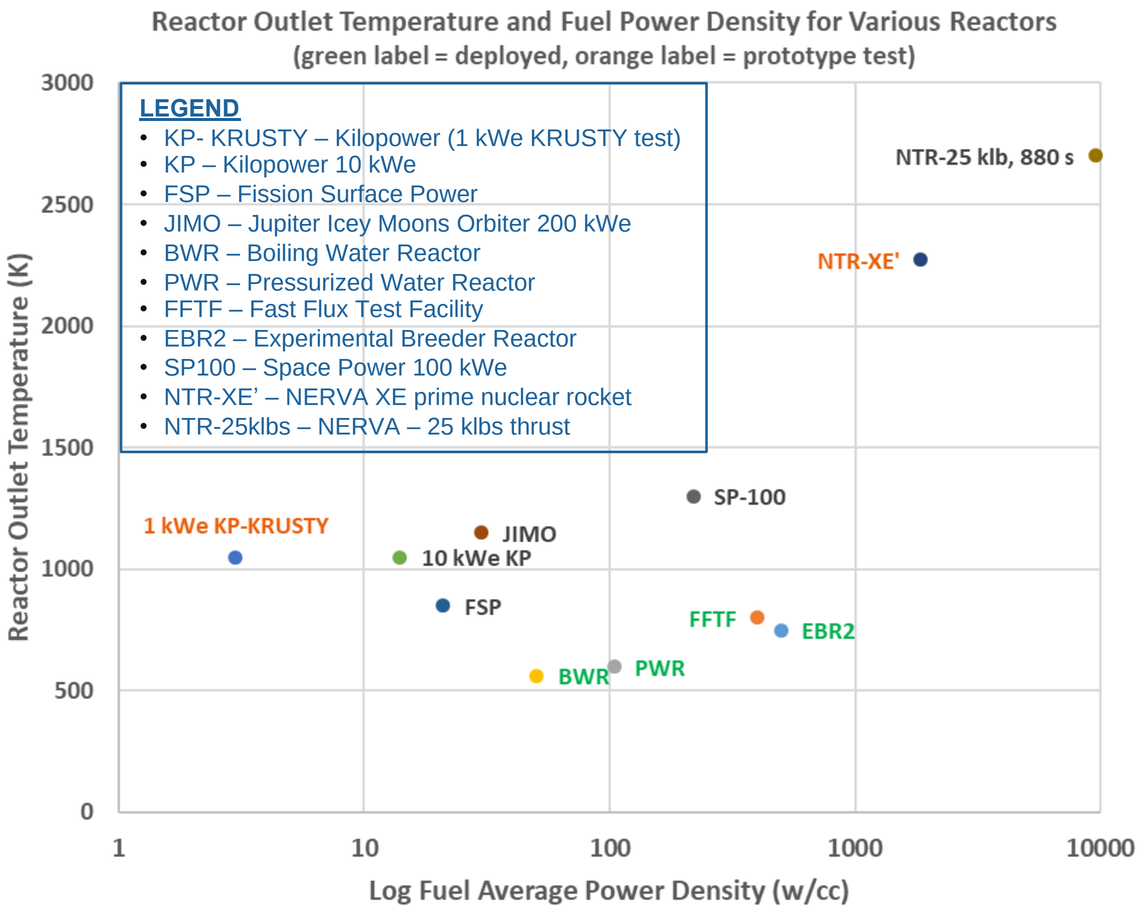


Figure 6.1. Graph of Reactor Temperature versus Power Density for Various Reactor Concepts

The accident progression can be evaluated by using a combination of logic codes such as event trees and physical phenomena codes such as heat transfer and fluid flow codes. In addition, phenomena such as explosions near the reactor may have to be evaluated in order to determine the impact of such an event on the reactor or the dispersal of a reactor given the event. These types of analyses must be planned out in advance in order to have the proper tools available.

