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Operational Considerations for Fission Reactors Utilized on Lunar In-Situ Resource Utilization Missions

A Report to the Nuclear Power & Propulsion Technical Discipline Team

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Acronyms

ALARA	As Low As (is) Reasonably Achievable
ANSI	American National Standards Institute
BeO	Beryllium Oxide
CLPS	Commercial Lunar Payload Services
D&D	Decommissioning and Disposal
FSP	Fission Surface Power
H_2	Hydrogen gas
HALEU	High Assay Low Enriched Uranium
HEU	High Enriched Uranium
HeXe	Helium-Xenon
HLS	Human Landing System
ISRU	*In Situ* Resource Utilization
KRUSTY	Kilopower Reactor Using Stirling TechnologY
kWe	Kilowatt Electrical
kWt	Kilowatt Thermal
LH_2	Liquid Hydrogen
LOx	Liquid Oxygen
MWe	Megawatt Electrical
NASA	National Aeronautics and Space Administration
NPR	NASA Procedural Requirement
O_2	Oxygen gas
PCS	Power Conversion System
PMAD	Power Management and Distribution
RTG	Radioisotope Thermoelectric Generator
SCRAM	Safety Control Rod Axe Man (Emergency Shutdown)
SP	Space Reactor Prototype
We	Watt Electrical

1.0 Introduction

This report identifies the considerations related to the operation of space nuclear power reactors that would be utilized for *In Situ* Resource Utilization (ISRU) missions on the lunar surface. The objective of this study is to evaluate the operational complexities of reactors that would provide electrical and thermal power to a growing lunar ISRU and mining outpost/base. This report examines the operational considerations for a sequence of ISRU missions that would be powered by fission surface power (FSP) systems building to a full-scale operational commercial ISRU system. This report describes the fission reactor considerations for a growing base, first for an ISRU demonstration system, second for an ISRU pilot plant platform, third for an initial ISRU production plant, followed by a full-scale commercial ISRU production plant. This report follows upon an initial report[1] that looked at the generic considerations for operating fission reactors in space applications and is intended as a deeper dive into the operational complexities related to specific lunar ISRU applications. This report does not 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[2,3].

1.1 Mission Description

The main premise of this mission is to deploy a sequence of reactors that would supply increasing amounts of electrical power and possibly even thermal power for resource recovery or mining activities for a growing ISRU presence on the lunar surface. This presence would start with an initial ISRU demonstration mission using only on the order of about 100 to 200 of We (Watt electrical). A mission at this electrical power level would not require a nuclear reactor power source and all necessary power could come from batteries, solar panels, or a radioisotope thermoelectric generator (RTG). The second mission in the sequence would be a pilot ISRU plant operation requiring up to 10 kWe that would be provided by a small nuclear reactor. The third mission would involve an initial ISRU production plant that could include a human habitat and use up to a 50-kWe reactor. Finally, these three precursor missions would be followed by a fully operational commercial ISRU production plant requiring 500 to 2,000 kWe.

The reactor for the pilot ISRU plant would be a low-power reactor operated as simply as possible. The initial production plant operation would be powered by a reactor of a similar type (but at a higher power level) as the one used to power the pilot plant in order to provide for a growing resource recovery and an increasing human presence. In the end, the full-scale commercial production plant would employ a very high-power reactor and systems that utilize advanced, pumped loop heat removal and recovery systems. These expanding operations allow our study to initially explore the operational complexities and the desired capabilities and requirements of the most simplistic reactor operations that are conceivable at this time, followed by expanding reactor operational complexities and considerations of high-power and multiple reactors to be developed and evaluated for large-scale ISRU and mining operations.

Considerable efforts have been conducted to discern the nature of lunar *in situ* resource utilization. Full design and mission studies have been conducted to characterize the needs of these applications. Elliott, et al. have described three specific architectures to collect water ice for the production and storage of LH_2 and LOx through electrolysis[4].

As shown in Figure 1.1 (Figure 2 from Reference 4), the extraction of H_2 and O_2 gas from lunar regolith starts by excavating the ice-bearing regolith. After collection, the ice is removed from the regolith, as volatile water vapor. This water will likely include a substantial quantity of contaminants that would be difficult to manage in downstream processing stages (e.g., electrolysis). To alleviate these issues, a purification system is added to remove these contaminants before an electrolysis system separates the hydrogen from the oxygen. These H_2 and O_2 gases are finally liquefied and stored at cryogenic temperatures.

Prospective ISRU missions such as these to the lunar surface involve considerable amounts of power for the ISRU activities, as well as for the operation of various rovers. While this reference does not specifically describe the power levels required for various development units, it does provide sufficient detail on the general needs for ISRU systems.

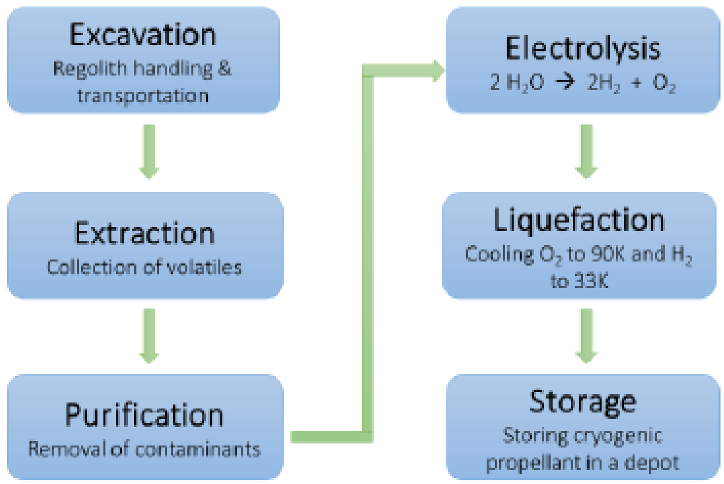

Fig. 2. Functional decomposition of ice-based propellant ISRU

Figure 1.1. Functional decomposition of ice-based ISRU (From Reference: Elliot, et al.)

1.2 Reactor Description

This section describes the general parameters and assumptions for the reactors to be used throughout the buildup of the ISRU outpost operations, including the three phases of the mission development that include nuclear reactor systems: a pilot ISRU plant mission, an initial ISRU production plant mission and a commercial ISRU production plant mission.

The general design for the ISRU pilot plant mission FSP reactor would include a fairly low electrical power output level, on the order of 10 kWe. This reactor would be placed in a fixed location on its original lander platform. The electrical power would be supplied either to a deployed ISRU plant or to a plant on the same lander as the reactor. This power system could also power small deployed rovers. The reactor would include a rather simple design using either high enriched uranium (HEU) or high assay low enriched uranium (HALEU) with a straightforward operational profile including full inherent power following for temperature changes, burnup, etc. One possible model for this type of reactor would be based upon a Kilopower reactor[5] with a solid reactor core and reflector, control drums embedded in the reflector, heat pipe heat transfer, Stirling engines for power conversion and simple radiators deployed on the lander to provide waste heat rejection. The reactor would require no hands-on maintenance. Additional details of this notional reactor configuration are included in Table 1-1.

Table 1-1. Notional ISRU Pilot Plant Reactor Parameters, Assumptions and Attributes

Reactor	10 kWe; 40 kWt HEU or HALEU metal fuel Na heat pipes Reflector control drums
Power Conversion and Heat Rejection	Twelve 1-kWe Stirling Engines Full power can be maintained with 10 Stirling Engines operating Heat pipes and panels heat rejection
Human Rating	Astronauts may work temporarily near the system System may be connected to a future habitat Human rating should be considered
Launch and Transport to Lunar Orbit	Reactor stowed until deployed on surface Power management and distribution equipment on same lander Multiple launch vehicles are available
Lander	Commercial Lunar Payload Services (CLPS) Lander Lander remains in place upon landing ISRU equipment and reactor on same lander Landing site will be at least 1 km from site of future habitat
Unpacking	Reactor remains on lander Radiators are deployed from lander – can remain attached Reactor health monitored during unpacking and setup Cameras to observe physical condition of the lander and reactor Radiation monitors operational during unpacking Sensors indicating equipment interlocks in correct status Power available on the lander to support unpacking Reactor itself requires no unpacking Unpacking is done remotely and without astronaut participation
Startup	Startup managed from Earth Battery or fuel cell to support startup Control rod safety interlocks removed Neutron flux, temperature, control rod position, radiation levels monitored Control rod pulled a predetermined amount to achieve desired temperature ~3 hours of operation to melt the Na in the heat pipes Stirling engines are activated
Power Management and Distribution (PMAD)	PMAD to be set up robotically The reactor will be shut down during PMAD assembly Future cables of up to 1 km may support habitat operations Setup will include cables, service node near the lander, rover battery recharging station, thermal management, video imagery, communications/data transfer, ISRU power connections

Operation	Reactor parameters will be monitored from Earth Reactor is completely self-regulating, based on power demand A minimum of 5 years of full power operation Reactor and power conversion system maintenance will be limited to cleaning radiators should they inadvertently be covered with dust by nearby operations Astronaut maintenance may be performed on the PMAD system Astronauts will not generally be present near reactor NASA radiation limits will determine time and distance requirements from reactor
Decommissioning	Lander and reactor will remain in place at end-of-life Reactor control rods and drums will be locked in place Reactor will be rendered incapable of future criticality Radiation levels monitored for at least 10 years following shutdown

The reactor to be utilized for the initial production ISRU plant could use technology that is similar to that used on the reactor utilized on the pilot plant but designed to operate at a significantly higher power level. It is estimated that the Kilopower class reactor technology could be scalable to about 100 kWe. This would allow the outpost to generate significantly more product and provide power to a larger crew base, if needed. Accordingly, the reactor chosen for this second phase of the deep dive study would operate at up to 50 kWe. Additional details of this notional reactor configuration are included in Table 1-2.

The commercial ISRU production plant operation would continue to employ the reactors deployed in the earlier phases of the mission and add on a high-power FSP plant that would utilize pumped loop core heat removal and advanced thermal to electric power conversion technologies. This advanced reactor could include system configurations using liquid metal or gaseous core heat removal and transport systems and Brayton, Rankine, or other power conversion technologies. However, for the purposes of this study, a 500-kWe pumped liquid metal loop primary heat removal system coupled through a liquid metal to gas heat exchanger providing high quality heat to a helium-xenon (HeXe) Brayton power conversion system is assumed. Such advanced reactor to power conversion system configurations were considered during and after the SP-100 Program and will be assumed for this study[6]. However, this study does not need to fully define these capabilities and technologies at this point in order to further explore the operational complexities or characteristics of these systems. Additional details of this notional reactor configuration are included in Table 1-3.

Table 1-2. Notional Initial ISRU Production Plant Reactor Parameters, Assumptions, and Attributes

Reactor	50 kWe; 200 kWt HEU or HALEU metal or ceramic fuel Na heat pipes Reflector control drums
Power Conversion and Heat Rejection	Twelve 5-kWe Stirling Engines Full power can be maintained with about 10 Stirling Engines Pumped loop and panels heat rejection

Human Rating	Astronauts may work temporarily near the system System will power a lunar habitat Human rating will be required
Launch and Transport to Lunar Orbit	Reactor stowed until deployed on surface Power management and distribution equipment on same lander Multiple launch vehicles are available
Lander	Human Landing System (HLS) Cargo Lander Lander remains in place upon landing Crew delivered on separate lander ISRU equipment and reactor on separate lander Free ranging rovers included on separate lander The landing site will be at least 1 km from site of future habitat
Unpacking	Reactors are deployed from or may remain on lander Radiators are deployed from power system Reactor health monitored during unpacking and setup Cameras to observe physical condition of the lander and reactor Radiation monitors operational during unpacking Sensors indicating equipment interlocks in correct status Power available on the lander to support unpacking Reactor itself requires limited or no unpacking Unpacking is done remotely and without astronaut participation
Startup	Startup managed from Earth Battery or fuel cell to support startup Control rod safety interlocks removed Neutron flux, temperature, control rod position, radiation levels monitored Safety and control rod(s) pulled as needed for startup Control drums (if included) activated for rector control ~3 hours of operation to melt the Na in the heat pipes Stirling engines are activated
Power Management and Distribution (PMAD)	PMAD to be set up robotically The reactor will be shut down during PMAD assembly Cables to support ISRU operations will be at least 1 km long Future cables of up to 1 km may support habitat operations Setup will include cables, service node near the lander, rover battery recharging station, thermal management, video imagery, communications/data transfer, ISRU power connections

Operation	Reactor parameters will be monitored from Earth Reactor is completely self-regulating, based on power demand Targeting 10 years of full power operation Reactor and power conversion system maintenance will be limited to cleaning radiators should they inadvertently be covered with dust by nearby operations Astronaut maintenance may be performed on the PMAD system Astronauts will not generally be present near reactor NASA radiation limits will determine time and distance requirements from reactor
Decommissioning	Lander and reactor will remain in place at end-of-life Reactor control rods and drums will be locked in place Reactor will be rendered incapable of future criticality Radiation levels monitored for at least 10 years following shutdown