6.3 Radioactive Material Transport Mechanisms

A terrestrial reactor has two main means of providing a dose to workers and the public. The first is direct shine from the reactor core or fission products. This dose is typically gamma radiation, with the possibility of neutrons if the reactor is still running. This means of providing dose will be identical for a space reactor and will be discussed later in the consequence section. The second means of providing dose is the transport of radioactive fission products in the form of aerosols. This typically occurs when the driving force from a reactor, such as steam in a light-water reactor, lifts the radioactive aerosols into the air where wind would carry the aerosols to the public. The primary means of exposure is through inhalation of the aerosols. For a space reactor this means of providing dose many not be applicable if the reactor is in a vacuum.

In deep space or on the moon the environment is a vacuum. With no wind present, the release of fission products may not move very far in the absence of another driving force. For a gas-cooled reactor, a driving force may exist to expel fission products toward a place of human habitation if high-pressure gas is present during the accident. In a heat-pipe reactor or liquid-metal-cooled reactor this high-pressure gas driving force will not exist. So, the fission products may be produced but not travel very far from the reactor location without a force to move them. In general, it is believed that for these situations the fission products will thermally diffuse to the nearest cold surface and attach themselves. This could be parts of the reactor/spacecraft for a deep space reactor or the lunar regolith for the moon.

For Mars, the atmosphere is very thin (5% of the pressure of Earth), but substantial winds do exist that can transport fission products. However, astronauts outdoors may be in space suits and habitats could be protected from the outside environment, so inhalation of fission product aerosols may not be the appropriate vehicle for a dose to the astronauts. What may be more important is the potential contamination and the effects it could have on humans from being tracked into the habitat. Since this would be a difficult value to calculate and evaluate for impact, it is recommended that core melt be determined to be an undesirable consequence and assign a probability below which the designer/safety analyst must show compliance. Given that core melt accidents on Earth are required to have a frequency of 1.E-4 per year, then a probability of core melt over a mission lifetime could be conservatively set at 1.E-4.

Atmospheres may exist on other planets or moons in the solar system that have similar atmospheric transport capabilities to Mars. Some of the ocean worlds on the moons of Saturn and Jupiter are examples. These locations may necessitate examining undersea accidents as well. These planetary bodies would have to be evaluated on a case by case basis.

6.4 Radiation Impact Assessments

In review, there are three primary types of consequence

- Mission impact (total or partial loss of mission)
- Direct shine dose from gammas and neutrons
- Potential for contamination/dose from atmospheric transport

Evaluating failures for partial or total loss of mission is fairly straightforward and can be done as part of assessing early accident initiator and accident progression. The loss of mission can have a probability set to some value that is determined by the individual mission. This may be a function of how mission critical the reactor is, the cost of the mission, etc.

The evaluation of the dose from shine can be accomplished using the same standard set of tools as for terrestrial applications. Table 4.2 presented a study for a 40-kW sodium cooled reactor on the lunar surface by Poston[39]. The table presents dose estimates after reactor shutdown at a location 1 m from the reactor centerline based on the required shielding for the project. The goal of the analysis was to present mission planners with guidelines on astronauts approaching the reactor to perform maintenance. This analysis was performed with the Los Alamos radiation transport code MCNP[40] and is typical of the types of dose calculation done for active or shutdown reactors. Dose criteria to astronauts can be mission specific if local radiation is high. As noted previously, the radiation levels drop dramatically a short time after shutdown.

Similar analysis can be done to estimate standoff distance for a crew habitat for an operating reactor. Figure 6.3 shows an example of the total dose rate (including both neutron and gamma dose) for the operation of four 10-kWe Kilopower-type reactors on the Martian surface. The blue curve shows the total dose rate for the four reactors in a perfect line and the red curve shows the effect of a minor misalignment of two of the reactors. The figure shows that a separation distance of 2 km (reactor to habitat) in addition to mission specific shielding requirements was needed to meet the NASA imposed requirement of 3 mrem per hour. These calculations were also done with MNCP for a specific version of the Kilopower reactor with a full shield around the reactor. Multiple reactors in the same location may also require analysis of local contamination following a single reactor accident impacting the other reactors.