Table 1-3. Notional ISRU Commercial ISRU Production Reactor Parameters, Assumptions, and Attributes

Reactor	Full details to be determined Assumed between 500 kWe to 2 MWe HEU or HALEU fuel Pumped liquid metal loop core heat removal Launch safety control rods are likely to be needed Reflector control drums
Power Conversion and Heat Rejection	Full details to be determined Brayton cycle chosen for study Multiple convertors with spares for fault tolerance Most active components shielded to facilitate maintenance Pumped loop and panels heat rejection
Human Rating	The system will power a lunar habitat Astronauts may operate in the area Human rating is required
Launch and Transport to Lunar Orbit	Reactor stowed until deployed on surface Power management and distribution equipment on same lander Multiple launch vehicles are available
Lander	HLS Cargo Lander May require multiple flights to deliver reactor and subsystems Lander remains in place upon landing Crew delivered on separate landers ISRU delivered on separate landers Free ranging rovers delivered on separate landers The landing site will be at least 1 km from the site of any habitat The landing site will be away from operating reactors

Unpacking	Reactor is deployed from lander Radiators are deployed from the power system Reactor site is excavated to permit below-grade installation Reactor installed in excavation to provide shielding Reactor health monitored during unpacking and setup Cameras to observe physical condition of the reactor Radiation monitors operational during unpacking Sensors indicating equipment interlocks in correct status Unpacking is done remotely and without astronaut participation Power available on the lander to support unpacking Reactor itself requires no unpacking
Startup	Startup managed from Earth Battery or fuel cell to support startup Control rod safety interlocks removed Neutron flux, temperature, control rod position, radiation levels monitored Safety control rods removed from core Control drums turned a predetermined amount to achieve desired temperature Startup time to be determined Power conversion system is activated Radiators activated System thaw initiated for units with primary or secondary liquid metal coolant
Power Management and Distribution (PMAD)	PMAD to be set up robotically The reactor will be shut down during PMAD assembly Cables to support ISRU operations will need to be determined Future cables of up to 1 km may support habitat operations Setup will include cables, service node near the lander, rover battery recharging station, thermal management, video imagery, communications/data transfer, ISRU power connections
Operation	Reactor parameters will be monitored from Earth control center Reactor control and power management to be determined Targeting 15 years of full power operation Reactor will require no maintenance other than replacing sensors Power Conversion System maintenance will be limited, but possible for a specified set of components Radiators may need cleaning if they are inadvertently covered with dust from nearby operations PMAD system maintenance may be performed by astronauts Astronauts will not generally be present near the reactor NASA radiation limits will determine time and distance requirements from reactor

2.0 Radiation Exposure Considerations

It is fully expected that the radiation exposures to ISRU mission crew members will be designed and monitored to be kept as low as reasonably achievable (ALARA), within the parameters of the mission. ALARA will be assured through the design of the reactor system, the design of the crew habitat and the monitoring background and reactor radiation fields. Each crew member's radiation exposures will be continuously monitored. It is most probable that the largest radiation doses received by crew members will come from naturally occurring cosmic galactic radiation, with only a small amount of exposure coming from the utilization of a fission reactor to generate power.

The lunar ISRU outpost is expected to grow from the demonstration mission through the full deployment of a commercial production plant. There likely will be intermittent and rather short-term occupation by astronauts, with frequent crew changes, during the demonstration and pilot plant missions and extended individual occupations during the production plant missions. Thus, it can be expected that the individual astronaut total radiation exposures and the rates of those radiation exposures will change throughout these missions. It will be important for the mission designers, mission managers, and mission health physicists to adequately plan and continuously track the radiation exposures received by the astronauts on all of these missions from all natural and reactor originated radiation.

2.1 Radiation Exposure Limits

NASA has studied the expected radiation exposures to astronauts for many decades and has established radiation exposure limits and guidelines that will need to be monitored and met by crew members on any space mission. An overview of radiation exposure limits is provided in Reference 1. Mission designers will need to be cognizant of the current expectations for radiation protection in the preparation for the mission and in the design of the reactor systems.

2.2 Potential Human and Equipment Radiation Exposure Pathways – Pilot Plant Mission

The proposed reactor for the pilot project mission, a Kilopower-type reactor, will not be operated, and will not generate fission products prior to reaching an operational readiness condition on the lunar surface. The reactor system will be located away from any crew habitat. There are very few mechanisms available to transport radioactive materials away from the reactor, either during normal or abnormal operating conditions. Thus, the possible radiation exposure pathways are very limited to a member of the surface crew. The ISRU pilot plant phase is to be deployed prior to the establishment of a permanently inhabited base, so there will be periods when no crew members are present and any crew members that visit the site will change frequently.

It may be possible for a crew member to inadvertently enter a high radiation area created by the operational radiation emanating from the reactor core, reflector, or any structures that scatter core radiation. It is also possible for a crew member to enter an area with elevated radiation levels during shutdown. Both of these occurrences should be very low probability events if sufficient radiation field mapping and controls are implemented. Mapping the radiation fields and establishing restricted areas can ensure astronaut safety. Additionally, it is expected that the suits worn by crew members when they are outside of the habitat areas will include radiation detectors that can be set to alarm when, and if, a higher than expected radiation level is encountered as the crew members work on the lunar surface.

While spread of contamination from the reactor could conceivably threaten astronaut safety or contaminate work areas, such events can be largely precluded through proper design and the fact that there is no atmosphere to transport radioactive materials. Such accidents could include reactivity insertion events or failure of a pressurized primary coolant system. Proper design should preclude these events from posing a significant risk, but the low risk should be confirmed once sufficient design information is available.

Reference 1 also discussed the general means to minimize crew exposures and planned response for possible crew radiation overexposures that can be met through sound system design engineering, radiation protection practices, and emergency radiation management procedures and training.

2.3 Potential Human and Equipment Radiation Exposure Pathways – Initial ISRU Production Plant Mission

The primary differences for the reactor operation and radiation exposure pathways for an initial ISRU production plant mission's reactor include a 50-kWe power level that is approximately 5 to 10 greater than the pilot plant reactor, the orientation of the reactor's thermal radiators may be different, and the mapping of the radiation fields may be complicated if there is overlap between the pilot plant and the ISRU reactor units. The orientation of the radiators, deployed horizontally versus vertically, can significantly reduce the scattered radiation component off. Detailed analytical predictions can be made on radiation fields prior to delivery to assist in locating the new reactors and in establishing the orientation of the radiators. Regardless, the radiation fields for both reactors will need to be mapped and estimated prior to the launch of the second reactor as well as after the reactors are both in place on the lunar surface.

The initial ISRU will be designed to ensure that the possibility of an accident resulting in core damage has a very low probability. If the initial ISRU reactor design is similar to a Kilopower reactor proposed for the pilot plant mission, then it will include shutdown and integrated heat pipe cooling. This will ensure that the possibility of an accident leading to the release of radioactive material is acceptably low.

2.4 Potential Human and Equipment Radiation Exposure Pathways – Commercial Production ISRU Plant Mission

Radiation exposure to the crew could be different for the higher power CP-ISRU plant due to the notable difference in design, technology, and power output. It is also likely that this phase will coincide with a permanent human presence on the moon and extended crew member stays, which will impact the time spent near the reactors. If the reactor system has liquid metal in the primary and secondary coolant loops, then the coolant may become radioactive during operation through neutron activation of the coolant, impurities in the coolant, and corrosion from core and primary piping surfaces. Activation of the primary and secondary coolant loops may increase the radiation fields surrounding this reactor during operation. Proposed designs will have to be evaluated and the full radiation fields coming from the reactor system will need to be analyzed before delivery and mapped once the reactor is on the surface and operating.

2.5 Means to Minimize Crew Exposures and Provisioning for Crew Radiation Exposures

Both the minimization of routine crew exposures and provisioning each mission for the possibilities of needing to manage the emergency care for a crew member who is over exposed on the lunar surface during their mission will need to be considered. These topics were introduced in Reference 1 and will be important considerations for these reactor missions. However, the specific details will need to be determined once the missions and reactors are more fully designed.

3.0 Managing Access to a Reactor

During launch and delivery, the reactors are safe to be handled by launch site personnel and safe to be accessed during spacecraft docking and transfer maneuvers. In fact, prior to startup of the reactors on the lunar surface, they pose no radiation hazard and can be approached by astronauts or robots without concern. This feature allows astronauts and robots to have an active role in the installation and setup of the systems, if desired. The early reactors are likely to be self-deployed via commands from Earth. The later reactors may require some on-site off-loading, deployments, or assembly. All the reactors will supply power to the various user loads via a long-distance (~1 km) power cable and electrical power interface (possibly 120 Vdc) that provides safe separation from the reactor-induced radiation. Concepts have been proposed that use a wheeled cart that unfurls the power cabling as it moves away from the reactor. The cable cart concept could be used for both nuclear and non-nuclear power sources that must be remotely landed from the crew habitat area or ISRU mining area to prevent landing ejecta from damaging sensitive systems.

In some cases, it may be necessary to approach a reactor for maintenance activities or other operations associated with the surface mission. When approaching a reactor, astronauts will wish to minimize the radiation exposure that occurs during the approach and subsequent operations. The reactor will be designed with sufficient shielding in order to protect future human habitation areas or equipment and payload areas. System shielding, or possibly placement of additional temporary shielding, will facilitate astronaut approaches to the reactor but needs to be assessed for each case. Due to mass considerations, non-uniform shielding strategies may be considered with less shielding on the side away from astronaut approach. Separate consideration and access constraints will be necessary for personnel and robotic equipment.

The reactors can be temporarily shut down for periods to allow closer human and robotic access. Preliminary studies have suggested that reactor radiation will reduce to safe levels for robotic access in several days and human access in several weeks. This feature permits possible maintenance to be performed on non-operating reactors and offers the potential for relocating smaller systems that can moved with construction rovers. After maintenance is performed or after the system is relocated, it can be restarted and brought back to full power operations.

3.1 Three-Dimensional Radiation Mapping, Control and Monitoring

For surface fission power, radiation control for an approach to the reactor is largely two dimensional. The control will become more three-dimensional close-in to the reactor and will need to allow for radiation scattering. 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 reactor. Initial planning and mapping may be done with models and analyses, but measurements are recommended for validating the expected radiation fields. Measurements can discover unanticipated scattering paths. Further, 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 due to the buildup of fission products and actinides
- Buildup of activation products in surrounding structures and materials
- Changes or degradation in the shielding configuration or materials
- 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 will be required whenever humans approach a reactor for maintenance or other purposes.

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 radioactive contamination to adhere to equipment or space suits, then additional planning for decontamination and precautions to avoid contaminated areas 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 operations near the reactor, radiation detection should be employed to verify the anticipated radiation fields and implement appropriate radiation worker protection.

3.2 Docking and Spacecraft Assembly

The reactor will remain shut down until after landing on the lunar surface. As a result, there are no radiation hazards for astronauts to consider during docking and spacecraft assembly operations. They may work alongside the reactor as necessary. The only concern is to ensure that no damage occurs to the reactor system during these operations that could render it unsafe when started. If damage occurs, it will need to be assessed and remedied before the mission can continue.

3.3 Accessing a Reactor on the Lunar Surface

The reactor and related systems should be designed and developed to minimize or avoid the need to approach the reactor. There are currently no specific procedures or guidelines for human approaches, should they be necessary. Some guidance can be found in NASA's Human Integration Design Handbook, which provides guidance on design of extravehicular activity translation paths and the need to avoid exposing astronauts to unnecessary hazards[7]. Radiation needs to be included along with other hazards that could adversely impact the astronauts.

Previous work has suggested separation distances between reactors in the 10-kWe class and a habitat of 500 m to 1 km[8]. 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. It is expected that even the larger reactors will be sufficiently shielded to allow similar separation distances. If such shielding is provided, precautions should be unnecessary for temporary approaches that do not come within 500 m of the reactor. Detailed calculations might further reduce the area of concern, particularly for short duration incursions.

The reactor shielding should be designed to facilitate any planned approaches to the reactors. That shielding need not be uniform on all sides. For example, there could be additional shielding on the side facing the power management and distribution equipment if that equipment is expected to need astronaut attention. Portable shielding or even mounding of surface materials can be employed if necessary.

3.3.1 Access to ISRU Pilot Plant Mission Reactor

Access to the ISRU pilot plant mission reactor is not anticipated to be necessary, particularly while it is operating. During the pilot plant mission, the reactor is not providing power to a habitat or other systems essential to the well-being of astronauts. No maintenance or other activities should be needed in a shorter time period than can be accounted for by shutting the reactor down and waiting for radioactive decay. The necessary wait times are discussed in Section 4. If the reactor later becomes a source of backup power to a habitat or other critical system, then safe access to the reactor may need to be considered. However, both the reactor and power conversion system are planned to be designed to be maintenance-free over the lifetime of the system. If an approach to the reactor becomes necessary, then the guidance discussed below in Section 3.3.4 becomes important.

3.3.2 Access to Initial Production ISRU Plant Reactor

The design philosophy of the initial production ISRU plant reactor is the same as for the pilot plant reactor, that is, no maintenance is anticipated. However, this reactor is intended to provide power to a habitat, and as discussed in Section 4, emergency maintenance may be considered, primarily for the heat rejection and power distribution equipment. Generally, the reactor should be shut down prior to approach for as long as is practical, and the guidance of Section 3.3.4 should be followed.

3.3.3 Access to Commercial Production ISRU Plant Reactor

The commercial production plant reactor may provide power to both a habitat and mission-critical ISRU equipment. It is also a more complex system, involving active components. Section 4 discusses the possible maintenance needs for such a reactor. Due to the higher power, the commercial production reactor may require maintenance as compared to the two smaller designs. Because of this, the design needs to provide sufficient shielding and controls to allow access to components that may require maintenance. For a system that may need to be human rated, it is important to consider not only planned maintenance, but also emergency maintenance. Contingency plans for approaching the reactor under various scenarios need to be developed. Section 3.3.4 provides additional guidance for approaching any of the three reactor types.

3.3.4 General Guidance for Approaching the Reactors

Should the need to approach the reactor arise, then the commonly used ALARA principle is appropriate. The reactor should be shut down as long as possible prior to the approach. Positive controls or locks should ensure that the reactor remains shut down during the approach and related activities. Based on prior radiation mapping and surveying, paths of ingress and egress can be determined. Radiation monitoring should be employed during the approach to verify expected radiation levels. Markers and physical constraints can be used to prevent inadvertent passage into high radiation areas. However, within a few days of shutdown, the latter precautions should not be necessary unless the astronauts are working adjacent to the reactor. Dosimetry should assess the doses that are received by the astronauts. Finally, caution should be taken to avoid transporting contaminated materials back to the astronaut habitat area. Possible considerations in developing a plan for approaching the reactor include:

- Minimize the time needed to carry out planned operations, e.g., simplify tools and procedures
- Provide markers and/or physical controls and barriers to prevent inadvertent entry into a hot zone
- Two-person rule to allow quick removal of an injured person from a radiation area
- Provide appropriate radiation monitoring and dosimetry
- Establish safe paths for ingress and egress
- Create decontamination zones for the return to the habitat

3.4 Multiple Reactors

The initial ISRU pilot plant mission only involves a single reactor. As the additional reactors are added during later phases of site development, the issues of shielding and reactor access will become more complex. The design of the shielding of each reactor should consider the possibility of additional reactors and the need to approach any of the reactor systems. In some cases, there may be one reactor operating while another is shut down. Plans for an approach to the proximity of any one of the reactors must consider the radiation effects of the other reactor(s). The exclusion/hazard zones need to be defined to consider the combined effects. If multiple reactors are collocated, it may be necessary to temporarily 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. As noted above, because maintenance operations are temporary, separation distances can be much less than between the reactors and a habitat. 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.

4.0 Managing Reactor Maintenance

4.1 General Maintenance Considerations

Some general maintenance requirements for space reactors were discussed in Reference 1. The maintenance requirements will vary significantly by reactor design, mission, and whether the systems are human rated. Ideally, manual maintenance requirements for reactors and associated systems should be minimized. Manual maintenance activities may incur a number of risks to astronauts. There is increased potential for radiation exposure, along with the normal risks of astronauts performing activities outside of a 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 the ISRU pilot plant reactor, tend to require no maintenance as compared to a large reactor with a complex system configuration. 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 maintenance activities that are a result of failures after landing. Some components will most likely not be amenable to any maintenance. It is also possible that the reactor will be located in an area difficult for astronauts to access, for example, in some of the permanently shadowed regions. Maintenance may only be possible robotically or not at all in those cases. When maintenance is possible, planning must minimize the risks to astronauts, including expected radiation doses.

For cases where maintenance is possible, it is important to distinguish between planned maintenance and the 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[9]. As with most design issues, this may lead to tradeoffs. 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, increasing the burden on astronauts.

4.2 Fuel and Passive Reactor and Primary System Components

Refueling or maintenance on reactor core and primary system components is unlikely to be feasible for any of the reactors due to radiation levels and inaccessibility. These components include core support structures, reactor vessels, piping, instrumentation, and other passive items in or near the reactor core or primary cooling system. Sufficient fuel must be provided for the entire mission length. The fuel itself must be designed to operate with a high probability of success over the lifetime of the mission. All materials in and around the reactor and primary cooling system must be designed for anticipated radiation effects and thermal loads assuming that maintenance will not be possible. There should be sufficient redundancy in the instrumentation to accommodate for failed sensors. The design should also address expected impacts of meteoroids. If the system is to be human rated, then NASA specifies that systems should be single-failure tolerant, with the exceptions that:[9]

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, Johnson Space Center (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.

Passive reactor system components, including heat pipes and static power conversion are not amenable to maintenance activities, either planned or unplanned. For those components and systems where maintenance will not be possible, it is important to implement rigorous quality and reliability standards, along with robust design margins. NASA standards can be found at https://standards.nasa.gov/nasa-technical-standards. For example, Reference 10 addresses NASA reliability and maintainability standards. These and other standards may be applicable to ensuring the reliability of non-maintainable components and systems. However, the NASA standards have not been developed with nuclear reactors in mind. Given the unique nature of nuclear reactors for planetary applications, new American National Standards Institute (ANSI) standards tailored to space reactors should be developed, along with corresponding updates to NASA standards.

4.3 Maintenance for ISRU Pilot Plant Mission

For the pilot plant mission, maintenance will be extremely limited. The reactor will not be providing life support or other functions that might require emergency maintenance important to astronaut survival. For that reason, it should be possible to shut down the reactor for a significant length of time prior to when an astronaut needs to approach the reactor system. Table 4-1 shows approximate radiation levels versus time after shutdown for various distances from the reactor centerline, given 1 year of full power operation. These calculations are adapted from those presented in Reference 11.

4.3.1 Active Components in the Reactor Core or Primary Cooling System

The only active components to be considered here are in the reactivity control system. The heat pipe design in this first reactor system does not contain active 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 for any design and is precluded for this reactor system. Therefore, the reliability of such components must be assured. Drive motors outside the core region may be amenable to maintenance. However, maintenance on any part of the active reactivity control system has the potential to induce a reactivity event and will not be considered for this pilot plant mission. Thus, the quality and reliability of these components will also be important.

One exception where maintenance might be practical is the locking mechanism on the reactivity control system that renders the reactor safe during transport. If, for example, the locking mechanism fails to release for startup, a future mission might allow for the repair of the mechanism and unlock the system.

Table 4-1. Approximate Dose Rates for Various Times after Shutdown for 10-kWe Pilot Plant Reactor*

Time after Shutdown	1 m	10 m	100 m	1 km
At Power	3E+2	3E+1	3E-1	3E-3
1 hour	3E0	3E-2	3E-4	3E-6
1 day	8E-1	8E-3	8E-5	8E-7
1 week	2E-3	2E-5	2E-7	2E-9
1 month	7E-4	7E-6	7E-8	7E-10
1 year	3E-4	3E-6	3E-8	3E-10

*Dose rates in rem/hr, where 1 Sv = 100 rem

In this case the reactor will be cold with no radiation hazard to the astronauts. Examples of the factors that might be relevant to this repair operation are:

- The unlocking mechanism must be designed to allow access
- The astronauts should practice the repair on Earth per typical NASA training requirements
- Appropriate tools will need to be provided
- The drive motors must be disabled to prevent rod motion subsequent to unlocking
- Radiation levels must be verified prior to approaching the reactor
- The astronauts must move to a safe distance prior to reactor startup

4.3.2 Power Conversion and Heat Rejection Systems

The pilot plant system contains approximately twelve 1-kWe Stirling engines. These engines can each be increased in power such that only about ten of the engines are required to provide full power. With this level of redundancy, no maintenance will be required. Quality control and testing is important to ensure that there are no common cause failures important to the system reliability.

Heat rejection will occur through radiator panels, with embedded heat pipes that distribute the waste heat across the panels. An active cooling loop (or multiple loops) between the Stirling engines and radiators may be used that includes redundant pumps and piping that is protected from micrometeoroid damage. No maintenance on the fluid loop, heat pipes or panel structures is anticipated. If the panels fail to deploy, then a future mission may be used to repair the panels. Similar to the control rod locking mechanism, factors to consider include:

- The panels and release/deployment mechanisms must be designed to allow access
- The astronauts should practice the repair on Earth per typical NASA training requirements
- Appropriate tools will need to be provided
- The reactor will remain shut down prior to the maintenance
- Radiation levels must be verified prior to approaching the reactor
- The astronauts must move to a safe distance prior to reactor startup

Once the panels are deployed and reactor is operating, no further maintenance is anticipated. However, it is possible that future activities could kick up dust that collects on the radiator panels. Possible solutions include providing vertically oriented panels or self-cleaning technology. Otherwise, simple cleaning of the radiators could be achieved either robotically or by astronauts. As the radiator panels will be located near the reactor, the following considerations are relevant:

- The panels must be oriented so that the surface to be cleaned can be reached
- The astronauts should practice the repair on Earth per typical NASA training requirements
- Appropriate tools will need to be provided, long enough to reach the entirety of the panels
- The reactor will shut down prior to the maintenance for approximately a day to a week if they are attached to the lander in close proximity to the reactor
- Radiation levels must be verified prior to approaching the reactor
- The astronauts must move to a safe distance prior to reactor restart

4.3.3 Power Management and Distribution (PMAD)

The PMAD and related cabling will be set up robotically prior to reactor startup. The service node will likely be at least a few meters away from the reactor and lander and could be approached 1 day after shutdown, according to Table 4-1. Should the setup process fail, a future mission could provide repairs and complete the setup. Considerations similar to those for failure to deploy the radiator panels would apply. The reactor would remain shut down until the PMAD setup was complete and the astronauts had moved to a safe distance. If maintenance is needed after the reactor has been started, then the considerations discussed below in Section 4.6 apply.

4.3.4 Summary of Maintenance for ISRU Pilot Plant Mission

As noted above, the ISRU pilot plant mission does not anticipate any planned maintenance activities and very few options for unplanned maintenance. Thus, care in designing and manufacturing the reactor and related systems to high reliability and quality standards with robust design margins is critical. The maintenance strategy for this mission is summarized in Table 4-2.

Table 4-2. Maintenance Strategy for ISRU Pilot Plant Mission

	Planned Maintenance	Unplanned Maintenance Possible	Reliance on Standards and Design Margins
Reactor Core and Passive Reactor Components	No	No	Yes
Active Primary System Components	No	Limited to Unlocking Control Systems	Yes
Power Conversion and Heat Rejection	No	Limited to Deployment and Cleaning of Radiator Panels	Yes
Power Management and Distribution	No	Yes	Yes

4.4 Maintenance for Initial ISRU Production Plant Mission

The 50-kWe reactor design is similar in many respects to the pilot plant mission reactor. Like the pilot plant mission, these reactors will rely heavily on passive components and a self-regulating design. Therefore, the maintenance considerations will be similar to those for the pilot plant reactor, that is, maintenance will be extremely limited. One significant difference is that these reactors may provide power to a habitat and, thus, may be human rated. In that case, emergency maintenance possibilities need to be considered. The availability of multiple reactors for the initial ISRU production mission, combined with the existence of the pilot plant reactor, would provide significant advantages for mission-level fault tolerance. It is assumed that the follow-on reactors will be shielded sufficiently that radiation doses near the reactor will be similar to those for the pilot plant system, and the information in Table 4-1 will still apply.

4.4.1 Active Components in the Reactor Core or Primary Cooling System

The only active components to be considered here are in the reactivity control system. As with the pilot plant reactor, the heat pipe design in this second reactor system does not contain active 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 for any design and is precluded for this reactor system. Therefore, the reliability of such components must be assured. Drive motors outside the core region may be amenable to maintenance. However, maintenance on any part of the active reactivity control system has the potential to induce a reactivity event and will not be considered as part of a planned maintenance program. Thus, the quality and reliability of these components will also be important.

As with the pilot plant reactor, repair of the reactivity control systems locking mechanism before startup may be considered, following the guidance discussed for the pilot plant reactor. In addition, since the initial production reactor may be human rated and provide power to a habitat, the possibility of emergency maintenance should be considered for drive motors or other active components. In this case, the following factors are important:

- The reactor must be confirmed to be in a safe, shut down state
- Backup power must be sufficient
- The drive motors and related components must be designed to allow access
- The time that can be allowed before the start of repair activities will reduce the doses to astronauts
- Shielding design, including portable shielding, should be employed to minimize radiation doses to astronauts
- The astronauts should practice possible repairs on Earth per typical NASA training requirements
- Appropriate tools and spare parts will need to be provided
- The drive motors must be disabled to prevent rod motion during or subsequent to repair
- Radiation levels must be verified prior to approaching the reactor
- The astronauts must move to a safe distance prior to reactor startup

4.4.2 Power Conversion and Heat Rejection Systems

The initial ISRU production plant system will contain twelve 5-kWe Stirling engines, and approximately ten of these engines will be required to provide full power. Even less power is likely needed for minimum habitat power for astronaut safety. With this level of redundancy, no maintenance will be considered. Quality control and testing is important to ensure that there are no common-cause failures important to the system reliability. With this in mind, it is unlikely that more than a few of the engines would fail suddenly on all of the reactors before the astronauts have time to make plans for alternative power or to evacuate.