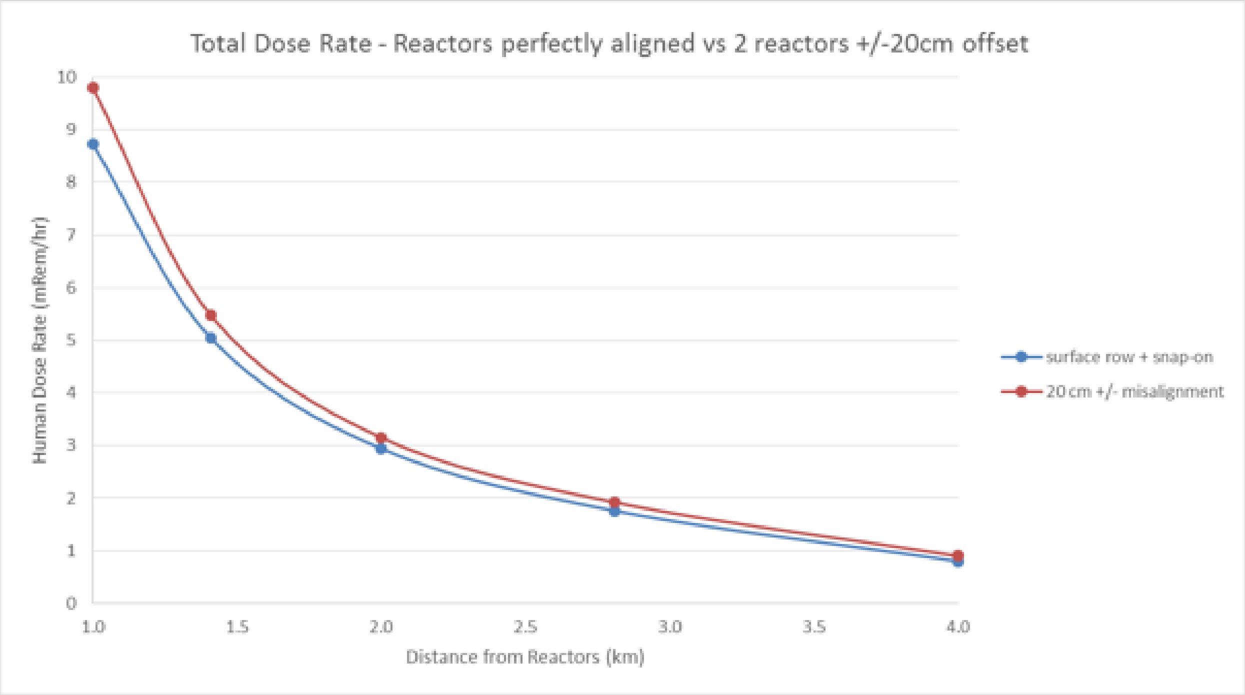


Figure 6.3. Example of shine dose at a distance for four Kilopower 10-kWe reactors on Mars Reactors aligned to habitat or with offset.

As was stated in the previous section, evaluating contamination via atmospheric transport processes may be difficult. Current terrestrial models are based upon experiments performed many decades ago using standard Earth air and gravity. These correlations may be completely unacceptable for examining contamination on another planet such as Mars. Instead, first principles models may have to be developed to understand the extent of contamination from a full core melt of a space surface reactor. The recommended alternative is to state that core melt is an undesirable consequence and must be below a probability with which the designer/safety analyst must show compliance. Given that core melt accidents on Earth are required to have a frequency of 1.E-4 per year, then a probability of core melt over a mission lifetime could be set at 1.E-4[1,41].

As missions and system designs become more defined and complete, full accident consequence assessments can be completed. These could help form the probabilistic and safety analysis reports that will be a part of the mission and launch approval process for each mission.

7.0 Destination Impacts and Planetary Protection Considerations

Planetary protection is a high priority of NASA and the international space community. However, most of that focus to date has been on biological contamination and concerns relating to impacting indigenous life forms or returning biological contamination to the Earth.[42,43] Biological concerns are addressed according to graded requirements in 5 categories, depending on the potential for life or its precursors to be present at the destination. While the potential for nuclear contamination is not likely to be a driving factor with respect to planetary protection concerns, it is still appropriate to consider any issues that might arise.