As with the pilot plant system, heat rejection is expected to occur through radiator panels, with passive heat pipes carrying fluid to the panels. Alternatively, an active cooling loop (or multiple loops) between the Stirling engines and radiators may be used that includes redundant pumps and piping that is protected from micrometeoroid damage. No maintenance on the heat pipes or panel structures is anticipated. As with the pilot plant reactor system, provisions should be made to deal with panels that fail to deploy or dust on the panels. There is no difference from the pilot plant system except that there will be more and larger panels. If an active cooling loop is used, then provisions for emergency maintenance should be considered for external parts of the pumps. In that case, the factors would be similar to those discussed in Section 4.4.1, except that the radiation levels are likely to be lower if the pumps are farther away from the reactor.

4.4.3 Power Management and Distribution (PMAD)

The PMAD system and related cabling will be set up robotically prior to reactor startup, potentially utilizing the cable cart concept presented above. The discussion here assumes a single PMAD shared by all the reactors in the initial ISRU production system. Alternatively, there could be separate PMAD systems for each reactor. The service node will likely be at least a few meters away from the reactors and lander and could be approached 1 day after shutdown, according to Table 4-1. Should the setup process fail, a future mission could provide repairs and complete the setup. Considerations similar to those for failure to deploy the radiator panels would apply. The reactors would remain shut down until the PMAD setup was complete and the astronauts had moved to a safe distance. Depending on the design of the service node and associated connectors, some planned maintenance, or at least inspection activities, may be necessary. In this case the service node should be located as far as possible from the reactors, perhaps allowing for the possibility of approach while the reactors are still operating. The information in Table 4-1 is relevant for determining safe distances, depending on the repair time required. As with other planned maintenance activities, the considerations discussed in Section 4.6 also apply.

4.4.4 Summary of Maintenance for the Initial Production Mission

As noted above, the ISRU pilot plant mission does not anticipate any planned maintenance activities and very few options for unplanned maintenance. Thus, care in designing and manufacturing the reactors and related systems to high reliability and quality standards with robust design margins is critical. The maintenance strategy for this mission is summarized in Table 4-3.

Table 4-3. Maintenance Strategy for the Initial ISRU Production Plant Mission

	Planned Maintenance	Unplanned Maintenance Possible	Reliance on Standards and Design Margins
Reactor Core and Passive Reactor Components	No	No	Yes
Active Primary System Components	No	Yes, for unlocking control Systems or repairing drive systems	Yes
Power Conversion and Heat Rejection	No	Limited to Deployment and Cleaning of Radiator Panels or active cooling pumps	Yes
Power Management and Distribution	Yes	Yes	Yes

4.5 Maintenance for Commercial ISRU Production Plant Mission

The projected reactor design to be used in the commercial ISRU production plant mission is significantly different from the first two types of reactor. It contains many more active components and control systems that may have very different maintenance considerations. It is expected to be human rated and may need both planned and unplanned maintenance capabilities.

It is assumed that this reactor will be shielded sufficiently that radiation doses near the reactor will be similar to those for the pilot plant and initial production mission systems, and the information in Table 4-1 will still apply.

4.5.1 Special Shielding Considerations for the Commercial ISRU Production Plant Reactor

Due to the large mass of shielding that may be necessary for the commercial ISRU production plant reactor, shielding may be produced in place rather than transported from Earth. Such shielding could be accomplished by moving lunar regolith, either by digging a hole for the reactor or by constructing a berm around the reactor. Alternatively, water or other materials could be obtained locally to use in the construction of shielding structures. Regardless of the shielding approach used, consideration of access to key components for maintenance is important. For planned maintenance activities, components should be located outside the primary reactor shielding. In this case the reactor shut down time can be as short as possible prior to undertaking the maintenance procedures. Emergency or unplanned maintenance could address components located inside the shielding at the expense of longer shut down times, the need to physically remove or configure shielding to allow access, and higher radiation doses to astronauts. For bermed or buried reactors, it may be possible to leave an opening to allow access on the side away from the habitat. This will result in an asymmetric exclusion area around the reactor and could impact the allowed location of ISRU activities.

At higher power levels, radiation levels in coolant and primary system components can become important due to neutron activation and release of fission gases from the reactor. The radiation levels in the coolant depend upon the particular coolant chosen. For example, radioactive Na-24 can build up in a sodium-cooled reactor. However, it has a half-life of 15 hours, decays primarily through beta decay, and is of little threat unless it leaks from the primary system. In any case, components located outside of the primary shielding may require some shielding and may still need to be approached carefully.

4.5.2 Active Components in the Reactor Core or Primary Cooling System

As with the first two reactor types, maintenance on the active neutron absorbing part of a control system, such as a control rod or drum, is unlikely to be practical for any design and is precluded for this reactor system. Therefore, the reliability of such components must be assured. Also, similar to the initial ISRU production reactors, control system drive motors located outside the core region may be amenable to emergency or unplanned maintenance. Unlike the first two reactors, this commercial production reactor system does contain active pumps and valves. Due to the potential hazards and complexity of maintenance for primary system components, it is recommended that there be no planned maintenance on these components. That is, the systems should be designed to operate for 15 years without maintenance. Thus, the quality and reliability of these components will also be important.

As with the pilot plant and initial production reactors, repair of the reactivity control system’s locking mechanism before startup may be considered, following the guidance discussed for the pilot plant reactor. In addition, since the commercial ISRU production reactor will be human rated and provide power to a habitat, the possibility of emergency maintenance should be considered for drive motors or other active components. Due to the complexity of the operations, the following items should not be considered for maintenance in the primary cooling system:

- Replacement of primary coolant pumps (drive motors and controllers may be amenable to maintenance)

- Replacement of valves (actuators may be amenable to maintenance)
- Replacement of heat exchangers or surge tanks
- Any operations involving pipe cutting or welding
- Any operations involving draining the primary coolant system

Repairs that can be considered are those that do not compromise the integrity of the primary cooling system. This includes sensors, actuators, controllers, electric drive motors and external parts of pumps. Similar to the initial ISRU production reactors, the following factors are important:

- The reactor must be confirmed to be in a safe, shut down state
- Backup power must be sufficient
- Components must be designed to allow access
- The time between shutdown and the start of repair activities should be maximized to reduce the doses to astronauts
- Shielding design, including portable shielding, should be employed to minimize radiation doses to astronauts
- The astronauts should practice possible repairs on Earth per typical NASA training requirements
- Appropriate tools and spare parts will need to be provided
- The control rod/drum drive motors must be disabled to prevent rod/drum motion during or subsequent to repair
- Radiation levels must be verified prior to approaching the reactor
- The astronauts must move to a safe distance prior to reactor startup

4.5.3 Power Conversion and Heat Rejection Systems

The power conversion system (PCS) used on the commercial ISRU production reactor system is anticipated to be a Brayton cycle system with a number of active components. The system may include one or more loops with each loop containing a turbine generator, compressor, heat exchanger, and possibly pumps and valves. The Brayton loop may reject heat directly through radiator panels or through a heat exchanger that connects to an additional loop to the radiator panels. The systems should be designed for the targeted 15-year mission without scheduled maintenance, and quality control and testing will be extremely important. Maintenance in the PCS is more practical than in the primary system, due to the lower radiation levels. The coolant should not be radioactive unless there is leakage through a primary system heat exchanger, and most components should be largely shielded from neutron activation. Despite this, the coolant should be monitored for radiation levels to detect leakage, and radiation levels should be measured prior to approaching the PCS for maintenance. If components are located outside the shielding, it may be possible to perform simple maintenance operations, e.g., replacing a sensor, without shutting down the reactor. If multiple cooling loops are present, then it may be possible to only shut down the affected loop. Any maintenance actions that could completely disrupt the cooling function should only occur after reactor shutdown. Further, the shutdown should be long enough to prevent the reactor from overheating from decay heat if the cooling function is disrupted. This should not be a problem in a few hours to a day or two after shutdown.

As with the primary system, certain components should not be considered for repair due to the complexity of their operation. Thus, the following items should not be considered for maintenance in the primary cooling system:

- Replacement of main turbine-generator components, such as turbine blades
- Replacement of heat exchangers or surge tanks
- Replacement of compressors
- Replacement of valves unless specifically designed for replacement

There are some additional operations that are unlikely to be practical but may become amenable to emergency maintenance as capabilities become more advanced in a space environment and as advanced industrial capabilities are developed on the lunar surface. These include:

- Any operations involving pipe cutting or welding
- Any operations involving draining a coolant loop
- Replacement of valves or other components where the piping and valve system is designed for uncoupling and removal.

In performing such maintenance, the following factors are important:

- The reactor must be confirmed to be in a safe, shut down state without the need for decay heat removal
- Backup power must be sufficient
- Components must be designed to allow access, preferably outside shielding
- Pressure safety may be important
- The astronauts should practice possible repairs on Earth per typical NASA training requirements
- Appropriate tools and spare parts will need to be provided
- Radiation levels must be verified prior to approach, including levels in the coolant
- The astronauts must move to a safe distance prior to reactor startup

For a number of components, maintenance will be possible with appropriate design, planning and preparations. This is important for a reactor that is human rated and providing power to a habitat, as well as support to ISRU operations. These components include sensors, actuators, controllers, electric drive motors and external parts of pumps, valves, compressors and turbines. While the components may be designed for the full 15-year mission, it is appropriate to allow for unscheduled maintenance. Similar to the initial ISRU production reactor, the following factors are important:

- The reactor should be confirmed to be in a safe, shut down state without the need for decay heat removal; if the activity will occur without shutdown, it must be verified that heat removal will not be disrupted
- Backup power must be sufficient
- Components must be designed to allow access, including shielding from the reactor
- The time that can be allowed before the start of repair activities will reduce the doses to astronauts
- Shielding design, including portable shielding, should be employed to minimize radiation doses to astronauts

- The astronauts should practice possible repairs on Earth per typical NASA training requirements
- Appropriate tools and spare parts will need to be provided
- Radiation levels must be verified prior to approaching the reactor and components
- The astronauts must move to a safe distance prior to reactor startup

Ultimate heat rejection will occur through radiator panels. These panels may be part of the Brayton loop or in a separate loop connected by a heat exchanger. It is anticipated that no additional pumps or valves will be needed for the radiator panels and that they will perform their function passively. No maintenance on the piping or panel structures is anticipated. As with the pilot plant system, provisions should be made to deal with panels that fail to deploy or dust on the panels. If an active cooling loop is used, then provisions for emergency maintenance should be considered for external parts of the pumps. In that case, the factors would be similar to those discussed in Section 4.4.1, except that the radiation levels are likely to be lower if the pumps are farther away from the reactor.

4.5.4 Power Management and Distribution (PMAD)

The PMAD and related cabling will be set up robotically prior to reactor startup. The service node will likely be at least a few meters away from the reactor and lander and could be approached 1 day after shutdown, according to Table 4-1. Should the setup process fail, a future mission could provide repairs and complete the setup. Considerations similar to those for failure to deploy the radiator panels would apply. The reactor would remain shut down until the PMAD setup was complete and the astronauts had moved to a safe distance. For the commercial ISRU production reactor, it is likely that changes to ISRU operations and habitat configurations will occur over time, resulting in the need to approach the service node for both reconfiguration and possible maintenance. As a result, the service node should be located as far as possible from the reactor, allowing for the possibility of approach while the reactor is still operating. The information in Table 4-1 is relevant for determining safe distances, depending on the access time required. As with other planned maintenance activities, the considerations discussed in Section 4.6 also apply.

4.5.5 Summary of Maintenance for Commercial ISRU Production Mission

As noted above, the ISRU pilot plant mission does not anticipate any planned maintenance activities with some options for unplanned maintenance. Thus, care in designing and manufacturing the reactor and related systems to high reliability and quality standards with robust design margins is critical. The maintenance strategy for this mission is summarized in Table 4-4.

Table 4-4. Maintenance Strategy for Commercial ISRU Production Mission

	Planned Maintenance	Unplanned Maintenance Possible	Reliance on Standards and Design Margins
Reactor Core and Passive Reactor Components	No	No	Yes
Active Primary System Components	No	Yes, for unlocking control Systems, repairing drive systems or accessible external	Yes

		parts	
Power Conversion and Heat Rejection	No	Deployment and Cleaning of Radiator Panels, repair of accessible external parts	Yes
Power Management and Distribution	Yes	Yes	Yes

4.6 General Considerations for All Maintenance Activities

For all maintenance activities, the following considerations may apply:

- Consider robotic maintenance as an alternative to using astronauts
- Provide redundancy, e.g., in sensors, to avoid maintenance
- Allow for sufficient reactor shut down time to reach safe radiation levels (see Table 4-1)
- Provide both in-place and portable radiation monitoring
- Design systems for access and ease of maintenance
- Provide proper tools and training
- Minimize astronaut exposure time for maintenance operations
- Provide access to spare parts
- Set up appropriate keep-out zones to restrict maintenance activities to safe areas, supplemented as appropriate by physical controls and barriers
- Move astronauts at a safe distance prior to restart
- Implement decontamination procedures for astronauts prior to entering landers or habitats

5.0 Reactor Control and Health Monitoring

The general nature of considerations for the control, operation and health monitoring of FSP reactors has been discussed in Reference 1. With the three reactors considered for the lunar ISRU missions being different from each other, either by power level or by technologies used, specific reactor controls, procedures and instrumentation will need to be part of the design for each reactor system. Consideration will need to be given to the similarities and differences between these important operational choices.

5.1 Initial Reactor Setup and Startup

The setup and startup procedures for the pilot plant and initial production plant phases of the ISRU missions can be expected to be similar since the technologies used for both reactors will be comparable, and the reactors are largely differentiated by power level. Additional radiator surface will be needed for the larger reactor configuration. The setup and startup requirements for the commercial production plant reactor will likely be very different from those of the earlier reactors because of the use of different technologies to achieve higher power operation.

Since the pilot plant reactor, power conversion system and its radiators will remain on the lander and the power level of this reactor is rather small, a vertical orientation of the radiators can be expected to be sufficient for the rejection of the approximately 30 kWt needed for this reactor operation. In contrast, the initial production plant reactor system could either remain on its lander or be deployed separately from the lander. This will be a design choice of the mission and reactor designers, based upon their experience with the pilot plant reactor and the needs to shield the higher radiation levels coming from the initial production plant reactor core. As the ISRU outpost grows with the addition of reactors, additional operational aspects for monitoring multiple reactors in the close vicinity of each other will be needed. These are discussed elsewhere in this report.

As the commercial production reactor operates at a relatively high-power level, it is expected to be deployed separately from the lander on which it arrives at the lunar surface. Thus, the setup and preparation of the landing site will be considerably different from a reactor that stays on the lander. Operations including excavation of a shielding cavity, mounding of lunar regolith to provide shielding, and the extension of extensive piping and cabling will need to be developed and employed for this system. Significantly larger radiators, including pumped loops can be expected on this system, which will add complexity to their deployment when compared to the much simpler heat pipe radiators of the pilot plant and initial ISRU production reactor systems.

Reactor startup can vary in complexity from easy to complex depending on the type of design. The small 10-kWe Kilopower-type system (or the ISRU pilot plant reactor) will have a very simple startup. A reactor that produces 500 kWe or more and uses a pumped liquid metal system may have a more complex startup sequence.

For a very simple system like the small 10-kWe Kilopower system, startup is very simple. The control and shut down rod can be slowly removed at a pre-programmed speed. As the reactor heats up the sodium in the heat pipes it will thaw and then vaporize. After the vaporization of the sodium, the heat pipe is “on” and a cycle will be established that delivers heat to the hot end of the Stirling engines. From this point onward, the steady-state power produced and delivered by the reactor will equal the power drawn from the system, whether actively or passively. This behavior is dictated by the inherent reactor physics of the system. The temperature of the core is set by the control rod position and the reactor power adjusts to maintain that temperature like a thermostat. When the system has reached a temperature that allows for power production by the Stirling engine, a signal will be given to start the Stirling engines. This is as simple as a small electrical bump of the Stirling engine piston to set each one in motion. At this point, electrical power is produced and the reactor core will follow the load demand of the Stirling engines. This sequence will be completed over a time period of about 3 hours to allow for the system to be in a quasi-steady-state mode at all times during startup. In a constant environment, e.g., a permanently shaded region, the system would reach a full steady-state power condition in a few days.

For a large reactor, such as a pumped liquid-metal cooled reactor in the hundreds of kilowatts electric power range, reactor startup will be more involved. Traditionally, these concepts approach startup by first thawing the liquid-metal coolant in the reactor core and associated piping and pumps. This can be done with electrical heaters or with a combination of electrical heaters and some amount of core thermal heating. The goal is to establish coolant flow before bringing the core up to full temperature. Similarly, the gas flow on the power conversion side may have to be established to allow for heat to be delivered to the heat rejection system, which subsequently may need to be established before bringing the reactor to full power. After these systems have fluid circulating through them, the reactor can be slowly brought up to operating temperature. In many systems, the power produced by the reactor will be a function of both the temperature of the reactor and the heat removed by the pumped coolant. A coordinated raising of both the fluid flow, controlled by the pump, and the reactor temperature and power level, controlled by drums or rods, will be done to bring the reactor to a steady-state power condition.

This process will take several hours and will require a significant and independent power source and will rely on the functionality of many instrumentation and control components. The power source will be used to thaw the sodium coolant and to power pumps on startup. Additionally, establishing any self-regulating features in such high-power reactors will most likely not be possible because of the interdependency of the flow and power-conversion control systems.

5.2 Impact of Multiple Reactors on Spacecraft and Surface Outposts

Since all three (or more) reactors will be in operation at the same time during the commercial ISRU production plant stage of the missions, the issues of multiple reactors will need to be considered very early in the mission design process. However, consideration of the specific landing sites for all three reactors should take place very early in the mission design process, with adequate and appropriate margin included should the landings not take place in exactly the expected locations. Plans will need to include contingencies for reactors landing closer to each other or farther away from each other than planned to accommodate reactor and ISRU plant operations.

5.3 Dynamic Operations and Restarts

The technologies chosen for these three reactors will drive their operational envelopes. The simple operational direction for the pilot plant and initial production reactors should allow for reasonable startup, power-level control, steady-state operations and shutdowns. As the technology of pumped loops and convective heat transfer include the increased complexity of pumps and heat exchangers, the large-scale reactor system will necessarily have a much more complicated design and procedures for startup, power-level maneuvering, and shutdown. Multiple restarts and power-level variations need to be incorporated in the instrumentation and controls for all three of these reactors.

If a reactor is providing life support and other critical functions, it is important to consider how fast a reactor may need to be restarted should it trip offline. There are a number of factors that may influence how fast a reactor can be restarted, especially if the design is moderated to use thermal neutrons. Xenon and other poisons can build up after restart, making startup difficult for many hours after shutdown and somewhat hard to control. Whatever design is chosen, backup power should be sufficient to allow the necessary time for reactor restarts.

5.4 Impact of Autonomous Control and Health Monitoring

While there are likely to be crew members around the power and ISRU plants, it is highly probable that these reactors will be required to include considerable autonomous reactor control and that having a designated crew member or members to serve as reactor operators will be unlikely. Thus, it is expected that these reactors will need to utilize considerable amounts of autonomous control. The astronauts involved on these missions will likely need to be able to shut down the reactors locally by hitting a Safety Control Rod Axe Man (SCRAM) button; however, having one local crew member constantly watching a reactor control board and taking small or large operator actions should be avoided. Since there will be a time delay between the Earth-based mission control room, those who are monitoring the mission health will also not be able to send other than the simplest and fundamental commands to the lunar-based reactors. Thus, designing the autonomous controls for these reactors early in the reactor design process will be critical to mission success. The aim for these control systems should be to design them to setup, startup, make power-level changes, operate, and shut them down as simply as possible.

6.0 Reactor Accident Scenarios

A reactor on the moon presents two unique hazards, direct exposure to ionizing radiation and the potential release of radioactive material. Both hazards are summarized in this section.

6.1 Direct dose

The direct dose from ionizing radiation is present when the reactor is operational and present after an operating reactor is shut down. The dose is at its highest when the reactor is operating and is considerably lower when the reactor is shut down. The amount of dose present after reactor shutdown is a function of time of operation but also, and primarily, a function of time after shutdown. An example of the dose after shutdown and as a function of distance was presented in Table 4-1. This issue was discussed at some length in previous sections but is summarized here.

The direct shine dose from the reactor is mitigated by shielding, distance, and timing. For the operating reactor, a combination of shielding and distance (the habitat will be at least 1 km away) is used to ensure that the cumulative dose to the astronauts meets NASA criteria for radiation exposure. If astronauts need to move inside the reactor exclusion area, this is allowable, if the duration of time is short. The time will be dependent on how far the astronauts must move inside the exclusion area.

If the astronauts must get very close to the reactor, then the reactor can be shut down and allowed to “cool off”. Astronauts could approach the reactor in a day. If more than a week is used for cool off, then longer exposure times would be allowed.

6.2 Release of Radioactive Material

The accident behavior and thus the release of radioactive material for the small 10-kWe pilot plant reactor and the initial ISRU production plant reactor are assumed to be very similar. These two reactors’ designs will have much in common and are based on the Kilopower reactor concept. The larger reactor utilized for the commercial ISRU production plant reactor will be very different than the first two. Although some accidents and accident probabilities will be similar, many will differ greatly. The two types of reactors are examined separately. Sections 6.3 through 6.6 deal with the pilot plant and the initial ISRU production plant Kilopower-type reactors. Section 6.7 through 6.10 deals with a large 500- to 2,000-kWe liquid-metal cooled reactor.

6.3 Attributes of Pilot Plant and Initial ISRU Production Kilopower-type Reactors

The pilot plant and initial ISRU production reactors are assumed to be based on the Kilopower reactor design and assumed to have the following attributes:

- Metal fuel, fast neutron spectrum physics,
- Self-regulating physics for load following,
- Low power density (~1 to 10 watts/cc),
- Heat-pipe cooled,
- Stirling power conversion.

The reactor is assumed to behave similar to the results of the Kilopower Reactor Using Stirling TechnologY (KRUSTY) test[12]. The reactor should be load-following using physics, able to handle a loss of cooling/power generation using physics, have a low power density that allows it to easily move through transient situations, and finally, the ability to reject all of the decay heat through radiation only.

6.4 Accident Descriptions for a Kilopower-type Reactor

Reactor accidents can be postulated for a small Kilopower-type reactor on the lunar surface. It is important to note that no systematic safety analysis or risk assessment has been performed for this report. This report is based on previous studies, terrestrial reactor accidents, and author experience. The postulated accidents can be summarized as follows:

- Lander crashes during landing,
- Reactor goes critical during a crash on landing,
- Reactivity insertion accident on startup,
- Loss of power generation and no reactor SCRAM,
- Loss of ultimate heat sink, reactor core intact,
- Loss of ultimate heat sink, reactor core melts.

Each accident type is discussed in more detail in the following sections.

6.4.1 Lander Crashes During Landing

The spacecraft or lander may crash during the descent and landing process. A reactor that has crashed on landing could spread uranium across the lunar surface or could remain intact, but in a damaged state. This uranium has a very low amount of radioactivity and would present a low hazard to astronauts. It can only provide a dose if the uranium could be tracked back into a habitat where it could be inhaled. Inhalation from tracked contamination would not present a significant amount of dose given the low radioactivity and the difficulty in getting the uranium airborne inside the habitat. However, it would be recommended that the crash site be avoided by having an exclusion area. If astronauts are to be working in the area, the exclusion area should be carefully mapped out and marked. Any entry into the exclusion area would require careful planning and appropriate procedures. If the reactor is relatively intact, the exclusion area can be a few meters if it can be confirmed that the reactor did not go critical during the crash (described in more detail in the next section). Confirmation of criticality, or non-criticality, can readily be accomplished either by surviving instrumentation or by the astronauts on site who would be mapping out the crash site and any necessary exclusion areas.

In addition to the uranium, a small startup source (typically made of plutonium or americium plus beryllium and about the size of a pencil eraser) could be present. Sources are packaged to be very robust and will most likely survive intact. They are a mild emitter of neutrons, but not enough to present a significant hazard unless damaged to the point the material could be inhaled. Due to the low risk from either scattered uranium or a startup source, no additional safety design features should be necessary to deal with lander crashes not involving criticality.

6.4.2 Reactor Goes Critical During a Crash on Landing

The Kilopower reactors are designed to make going critical from impact with a surface a low probability event. Kilopower reactors are highly reflected fast reactors and they become subcritical with only minor neutron leakage from the core. Since the reflector is a highly brittle ceramic and the reactor core is a ductile metal, most impacts will cause cracks in the reflector that result in neutron leakage, thus making the core subcritical. Also, the reactor cannot go critical with the control rod in place, no matter the deformation of the core. The control rod mechanism is connected to the reflector, such that any event that would displace the control rod will also break or crack the reflector. Taken together, these design features mean inadvertent criticality on impact is a very low probability event. Note that the design must pass launch approval criteria for Earth departure that are more rigorous than would likely be necessary for a lunar landing, although specific safety criteria for a lunar landing have not been developed. Launch approval involves consideration of a large rocket and a nearby public. No additional reactor safety design features should be necessary for a lunar landing.

6.4.3 Reactivity insertion accident on startup

A small Kilopower-type reactor will have approximately $2 to $3 of excess reactivity before reactor startup. During startup, if the entire amount of excess reactivity could be inserted fast enough, the reactor could experience thermal stress to either melt the reactor core or cause the reactor to thermally disassemble. While neither is probable, reactor core melting is more likely than thermal disassembly.