7.1 Biological Impacts

Ionizing radiation has the potential to cause mutations in living cells that may be present. Therefore, there is the potential to impact indigenous life on an extraterrestrial body. However, for most of the solar system, high-radiation fields are already present from cosmic rays, solar emissions, and radiation emitted locally by the body in question. Contamination from introduced nuclear systems may only be incremental. Local doses following a nuclear accident may be high but will decay over time back to near background levels. For example, on Mars, astronauts might be expected to receive approximately 20 rem per year. Table 4.2 previously showed example dose rates that might be expected over time after shutdown. Similarly, stored nuclear waste will have relatively low radiation levels. Unless very large reactors are being built, there is little potential for significant impact to life on a solar system body's surface due to increased radiation.

Potentially of more interest could be any locations where ice is present. In these cases, heat from the reactor might melt the ice, thereby producing a different environment for any potential life development. It may be important to locate the reactor away from ice or provide appropriate insulation. Another possible issue could arise in areas where naturally occurring radiation is precluded, such as deep underground. If there is potential for life that has not evolved in a radiation environment, then the impact on such life should be considered prior to undertaking such missions.

7.2 Treaty and Operational Impacts

Planetary protection was addressed in the Outer Space Treaty, Article IX.[44] While providing few specifics, it states that

> *"Parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination ... and, where necessary, shall adopt appropriate measures for this purpose. If a State Party to the Treaty has reason to believe that an activity or experiment planned by it or its nationals in outer space, including the Moon and other celestial bodies, would cause potentially harmful interference with activities of other States Parties in the peaceful exploration and use of outer space, including the Moon and other celestial bodies, it shall undertake appropriate international consultations before proceeding with any such activity or experiment."*

The Outer Space Treaty implies that mission and system design should minimize the possibility of radioactive dispersal and that siting of reactors and waste storage systems should not interfere with planned activities of other nations.

7.3 Consideration for Types of Missions

Chapter 5 of NASA Procedural Requirement 8020.12D describes the categories of solar system bodies and how they should be treated[32]. This discussion includes probability criteria for contamination of certain bodies, e.g., Mars. It is fairly straightforward to subsume the requirements for nuclear-induced biological impact within these criteria. In most cases, the nuclear impact may be negligible. For Categories I and II, e.g., metamorphosed asteroids, Io, Venus, Moon, Comets, Jupiter, Jovian Satellites except Io, Ganymede, and Europa, Saturn, Saturnian Satellites other than Titan and Enceladus, Uranus, Uranian Satellites, Neptune, Neptunian Satellites other than Triton, Pluto, Charon, and Kuiper-Belt Objects, no considerations of nuclear contamination need be considered other than possible subsurface liquid-water environments. For Category III and IV missions, e.g., Mars, Europa, and Enceladus, nuclear-related biological impacts should be considered, but should be readily dealt with per the discussions above.

7.4 Potential for Interference

While radiation-related impacts on biological systems are expected to be minimal, there is the potential for nuclear accidents or operations to impact access to a certain site or region. Nuclear systems are already designed with safety in mind as discussed elsewhere in this report. No additional requirements should be necessary beyond the need to consider whether the siting of nuclear systems or waste storage areas could impact future operations by the U.S. or others. Sites containing nuclear material should be identified and communicated to others. Possible related topics to address include:

- Notification/mapping of radiation areas
- Disposal plans
- Avoid contaminating water bodies
- Avoid contaminating areas where mining operations could occur
- The reactor system must be designed to allow for biological decontamination prior to Earth departure

8.0 Post-Operational Decommissioning and Disposal

Very few requirements or international agreements exist to guide post-operational decommissioning and disposal (D&D). As noted previously, the Outer Space Treaty implies that siting of reactors and waste storage systems should not interfere with planned activities of other nations. Previously, radioisotope thermoelectric generators (RTGs) or other small radioactive sources have been left in place on the Moon or Mars without any particular disposal strategy. For fission power systems more specific and intentional strategies may be warranted. Currently, there is abundant nuclear fuel available, and it could be extremely complex and costly to retrieve a space reactor for the purpose of recycling nuclear fuel or other components. Therefore, the strategies considered below may involve safe disposal that generally does not include return to Earth.

8.1 Missions Not Requiring Specific D&D Plans

Not every mission will need to consider D&D. These are missions where the reactor may not pose a future threat to personnel or equipment when left in its current location. Examples include:

- Reactors operating in sufficiently high orbits that fission products will decay to the actinide levels prior to reentry or impact. This can apply either to Earth or other bodies being orbited.
- Reactors orbiting bodies where future impact is of no consequence, e.g., the Sun or Jupiter, and collision with other orbiting bodies, e.g., a moon, is not of concern.
- Deep space missions where the reactor is not expected to return.

Such missions might involve NEP, NTP, or ISP fission systems. For FSP systems, at least a minimal consideration of D&D could be needed in all cases. There may be many missions where it is determined that D&D actions are not necessary, but an assessment to ascertain that fact is still appropriate.

8.2 Missions That May Require D&D

NEP, NTP, or ISP systems that do not meet the exclusion criteria of the previous section may require specific D&D plans. Except perhaps for deep space missions, it is assumed that the fission system will be shut down at the end of life, thus beginning a decay process that renders the reactor safer over time. Missions that could require specific plans are discussed below.

<u>Missions that include orbits below the sufficiently high orbit criteria</u> – Such missions can be addressed in a number of ways. Typically, for Earth orbits, the disposal could include boosting to a sufficiently high orbit per United Nations (UN) criteria[45]. Fuel to accomplish the final boost must be available. One alternative is to provide a positive dispersal/destruct system to allow for planned burnup on reentry, or a second alternative could be to provide for a targeted, or planned, reentry, such as was applied during the accident response for the RTG on Apollo 13 in 1968[46]. However, full dispersal is necessary and preferred, as the high-temperature reactor materials may make burnup difficult to achieve. Planned reentry would generally not be a first choice due to the possible political implications associated with reactor reentry.

For missions orbiting other bodies, the same approach involving boosting can be considered. Alternatively, a case would have to be made that eventual impact on the body poses no hazard to future personnel or operations. If impact is considered, then deliberate deorbiting to choose the impact location may be warranted.

For missions involving NEP or NTP where only part of the mission profile involves orbiting, the propulsion system could be used to direct the reactor into the Sun or another acceptable body or to direct it into deep space. The best choice may depend upon the mission profile and the capability of the spacecraft. Such approaches could be considered for reactors used for out-and-back transport missions to the Moon or Mars.

<u>Missions involving surface power</u> – Surface power missions that require D&D considerations are different in the sense that the reactor will likely not leave the body it resides on for disposal elsewhere. In all cases the reactor should be rendered safely shut down with no credible chance of a later criticality. Near-term surface power systems are likely to be tens to a few hundred kW. As shown previously in Section 4, the dose rates near the reactor are likely to be in the millirem range within a few years. In such cases, there is little reason to risk personnel exposures in handling or manipulating the reactor until significant decay has occurred. Plans should generally allow for the reactors to remain in place in the near term. That said, there are three possibilities for D&D:

- Allow the reactor to remain in place, with no intentional D&D activities beyond ensuring safe shutdown and possibly establishing an exclusion area prior to sufficient decay. This may be particularly appropriate on bodies where further human activities are not anticipated.
- Allow the reactor to remain in place with deliberate D&D activities. For example, the reactor might be buried in place or have other shielding, such as a berm, constructed around the reactor. Such shielding would protect personnel and equipment that might approach the area and reduce the size of necessary

exclusion areas. This approach would allow replacement reactor systems to be installed adjacent to the shut-down reactor and use infrastructure that is already in place. If removing auxiliary equipment from the reactor system, e.g., for spare parts for other reactor systems, is desired, then the capability for such operations needs to be factored into the design.