A reactivity insertion accident is not possible after the reactor has achieved steady state. Approximately $2 of the excess reactivity will be removed by the reactor reaching an operating temperature of 800 °C. The amount of excess that will be designed into the reactor will only be about $0.50 above the amount needed to get to temperature. Since $1.00 of reactivity is needed to have the reactor be operating on prompt neutrons, the reactor can't go prompt critical with less than this amount. So, by designing the reactor to have less than $1 excess reactivity at operating temperature, reactivity insertion accidents at operating temperature are precluded.

Reactor melting would probably terminate the accident given the geometry change in the metal core. The small amount of fission products and melted uranium metal would likely be contained in the reactor can and shielding. This consequence is discussed in more detail later.

Thermal reactor disassembly could send uranium metal and a small amount of fission products several tens of feet or more onto the lunar surface (the consequences are described in more detail later). Given no lunar atmosphere, the debris would likely not move beyond the area of disassembly. This accident is considered extremely unlikely because the control rod mechanism is designed to eliminate this accident. The control rod mechanism insertion and withdrawal speed will be mechanically limited by both gearing and the electric motor speed. The maximum allowable insertion rate will be much lower than what is needed to cause a reactivity insertion accident that leads to either melting or thermal disassembly. More detail on reactivity insertion accidents is presented in McClure et al[13].

6.4.4 Loss of Power Generation and no Reactor SCRAM

A loss of all Stirling engines is a possibility, even though it is very unlikely. During this loss of power generation event, a heat-transfer path from the core through the Stirling engines to the radiator panels is still preserved, although heat transfer is diminished. If this event were to occur and the reactor was not SCRAMed (i.e., rod inserted to shut down fission), the self-regulating reactor core will lower the power a value equal to the heat transferred to the radiator panels plus the heat radiated from the walls of the shielding. The ability of the Kilopower reactor to load follow was established during the KRUSTY test[14]. As long as the heat transfer exceeds the level of decay heat with no SCRAM, the ability of these heat transfer paths to cool the core will prevent melting. It is expected that the probability of this event will be low enough to ignore, but if not, the design should have sufficient heat transfer paths through the radiator panels and shielding.

6.4.5 Loss of Ultimate Heat Sink, Reactor Core Intact, Reactor SCRAMed

This accident assumes that the heat pipes all fail and no path to the radiator panels is available or that the radiator panels themselves are damaged and unavailable. This condition is an extremely low probability event, but it is postulated for completeness. Kilopower reactors have very low power density (~1 to 3 watts per cc) which is approximately two orders of magnitude lower than traditional terrestrial nuclear power reactors. Low power density means that transient events occur very slowly. A 10-kWe Kilopower reactor will have to reject about 1% of the decay heat several hours after shutdown. The thermal power of the reactor at full power is 40 kWt, which means the core has to reject ~400 watts of decay heat. In this scenario, the reactor core only has radiative heat transfer to reject these 400 watts (this conservatively assumes no means of conduction to the shielding or another solid surface is available). Hand calculations show that radiative heat transfer alone is enough to reject 400 watts of power. There is not much margin in the calculations, but if the core is just below the melting temperature of uranium (~1400 K) then the core will be able to reject the decay heat and keep the core intact. It is expected that the probability of this event will be low enough to ignore, but if not, the core heatup and heat transfer rates should be adequate and confirmed.

6.4.6 Loss of Ultimate Heat Sink, Reactor Core Melts

This scenario is the same as the previous scenario in that there is no means of core heat removal other than radiative heat transfer. In this scenario, the assumption is that the radiative heat transfer is not enough to prevent core melt and the core slumps in the core can and shielding until conductive contact is made with other materials. The core is cooled through a combination of conduction and radiative heat transfer and does not melt any further after the initial melt. Thus, the uranium material would be fully contained within the reactor assembly. This accident is largely precluded by the Kilopower design and is included here for completeness.

6.5 Failure Modes for a Kilopower-type Reactor

The primary failure modes fall into two broad camps, first, the failure associated with the spacecraft/lander and second those associated with the reactor power system.

Spacecraft/lander failure modes are multiple and can be seen as those that will cause a crash during landing. They will not be addressed in detail here, but it is assumed that these will be the focus of the reliability program for the spacecraft and lander.

The reactor has several failure modes, including:

- Failure of design to prevent criticality on impact,
- Failure of the control rod motor/gearing,
- Failure of the heat pipes,
- Failure of the Stirling engines,
- Failure of the PMAD subsystem, and
- Failure of the heat rejection subsystem.

6.5.1 Failure to Prevent Criticality Upon Impact

The Kilopower reactor is designed to prevent criticality upon impact with the lunar surface. The failure mode would be a design failure, such that the control rod is ejected in combination with the reflector staying intact. The design of the reactor makes this situation almost impossible since the rod housing is connected to the reflector. Also, the reflector is made of brittle beryllium oxide (BeO), which should crack upon impact. Very small cracks (on the order of millimeters or greater) will cause the system to lose enough neutrons that even though the control rod has been ejected the reactor still should remain subcritical.

6.5.2 Failure of Control Rod Motor/Gearing

The failure of the control rod drive mechanism could introduce a reactivity insertion. This condition is eliminated by the gearing and speed of the motor. A failure of the control rod drive mechanism could cause the inability to SCRAM or shut down the reactor. The latter does not cause an accident but due to the self-regulating nature of this reactor, this does mean that the reactor will run until another failure occurs which would cause the reactor to shut down.

6.5.3 Failure of the Primary Heat Pipes

The failure of the primary heat pipes will cause a reduction in the amount of heat removal from the reactor. Again, the ability of the reactor to adjust heat generation to this event will prevent an accident. If more than approximately one-third of the primary heat pipes fail, a situation could occur where the potential for the reactor core to melt will exist. Each Stirling engine string and its dedicated quantity of primary heat pipes is mechanically independent from other strings. The failure of one string will redistribute heat to the nearby strings, causing more thermal and mechanical stress, but each string has margin to allow for this condition. The system output power should not be significantly impacted until the number of heat pipe failures exceed the 33% estimate mentioned above. If additional heat pipes fail, the core will automatically adjust to failures given the load following capability of the reactor. So, failure of the primary heat pipes does not mean the core will melt since radiation heat transfer is sufficient to cool the reactor core (as discussed in Section 6.4.5). There is some uncertainty in this calculation such that it can't be completely ruled out, but it would be an extremely low probability event. Also, this means that other issues (such as micro-meteoroids) could damage the heat pipes and still not cause core melting.

6.5.4 Failure of the Stirling Engines

The failure of the Stirling engines causes the loss of power generation and the reduction in the amount of heat removal from the reactor. However, a reduction in heat removal does not cause an accident since Kilopower-type reactors will use negative-temperature reactivity feedback principles to load follow and reduce the heat produced by the core to the level being removed. A loss of power generation is a threat to the astronauts only for scenarios where the reactor is the only source of power for astronaut survival.

Load following is another way of stating that the reactor is self-regulating. The reactor will essentially adjust the power output of the reactor core to the power demand of the Stirling engines. The boron carbide control rod in the reactor acts as a thermostat to set the reactor supply temperature. As the power conversion system demands more or less power, the reactor automatically adjusts to the demand using reactor physics. The physics is based upon the negative temperature coefficient of the system. Essentially, if the power conversion demands less power, the lower demand heats the core, which then gets slightly bigger leaking more neutrons to adjust the reactivity down to achieve the new steady state. If the power conversion demands more power, the greater demand cools the core, which then gets slightly smaller lowering the leakage of neutrons to adjust the reactivity up to the new steady state.

This phenomenon would hold for reactors with the same physics and power conversion up to about 100 kWe in size. Larger systems could be designed to preserve this operating feature, but additional analysis and testing would be required to verify the performance.

6.5.5 Failure of the PMAD Subsystem

The failure of the PMAD will disrupt the power distribution to systems that need electricity. This may cause issues for the lunar installation and equipment but will have little effect on the reactor. The reactor will be shut down or the power lowered, and the excess power shunted to the heat-rejection subsystem. For a self-regulating reactor like Kilopower this reduction in power would be automatic as the reactor physics will bring the reactor into an equilibrium temperature that adjusts the power level to accommodate the heat rejected.

6.5.6 Failure of the Heat Rejection Subsystem

The failure of the heat-rejection subsystem would cause a loss of ultimate heat removal. The reactor would respond by heating up and lowering power produced to that which was being rejected by radiative heat transfer. Much like the loss of the heat pipes, this situation would not cause the reactor to melt down but lower the power output to a level that can be rejected. The reactor could still be shut down and no adverse impacts would be expected.

6.6 Accident End States, Transport of Radioactive Material and Consequences for a Kilopower-type Reactor

The accidents postulated in Section 6.1 can be assumed to terminate in the following end states:

- Reactor fuel is dispersed during impact on the surface,
- Reactor fuel and small amounts of fission products are dispersed because the reactor core thermally disassembles during a reactivity insertion event on startup,
- Reactor core melts and slumps inside the core can during a loss of ultimate heat sink accident; potential for radioactive aerosol breach of the reactor system.

Each is discussed in the following sections.

6.6.1 Consequences of Reactor Fuel Being Dispersed During Impact

The dispersal of uranium fuel during a crash will depend on many factors too complex to assess in this report. The gravity of the moon, the force of the impact, the size of the debris generated during the impact, will all influence the ballistic like trajectory of the debris. It is assumed that a debris field is generated that has debris of various sizes and is somewhat spread out (over many 10s of meters). Since the moon has no atmosphere it is assumed the debris will stay in place unless it is tracked back to the habitat by astronauts. The uranium fuel is mildly radioactive and emits radiation in the form of alpha particles. The debris will not impart a dose unless it is inhaled, and the amount must be substantial to deliver a dose that is considered life threatening. Other than contamination this end-state is not considered life threatening to astronauts. Operations near the reactor can take place without concerns except for bringing uranium into the habitat.

6.6.2 Consequences of reactivity insertion accident

A reactivity insertion accident that is of sufficient magnitude to thermally destruct the reactor will explosively disperse fuel and reactor debris out from the reactor in a debris field pattern. The size of the field will be dependent on the number of fissions caused by the insertion accident. Given that Kilopower-type reactors have only $2 to $3 of excess reactivity, the potential thermal disassembly will be bounded by approximately 5E17 fissions,[15] and the amount of energy available to disassemble the reactor will be relatively low. Still, it is assumed that the event could throw debris 10s of meters in any direction.

The fission products generated during a reactivity insertion on startup will be minimal. The fission product inventory is very low since the reactor was never operated (fissioned), except for a brief time during startup (10s of minutes or less). The amount of fission products would be about 100,000 times lower than a reactor that has operated months to years. The fission products will be mostly short-lived fission products that will completely decay away in a matter of minutes to months. Most of the radioactivity will be in the uranium fuel that is dispersed. In this manner, the consequences will resemble those from a crash on landing, except the debris field, may be smaller. The impact on astronauts is considered to be minimal except for local debris field contamination. If future operations are to be carried out in the area, the debris field should be mapped and an exclusion zone established.

6.6.3 Consequences of reactor core melt

The final accident end state is the potential for reactor core melt. Core melt will not be the energetic event it is for terrestrial reactors. First, a Kilopower reactor has low power density and only about 400 watts of decay heat. Neither does it have any pressurized energetic fluids like the high-pressure water/steam in a traditional light water reactor. So, the energetic release of radioactive aerosols will not occur.

It is theorized that a core melt would involve the core “slumping” to the bottom of the stainless-steel core can until it contacts the can and solidifies. Since the moon is essentially a vacuum, the uranium and fission products will have a lot of vapor pressure relative to their environment, thus vapor and aerosols are expected to form.

The main two mechanisms that act upon the radioactive aerosols and vapor are gravity and thermophoresis. Gravity will tend to keep the aerosols or vapor local since no atmospheric drivers (like wind) are present. Thermophoresis is the movement of aerosols due to a temperature gradient. What this means is that any loose aerosols or vapor will move from the hot reactor core and plate out on the nearest cold surface, like the reactor shielding or lunar surface. In a core melt scenario, the contaminated area will be immediately adjacent to the reactor. So, although the fission products are very radioactive, they will be confined to the area just around or inside the reactor.

Astronauts are not threatened by a core melt accident unless the reactor is approached, and the astronauts track contamination back to the habitat. A reactor that has operated for months or years will contain large amounts of highly radioactive elements. A dose can be received either through contact, direct shine if the astronaut is very close (~meters) or the inhalation of these fission products. A consequence can only be assumed if the reactor is approached, the astronaut remains in the area for a long time or the contamination is tracked back to the habitat, and the contamination is spread throughout the habitat such that it stays on the skin or is inhaled.

6.7 Attributes of a Large (~500 kWe) Reactor

A 500-kWe reactor will most likely have the following attributes:

- A gas Brayton power conversion system,
- Uranium fuel in cladded pins,

- Either direct gas cooling or liquid metal cooling with a heat exchanger to the gas used by the Brayton system,
- An active control system with control drums in the reflector. The control system can control the drums and pumps to adjust reactor operating conditions,
- A passive or active means of removing decay heat.

These assumptions will be used to postulate accidents, failure modes and consequences.