- Move the reactor to a safe location. For large colonies that may ultimately involve multiple reactors and other radioactive sources, it may be desirable to establish a disposal area far away from the colony. Following a few years of decay, handling of a reactor is feasible. The design is likely to be complex, such that the reactor can be readily decoupled from the rest of the power system, minimizing the transport requirements. Significant transport capability may be necessary, up to the order of a metric ton, depending on the reactor design. Further, hoists or cranes may be necessary, and the disposal location might need to be constructed and monitored.

Abnormally terminated missions – The discussions above assume that a fission reactor mission is terminated normally. In the event of an abnormal termination, e.g., a reactor accident, other measures may be necessary for D&D. In some cases, the event may render D&D impossible, e.g., if a propulsions system is needed and that propulsion system has failed. Likewise, an accident involving a surface power system may result in contamination or physical disruption that renders previous plans unworkable. If D&D is included in a mission plan, then it is appropriate to consider possibilities associated with abnormal mission termination.

Mission design implications – D&D activities need to be considered early in the mission design. For systems on spacecraft, fuel for orbit boosting or a final trajectory change may be required. If burnup is the strategy, then dispersal/destruct systems may be needed. All of these approaches may add mass to the mission requirements. If D&D handling operations are required for surface power, then the necessary equipment must be transported to the surface in question.

9.0 Documentation and Training Delivery

In order to fully develop the operational envelopes and details of all of the possible mission profiles and equipment needs there may need to be the concurrent development of the documentation necessary to safely launch, operate, decommission, and dispose of a space fission power and propulsion platform. Such documentation would necessarily include, but is certainly not limited to, the establishment of highly detailed mission and nuclear safety, design, and operational criteria, standards and procedures. Some of the operational procedures that may need to be developed include, but again, are certainly not limited to procedures for testing, startup, radiation protection, power management, emergency management, shutdown, instrumentation and control, autonomous and operator control, extended dormant periods, any maintenance activities, decommissioning, disposal, etc. Diligence, focus and quality control may need to be maintained during the development of this documentation in order to provide a maximal amount of confidence by the regulators, management, ground staff, and most importantly, the crews for these missions.

One example of such a document that may be required to be developed and/or updated is the set of safety and design criteria developed for the SP-100 Program[47]. This document identified and defined the policies, objectives, philosophies, criteria, specifications, and reports required in the development of the SP-100 space nuclear-power system by government agencies and their contractors. As space nuclear fission systems and missions are developed, there is no doubt that the volume of documents produced, reviewed and approved might grow dramatically.

Finally, complete and effective training programs for all operations and maintenance activities will need to be developed and delivered. This will be critical, whether or not the missions are locally operated and performed by astronauts, remotely operated by staff and operators on Earth, or operated autonomously in space or on a planetary surface. The interfaces and interactions between humans involved with any and all equipment included in a mission will need to follow world-class training processes and procedures, such as those developed by the Institute for Nuclear Power Operations (INPO) and the World Association of Nuclear Operators (WANO) in Atlanta, GA. Both of these organizations have vast and relevant experience in the operation of nuclear power systems, the evaluation of the operation of nuclear power systems, and the development and accreditation of nuclear power plant training programs. Their insight and guidance should be sought by NASA very early in the development of any missions utilizing nuclear power and propulsion systems for space.

10.0 Summary, Conclusions and Recommendations

This report identifies and documents various considerations for the operations of space nuclear fission power and propulsion systems from their startup through their several stages of operation and to their eventual decommissioning and disposal. While it is clear that detailed mission and reactor conceptual designs may be necessary in order to fully analyze all of the aspects discussed above, a few specific conclusions can be drawn at this time.

11.0 Conclusions

1. There are many details that need to be identified before any fission system could be launched on a mission in space; however, it is important to immediately identify the safety and design requirements, criteria, and standards that would guide the further development of space fission power and propulsion systems.
2. Due to the emanations of radiation from all fission power and propulsion systems, the early establishment of radiation exposure guidelines, criteria and standards for both people and equipment may enable both mission and reactor designers to move forward with detailed plans and designs.
3. Both normal operations and accident situations may open numerous pathways for radiation exposure for humans and equipment. The development of expectations, criteria and standards for measuring, predicting, and analyzing the possible radiation exposures around fission power and propulsion systems would help designers to plan for these possible exposures.
4. The need, and the allowability, for maintenance on and around a fission power or propulsion system should be minimized. Such maintenance could be complex and require consideration very early in the mission and system design phases for missions considering using fission reactors.
5. Reactor control and health monitoring may need to include and integrate both operator and autonomous control technologies in order to safely startup, operate, and shutdown space fission power and propulsion reactors. Standards and criteria for the operation of these reactors, along with the specific mission requirements may determine the level of

allowable autonomous control of these systems and should be developed early in the mission design process.

6. Considering, analyzing, and preparing for possible reactor accidents will be necessary for all fission power and propulsion systems. Establishing standards and criteria for accident analysis could be useful early in the design process for these systems.
7. It is important to consider the possible planetary impacts and the mechanisms for decommissioning and disposal of all fission reactor systems early in their design consideration. While the likelihood of large-scale and long-term radiation exposures to humans from these systems is small, early planning for these eventualities in the lifetimes of all reactors needs to be a significant part of their design.
8. Once a mission has been defined to utilize fission power, there will be a need for the complete development of operational procedures for testing, startup, radiation protection, power management, emergency management, shutdown, extended dormant periods, maintenance, decommissioning, disposal, etc.
9. Once a mission has been defined to utilize fission power, there will be a need for the complete development of instrumentation and control standards and systems, including roles and responsibilities for operator and autonomous controls.
10. Once a mission has been defined to utilize fission power, there will be a need to develop complete and effective training programs for all operations and maintenance activities. These will need to be established whether or not the missions are locally operated and performed by astronauts, remotely operated by staff and operators on Earth, or operated autonomously in space or on a planetary surface.

12.0 Recommendations

1. With the recent release of the ***Presidential Memorandum on Launch of Spacecraft Containing Space Nuclear Systems***[48] issued on August 20, 2019 and its recognition that "additional safety guidelines may be appropriate for the non-terrestrial operation of nuclear fission systems" it is critical that NASA immediately begin to consider the depth and breadth of the anticipated safety needs due to the operations of the systems discussed in this report.
2. As this report has been developed at a fairly high level of consideration, it is important to take a deeper look at the next level or two of specifics needed to further understand the scope and detail required for the complete operational safety requirements, criteria, standards applicable to space nuclear systems. For example, it is recommended that case studies be developed regarding the operations of space nuclear power and propulsion systems. Specifically, it could be useful to analyze a potential fission surface power application and a potential nuclear thermal propulsion application to more fully examine the next levels of details regarding specific mission requirements, specific design and safety requirements, and specific consensus standards that could be useful for future planning of these types of missions. Examples of this next level of specific details could include, but are certainly not limited to the criteria for design considerations and operating procedures, policies for operating crews (local vs. on Earth) vs. autonomous control of nuclear systems, standards for robotic vs. operator control, rapid restart capability, degraded performance operability and more.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
03/04/2020

2. REPORT TYPE
Contractor Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Operational Considerations for Space Fission Power and Propulsion Platforms

5a. CONTRACT NUMBER
80LARC17C0003

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Klein, Andrew C.; Camp, Allen; McClure, Patrick; Voss, Susan; Borenstein, Elan; VanDamme, Paul

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
869021.03.07.01.21

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/CR-2020-220569

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 20 Spacecraft Propulsion and Power
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report is aimed at identifying the issues related to the operation of various space nuclear power and propulsion reactors. The foci of the report include the possible human radiation exposure issues that might occur during different types of missions and different operational stages within those missions, managing the approach to and working around space reactors, maintaining these reactors for long-duration operations, controlling these reactors and monitoring their availability and health, evaluating possible reactor accident scenarios, planning for planetary protection due to their operation, and post-operation decommissioning and disposal.

15. SUBJECT TERMS
Fission Reactor; Inadvertent Reentry; Nuclear Power; Nuclear Thermal Propulsion

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	43	(443) 757-5802