6.8 Accident Descriptions for a Large Reactor

Reactor accidents can be postulated for a 500-kWe reactor on the lunar surface. These accidents are not based upon a particular design or a systematic safety analysis. This report is based on previous studies (an example is Dykes and Franks[16]), terrestrial reactor accidents, and author experience. The postulated accidents can be summarized as follows:

- Lander crashes during landing,
- Reactor goes critical during a crash on landing,
- Reactivity insertion accident on startup or during operations,
- Core damage during startup (freeze/thaw, etc.),
- Core damage during operation (fuel failure, etc.),
- Loss of primary system coolant,
- Loss of ultimate heat sink,
- Loss of power conversion with no SCRAM.

Each accident is discussed in detail in the following sections.

6.8.1 Lander Crashes During Landing

This accident will be identical to the one for the small Kilopower reactor. The uranium will be dispersed over an area. Consequences will be similar in that uranium fuel will be scattered and only present a dose issue if tracked back to the habitat.

6.8.2 Reactor Goes Critical During a Crash on Landing

This accident cannot be analyzed in detail, given that inadvertent criticality on impact is almost entirely a function of the reactor design, which is not detailed enough to speculate on in this report. Launch safety requirements will be imposed on the design, so the probability of this event will be very low, and additional requirements for landing are not expected to be necessary. The behavior of the reactor going critical will be similar for a Kilopower reactor, with uranium and fission products being spread over an area of the moon. The amount of fission products may be larger, depending on the reactor design.

6.8.3 Reactivity Insertion Accident on Startup or During Operations

This class of accidents covers a range of reactivity insertion events that can occur during startup or normal operations. The design will dictate how these events could occur, but in general, they would be the inadvertent control drum rotation, voiding in the coolant, or other general failures leading to a reactivity insertion. The most damaging would be those on startup since that is typically when the most excess reactivity is present, but others could occur during operation. These events could cause the reactor core to melt or thermally disassemble. The consequences will be discussed later.

6.8.4 Core Damage During Startup (freeze/thaw, etc.)

A class of accident that could occur is damage to the reactor core and primary system during startup. Examples include breaking of piping caused by the freeze/thaw cycle with liquid metal coolants, pressure-induced failures during startup, and thermally induced failures during startup. The result is the reactor will be shut down and the asset would be lost. The limited number of fission products produced would be contained within the reactor system, and any subsequent exclusion area around the reactor would be very small.

6.8.5 Core Damage During Operation (fuel failure, etc.)

The core could experience many failures during operation. Fuel pin leakage would be the primary failure. This could be caused by fuel swelling, fuel cracking, or corrosion of the fuel pin. Other failures include thermal failures in the core region such as fuel buckling or core block cracking. The anticipated result of these accidents is the release of fission products into the primary system. This may or may not result in the release of fission products outside the reactor. These failures could lead to a reactor shutdown and loss of the asset.

6.8.6 Loss of Primary System Coolant

The loss of the primary coolant could be caused by corrosion, a micrometeoroid, thermal stress, pressure stress, seal leakage, weld failure, and other holes in the primary system. The cause of these loss of coolant accidents will be very dependent on the particular design. A loss of coolant accident can cause a loss of heat removal from the reactor core that could induce a core melt. The melted core could then breach the primary system and cause a release of fission products to the lunar surface. The consequences of a full core melt are described in detail later in this section. Loss of flow due to pump failure is addressed in Section 6.9.5. Loss of flow does not in of itself lead to an accident but will cause the reactor to be shut down.

6.8.7 Loss of Ultimate Heat Sink

Even if the reactor is cooled by the primary coolant, there must be a heat transfer path to the ultimate heat sink, which for a lunar reactor will typically be radiator panels. The heat removal path for these radiator panels could be a pumped loop coolant. The causes for this accident could be the loss of a pump, the loss of coolant in the heat rejection system, the failure of a heat exchanger, the loss of gas in the power conversion system, or other failures that will be design dependent. The result of this accident could be a full core melt.

6.8.8 Loss of Power Conversion with no SCRAM

A failure mode for the reactor includes a failure of the power conversion system with the heat-transfer path to the ultimate heat sink and decay heat removal system still functioning. This will mean that the system is removing heat, but not to the level being produced by the reactor. If the system is shut down (SCRAMed) then no accident occurs. If this condition were to happen with no SCRAM, then the core would melt given the lack of adequate heat removal. This accident is considered to be an extremely low probability but is included for completeness. The end state would be a core melt accident. The melting of the core will most likely terminate fission and shut down the reactor.

6.9 Failure Modes for a Large Reactor

The failure modes for the greater than 500 kWe reactor will be very design specific. But a generalized set of failures will be postulated. Many of these failures can be either eliminated or made to be low probability by the design of the reactor. Generic failures include:

- Failure of design to prevent criticality on impact,
- Failure of the reactor control system,
- Failure of the thaw system during startup,
- Failure of core internals,
- Failure of fuel pins,
- Failure of the circulating pumps,
- Breach of the primary system boundary,
- Failure of power conversions system,
- Failure of the PMAD subsystem,
- Breach of power conversion boundary, and
- Failure of the ultimate heat sink (radiator loop).

Each is discussed in more detail in the following sections.

6.9.1 Failure of Design to Prevent Criticality on Impact

The greater than 100-kWe reactor should be designed to lessen the probability that it goes critical on impact. As an example, a typical design constraint is limiting each control element (the control drums) to be worth less than $1 in reactivity. Other potential design features include locked safety rods prior to landing, the potential use of burnable poisons and the height to diameter ratio of the core to be greater than 2. No additional features are likely to be needed beyond those required for launch approval.

6.9.2 Failure of the Reactor Control System

The reactor control system should be designed to eliminate failure that would inadvertently insert reactivity. This is accomplished by limiting drum speed through motor and gearing, limiting the amount of reactivity in each control drum to less than $1, or through other suitable design strategies. While positive power coefficients are to be avoided, the control system must be designed to handle any credible power excursions. The reactor should typically have multiple means of shutting down the reactor. This is accomplished by having a central control rod to shut down the reactor or a combination of control drums shutting down the reactor.

6.9.3 Failure of Thaw System for Startup

If this reactor uses a liquid metal for the primary system coolant, then this coolant must be thawed before reactor startup. A gas-cooled reactor will not require this system.

The thawing system is traditionally a combination of heaters and possibly low reactor power used to thaw the liquid metal coolant and establish flow through the core via a pump to the heat exchanger before going to full power.

This system could produce a situation where a frozen section blocks flow causing the pump to over-pressurize the system. As coolant is unfrozen simple expansion during the unfreezing process can stress components and cause failure.

6.9.4 Failure of Core Internals, Including Fuel Pins

Thermal stresses and induced mechanical stresses could cause the failure of reactor core internals including fuel cladding. The failure of internals could induce other failures leading to reactor shutdown or other accidents.

6.9.5 Failure of the Circulating Pumps

If the primary system or secondary (Brayton system) pumps fail, then the reactor will have to be shut down. The failure of either system could be part of a chain of failures leading to other accidents such as a loss of heat removal from the core. By itself, the loss of the pumps will not lead to an accident. Design specific analysis would be required to determine the reactor end-state.

6.9.6 Breach of the Primary System Boundary

The failure of the primary system boundary will be from either corrosion, micrometeoroids, or an induced stress failure. The breach of the primary system boundary could lead to a loss of coolant accident and, possibly, core melt. This will allow for the release of radioactive fission products that have escaped the fuel cladding boundary.

6.9.7 Failure of Power Conversions System

The failure of the power conversion system could be due to the loss of the circulation pump, the loss of the turbine, or due to a loss of the working fluid gas. The failure of the power conversion system may lead to a reduction in the ability of the reactor to remove heat but shutting down the reactor should terminate the accident.

6.9.8 Failure of the PMAD Subsystem

The failure of the PMAD will disrupt the power distribution to systems that need electricity. This may cause issues for the lunar ISRU installation and equipment but will have little effect on the reactor. The reactor will be shut down or the power lowered, and the excess power shunted to the heat rejection subsystem. For the larger reactor power system with a pumped loop cooling system, such power changes would need to be accomplished with the reactor protection system in order to balance the decay heat input to the cooling system with the capabilities of the heat rejection radiators and the power conversion system.

6.9.9 Breach of Power Conversion Boundary

This failure mode is essentially identical to the failure of the power conversion system. If the boundary fails, the working fluid would be lost and lead to the failure of the power conversion system.

6.9.10 Failure of the Ultimate Heat Sink (radiator loop)

The ultimate heat sink on the moon will be radiator panels. The heat removal mechanism most likely to be used is a pumped-liquid loop to the radiator panels. If the loop or the pumps fail, then the ultimate heat sink will fail. If the ultimate heat sink fails, then the only cooling mechanism will be the passive decay heat removal from the reactor core. Radiative heat transfer through the core internals to the shielding and outward into space is unlikely to be sufficient to keep the reactor core cool. A potential result of the failure of the ultimate heat sink is core melting.

6.10 Accident End States, Transport of Radioactive Material and Consequences for a Large Reactor

The reactor end states will essentially be the same as those for the small Kilopower reactor; however, with a larger inventory of fission products. The fission products in a large reactor are essentially linear with power. So, the fission product inventory of an ~500-kWe reactor will be approximately 50 times that of a Kilopower-type reactor.

The end states that will apply to the ~500-kWe reactor are then:

- Reactor fuel is dispersed during impact on the surface,
- Reactor fuel and small amounts of fission products are dispersed because the reactor core thermally disassembles during a reactivity insertion event on startup,
- Reactor fuel and large amounts of fission products are dispersed because the reactor core thermally disassembles during a reactivity insertion event during operation (although this is an extremely low probability event),
- Reactor core melts and slumps inside the core can during a core melt accident; potential for radioactive aerosol breach of the reactor system.

See Section 6.6 for more detail on each of these situations.

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[17,18]. These issues are not relevant to a lunar mission and are not addressed here.

7.1 Planetary Protection Requirements for Lunar Missions

NASA Procedural Requirement 8020.12D describes the planetary protection categories of solar system bodies and how they should be treated[17]. The Moon is a Category II object that requires limited analysis for a lander that is not returning to Earth. NPR 8020.12D does require documentation to confirm the limited impact on the Moon and specifies clean room requirements for assembly of the spacecraft.

7.2 Treaty and Operational Impacts

Planetary protection was addressed in the Outer Space Treaty, Article IX[19]. 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. It follows that sites containing nuclear material should be identified and communicated to others, including mapping of any resulting radiation areas.

Previous work has suggested that multiple reactors in the 10-kWe class can be located approximately 1 km from a habitat[8]. There is a tradeoff between shielding mass and the mass of cables that may be required for longer distances. It is assumed here that, even for the two larger reactors, it is not unreasonable to assume that sufficient shielding will be required to reduce a potentially hazardous radiation zone to less than 1 km. Outside of the hazardous zone, lunar operations can proceed without considering the presence of the reactor. The choice of 1 km might be reduced through further analysis and improved shielding designs. Note that if the reactor is not shielded equally on all sides, then an asymmetric hazardous zone may be needed. Whatever the final size and shape of the hazardous zone, it is important that activities of other nations are not planned for that area.

Following final shutdown, impacts are reduced to a radius of a few meters within a few weeks of shutdown. The ISRU pilot plant mission assumes that the reactor will not be moved after final shutdown. The other two missions assume that the reactors could be moved, if necessary, to a location that will not impact future operations. If a reactor is to be moved, there are a number of considerations:

- The reactor must be shut down with positive controls to ensure that it remains shut down during transport and final placement
- The reactor should be moved robotically
- Radiation monitoring should verify the state of the reactor during transport and final placement
- A transport path should be chosen that does not interfere with operations or provide a hazard to astronauts should the transport process be interrupted
- The final placement location should be clearly marked and communicated, with exclusion zones as necessary, depending on the radiation levels

While planetary protection impacts are expected to be minimal, there is a very low probability for nuclear accidents to spread contamination over a wider area. Nuclear systems are already designed with safety in mind, and the possible implications of nuclear accidents are discussed in Section 6. The probability of accidents causing interference with other lunar activities should be minimized.

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, RTGs or other small radioactive sources have been left in place on the Moon or Mars without any particular disposal strategy. For the ISRU pilot plant mission, it is anticipated that the lander and reactor will remain in place after final shutdown. For the initial and commercial ISRU production missions, the reactors may be removed from the lander, and theoretically could be moved again at the end of life.

8.1 Final Shutdown

D&D is considered when the reactor is shut down at the end of life. If the reactor is being put into standby mode for later use, it is not at the end of life, and the discussions in this section do not apply. For any of the three different reactor designs, the reactor will need to be shut down and verified to be in a safe state. This could be accomplished by reengaging the control rod/drum locking mechanism that was used during transport to the Moon. Safety rods could be inserted and locked in place. Alternatively, actions could be taken to change the configuration of the fuel or reflector to render the reactor permanently subcritical. Whatever means are chosen, the action should be verifiable and robust. This verification may require additional sensors or cameras to provide the confirmation.

8.2 Noninterference with Future Activities

8.2.1 ISRU Pilot Plant Mission D&D

As shown previously in Section 4, the dose rates adjacent to the reactor are likely to be in the millirem range within a few months of shutdown. In such cases, there is little reason to risk personnel exposures in working near the reactor until significant decay has occurred. Initial exclusion areas should be established, and radiation monitoring should continue until the radiation levels are benign at the surface of the lander (~1 year) and the permanent shut down status has been confirmed. The initial exclusion area for this pilot plant reactor can be approximately 10 m after 1 day. Such a small exclusion area is unlikely to impact future activities. However, if the need arises to access the lander in the future, procedures should be in place to ensure that the reactor cannot be damaged or inadvertently restarted.

8.2.2 Initial ISRU Production Plant Mission

Although the initial production plant reactors may operate at 10 times the power of the pilot plant reactor and have 10 times the fission product inventory, the shielding is expected to be designed to result in similar doses near the reactor. Therefore, since both reactors will follow a similar fission product decay profile, the dose rates adjacent to the initial ISRU production reactors are also likely to be in the millirem range within a few months of shutdown. The reactor can be treated the same as the pilot plant reactor in terms of exclusion areas and access controls. However, there is the possibility that the initial production plant reactors could be moved after final shutdown, either because they are in an inconvenient location with respect to ongoing operations or simply to move them to a safe disposal area far away from human operations. Such a move should be performed robotically. It may be preferable to move an entire reactor system including power conversion moved in one piece. Plans and procedures for such a move would need to be developed including:

- Positive and verifiable means to ensure that the reactors remain shut down
- Reactor design that allows for decoupling from power conversion and other equipment for transport, if necessary
- Availability of handling and transport equipment
- Selection of a transportation path that avoids human-occupied areas
- Contingency plans for breakdown along the transport path
- Preparation of the final site
- Final placement, possibly to include shielding or burial with regolith
- Means to monitor reactor status and radiation levels

- Development and management of exclusion areas around the final disposal site
- Disposal of any radioactive or hazardous components left behind at the reactor site
- Radiation survey to safely open up exclusion areas at the reactor site

8.2.3 Commercial ISRU Production Plant Mission

As with the initial production plant mission, reactor shielding is expected to be designed to result in similar low doses near the reactor. However, due to mass considerations, the commercial production plant reactor may rely on lunar regolith for part of the shielding. This may be accomplished by partially burying the reactor or providing berms around it. The area inside this shielding may experience higher radiation levels that those adjacent to the smaller reactors, thus complicating D&D activities. If the reactor is to remain in place, then it can be treated in much the same way as the two reactors discussed above. However, if it is to be moved, the operations will be more complex due to the larger size and the more complex cooling and power conversion systems that will have to be disassembled.

If the reactor is partially buried when it is installed, the final D&D could involve complete burial in place. This could occur after the reactor has cooled sufficiently to preclude melting after burial. The site should be marked and monitored for radiation following the burial but should pose no hazard to surrounding operations.

If the commercial production plant reactor is to be moved, a number of complex operations are involved. The reactor and associated systems will need to be disassembled into transportable sections. Due to the radiation levels this will need to occur robotically. The disassembly will likely be the reverse of the assembly operation that took place when the reactor was installed. However, some additional factors to consider for the full-size reactor are:

- Non-gaseous coolants are likely to be radioactive and will have to be contained and disposed of
- Gaseous coolants can simply be vented with appropriate radiation monitoring and astronaut protection
- There may be significant direct radiation shine from the components being transported

8.3 Abnormally Terminated Missions

The discussions above assume that a fission reactor mission is terminated normally. With proper design, any other outcome is unlikely. However, the robustness of the design must be verified, and for completeness, abnormal terminations are considered here. In the highly improbable event of an abnormal termination, e.g., a reactor accident, other measures may be necessary for D&D. In the unlikely event that fission products are scattered away from the reactor site, it is doubtful that it will be practical to fully clean up any potentially contaminated areas and separately dispose of the contaminated materials. If other activities are taking place in the area, it will be necessary to measure and map the radiation and contamination areas to establish appropriate exclusion areas. Detailed analysis will be needed to determine the time before the exclusion areas will be safe to approach. It is likely that these areas should be approachable within a few months for the pilot plant reactor and possibly longer for the larger reactors. Any radioactive materials available to be scattered are approximately proportional to the reactor power level; thus, there could be 50 times more such products available for the commercial ISRU production reactor than for the pilot plant reactor.

Since the moon has no atmosphere to transport fission products away from the site of an accident, the only mechanisms for scattering fission products are an energetic reactor accident (prompt criticality) or a high-pressure failure such as might be possible on the commercial ISRU production reactor. Otherwise, radioactive materials will remain at the reactor site, thus limiting the need for extensive exclusion areas. A special case may occur if the reactor is still intact but cannot be confirmed to be permanently shut down. In that case, a significant exclusion area may be needed around the reactor, perhaps on the order of a kilometer. Since abnormal termination adds significant complexity to D&D, it is important to keep the likelihood of such a termination very low, particularly accidents that involve a scattering of radioactive materials. Long-term plans will be needed for monitoring exclusion areas and ensuring that nearby operations do not encroach into those areas.

9.0 Documentation and Training Delivery

Each mission and planned activity within the mission will require the development of detailed procedures, plans, descriptions and documentation. As described in Reference 1 these will necessarily include "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."

Training will also need to be developed to accompany these procedures and operations in order to safely execute all of the mission details and activities. These will need to be developed along with the full development of the missions and reactor systems and cannot at this time be more completely described.

10.0 Conclusions

This report has described the operational aspects of a series of ISRU missions and the reactors that could be utilized to deliver electrical and thermal power to the ISRU plants and crew habitats. The proposed missions could facilitate the successful production of raw materials for use on the lunar surface and vehicle propellant material for crew and cargo transportation back to Earth and potentially on to Mars.

The full radiation fields surrounding all three reactors utilized to support these notional mission concepts will have to be analyzed and considered during the design of the system and the full radiation fields coming from the reactor systems will need to be mapped once the reactors are on the surface and operating. Any reactor shielding should be designed to accommodate crew approaches to the reactors, if astronauts will be working in the vicinity of these reactors. The design of the shielding for each of the multiple reactors at the outpost should consider the radiation fields coming from the other reactors and the possible need for astronauts and/or robots to approach any one of them. Plans for approach to the proximity of any one of the reactors must consider the radiation effects of the other reactors.

For any reactor system that may need to be human rated, it is important to consider not only the planned maintenance, but also any projected emergency maintenance. Contingency plans for approaching these reactors under various scenarios will need to be developed.

A wide array of possible maintenance scenarios for these reactors may exist, ranging from no planned maintenance on the pilot plant reactor to possible complicated maintenance scenarios, both planned and unplanned, for the commercial production plant. Some of the more important considerations include designing systems for ease of maintenance, extensive use of robotic maintenance to avoid using astronauts, providing redundancy, in place and portable radiation monitoring, and spare parts to facilitate repairs.

Reactor system setup and startup will need to be fully considered during the system design process. Each particular reactor will have its own special considerations. The inherent simplicity of the operation of self-regulating reactors during the early phases of the lunar ISRU outpost establishment will provide reactor and mission designers a degree of understanding and confidence as they move on to larger and more complicated systems. Keeping as many aspects of these missions as simple as possible will help to build the operational confidence in these systems. Restart of the reactors following shutdowns also needs consideration. This will be especially important if a reactor is providing life support and other critical functions and it is important to consider how fast a reactor may need to be restarted should it experience an operational anomaly.

It is expected that these reactors will need to utilize considerable amounts of autonomous control. Astronauts involved on these missions may need to be able to shut down the reactors locally by hitting a SCRAM button; however, having one local crew member constantly monitoring a reactor control board is impractical and should be avoided. Since there will be a time delay between the Earth-based mission control room, those who are monitoring the mission health will also not be able to send simple and straightforward commands to the lunar-based reactors. Thus, designing the autonomous controls for these reactors early in the reactor design process will be critical to mission success. The aim for these control systems should be to permit remote startup, make power changes, respond to environmental transients, and shut them down as simply as possible.

Using reactors on the moon presents unique hazards with respect to their possible abnormal operations. The full analysis of these highly unlikely events and malfunctions for each reactor will need to be accomplished during the mission and reactor designs. Detailed analysis will need to be applied to a variety of reactor malfunctions that could occur and these will be very system-design specific. Utilizing the simplest, self-regulating reactor and system designs on the early missions will build important understanding and experience to enable effective operations of larger, more functional systems in later missions.

Any planetary protection impacts of these reactors for the ISRU missions are expected to be minimal. There does remain a very low potential for nuclear accidents to spread contamination over a wider area. Nuclear systems are already designed with safety in mind, and the possible implications of nuclear accidents will need for be analyzed during the mission and system designs. The probability of accidents causing interference with other lunar activities should be minimized.

Post-operational decommissioning and disposal needs to be considered to ensure that the shut down reactors do not interfere with other planned activities. Exclusion areas should be established, and radiation monitoring should continue until the radiation levels are benign at the surface of the lander and the permanent shut down status has been confirmed. The initial exclusion area for the pilot plant reactor can be quite small and all three reactors can be treated very similarly in terms of exclusion areas and access controls. In the event of an abnormal termination, other measures may be necessary for D&D. In the unlikely event that fission products are scattered away from the reactor site, provisions may be needed to clean up the area and dispose of the fission products or control activities that are planned in the area. It will also be necessary to measure and map the radiation areas and establish appropriate exclusion areas.

11.0 References

1 A. C. Klein, et al., Operational Considerations for Space Fission Power and Propulsion Platforms, NASA/CR-2020-220569, March 2020.

2 A. Camp, A. Klein, P. McClure, P. McCallum, and S. Voss, "Potential Improvements to the Nuclear Safety and Launch Approval Process for Nuclear Reactors Utilized for Space Power and Propulsion Applications," NASA/TM-2019-220256, February 2019.

3 A. Camp, E. Borenstein, P. McClure, P. VanDamme, S. Voss, and A. Klein, "Fission Reactor Inadvertent Reentry," NASA/CR−2019-220397, August 2019.

4 J. O. Elliott, B. Sherwood, A. Austin, M. Smith, R. Polit-Casillas, A. S. Howe, G. Voecks, A. Colaprete, P. Metzger, K. Zacny, V. Vendiola, "ISRU in Support of an Architecture for a Self-Sustained Lunar Base," 70th International Astronautical Congress (IAC), Washington D.C., United States, 21-25 October 2019.

5 M. A. Gibson, D. I. Poston, P. McClure, T. J. Godfroy, M. H. Briggs, J. L. Sanzi, "Kilopower Reactor Using Stirling TechnologY (KRUSTY) Nuclear Ground Test Results and Lessons Learned," NASA/TM—2018-219941, October 2018.

6 L. S. Mason, C.C. Rodriguez, B.I. McKissock, J.C. Hanlon and B.C. Mansfield, "SP-100 Reactor With Brayton Conversion for Lunar Surface Applications", NASA/TM-105637, January 1992.

7 Human Integration Design Handbook, NASA/SP-2010-3407/Rev 1, June 5, 2014.

8 M.A. Rucker, "Integrated Surface Power Strategy for Mars," NASA, Nuclear and Emerging Technologies for Space, February 23-26, 2015.

9 NASA Procedural Requirement 8705.2C, Human-Rating Requirements for Space Systems, July 10, 2017.

10 NASA Reliability and Maintainability (R&M) Standard for Spaceflight and Support Systems, NASA-STD-8729.1, Revision A, June 13, 2017.

11 Poston, David I., "Kilopower Mars Surface Shielding Options," Los Alamos National Laboratory, presented to NASA Johnson Spaceflight Center, Houston, Nov 19th, 2015

12 D. I. POSTON, et al. "Results of the KRUSTY Nuclear System Test," *Nuclear Technol.*, **206** (2020).

13 P. R McClure, et al. "KRUSTY Experiment – Reactivity Insertion Accident Analysis," *Nuclear Technol.*, **206** (2020).

14 D. I. POSTON, et al. "Results of the KRUSTY Nuclear System Test," *Nuclear Technol.*, **206** (2020).

15 McClure, Patrick, “Kilopower Space Reactor Launch Safety, Maximum Credible Fissions for a Criticality Accident,” LA-UR-18-28896, Los Alamos National Laboratory, 2018.

16 Dykes, Andrew A and Frank, Michael V. “Identification of SP-100 Initiating Events,” Pickard, Lower and Garrick, PLG-0647, August, 1988.

17 Planetary Protection Provisions for Robotic Extraterrestrial Missions, NASA Procedural Requirement 8020.12D, Effective Date: April 20, 2011.

18 NASA Policy Directive, Biological Contamination Control for Outbound and Inbound Planetary Spacecraft (Revalidated 05/17/13 w/change 1) NPD 8020.7G, February 19, 1999.

19 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, October 10, 1967.

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14. ABSTRACT
This report identifies the considerations related to the operation of space nuclear power reactors that would be utilized for In Situ Resource Utilization (ISRU) missions on the lunar surface. The objective of this study is to evaluate the operational complexities of reactors that would provide electrical and thermal power to a growing lunar ISRU and mining outpost/base.

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