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Operational Considerations for Fission Reactors Utilized on Nuclear Thermal Propulsion Missions to Mars

A Report to the Nuclear Power & Propulsion Technical Discipline Team

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January 2021

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Nomenclature

ALARA	As Low as Reasonably Achievable
ANSI	American National Standards Institute
CME	Coronal Mass Ejection
D&D	Decommissioning and Disposal
DAV	Descent/Ascent Vehicle
DRA	Design Reference Architecture
ECLSS	Environmental Control and Life Support System
ECS	Engine Control System
EDL	Entry, Descent, and Landing
EVA	Extra-Vehicular Activity
FE	Fuel Element
FMEA	Failure modes and Effects Analysis
HALEU	High-Assay Low Enriched Uranium
HEU	High Enriched Uranium
klbf	Kilo Pounds Force
kN	Kilo Newton
kWt	Kilo Watt Thermal
LH_2	Liquid Hydrogen
MOC	Mars Orbit Capture
MTV	Mars Transfer Vehicle
MW	Megawatt
MWt	Megawatt Thermal
NASA	National Aeronautics and Space Administration
NbC	Niobium Carbide
NCRP	National Council on Radiation Protection & Measurements
NERVA	Nuclear Engine for Rocket Vehicle Application
NESC	NASA Engineering and Safety Center
NTP	Nuclear Thermal Propulsion
PRA	Probabilistic Risk Assessment
PSA	Probabilistic Safety Analysis
RTG	Radioisotope Thermoelectric Generator
SHAB	Space Habitat
SM	Service Module
SNRE	Small Nuclear Rocket Engine
TDT	Technical Discipline Team
TEI	Trans-Earth Injection
TMI	Trans-Mars Injection
TPCV	Turbine Power Control Valve
UC_2	Uranium Carbide
UC_2-ZrC	Uranium Carbide and Zirconium Carbide
ZrC	Zirconium Carbide
ZrH	Zirconium Hydride

1.0 Introduction

This report is aimed at identifying the implications associated with the operation of space nuclear power reactors that would be utilized for Nuclear Thermal Propulsion (NTP) missions to Mars. The objective of this study is to evaluate the operational features of reactors that could provide propulsion and possibly electrical power for future crewed and cargo missions to Mars. This report follows upon an initial report[1] looking at the generic considerations for operating fission reactors in space applications and is intended as a deeper dive into the operational features related to specific Mars NTP applications. This report does not intend to rehash the potential interactions and concerns 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 primary premise of this study is to explore the operations of fission reactors to deploy transportation spacecraft for one-way cargo and round-trip crewed missions utilizing NTP from Earth orbit to Mars orbit. There would be multiple reactors included on each of these spacecraft to provide added reliability for mission success.

The mission scenario is based largely upon data contained within “Human Exploration of Mars Design Reference Architecture 5.0” (referred to throughout this report as DRA5.0) and its two addenda (referred to as DRA5.0-ADD and DRA5.0-ADD2, respectively) that describe a prospective full mission to Mars.[4,5,6] The scenario assumed that each round-trip crewed mission would be preceded by two one-way cargo delivery missions that would be flown in parallel. One of the cargo trips would deliver the surface habitat (SHAB) for the crew to utilize once they arrived in Martian orbit. The second cargo mission would deliver the descent/ascent vehicle (DAV) to Mars orbit for the crew to take to the Martian surface. The crew would leave Earth orbit and arrive in Mars orbit in the crewed Mars Transfer Vehicle (MTV) after both cargo missions were deemed to be successful. The overall mission, including all cargo and crewed flights would take over six (6) years and be part of a two-mission scenario as depicted in Figure 1-1 (Figure 2-1 from NASA/SP–2009–566).

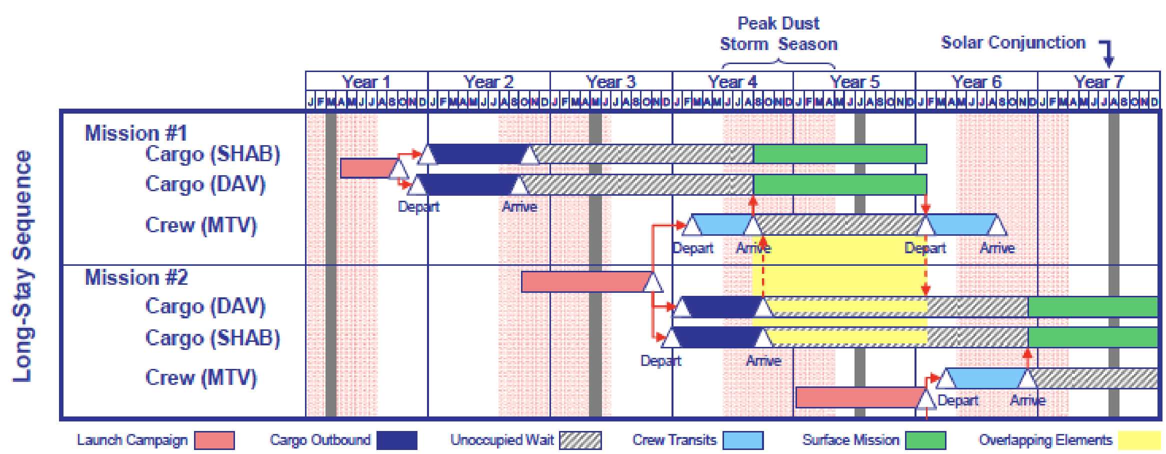

Figure 2-1. Mission sequence timelines.

Figure 1-1. Mars mission sequence timelines.
(Figure 2-1 from NASA/SP–2009–566)

Each of the cargo missions would include just one full power NTP reactor system propulsive burn for Trans-Mars Injection (TMI). The total NTP engine burn time for each cargo mission is expected to be approximately 39 minutes. The crewed mission is expected to include a total of three separate NTP engine burns, one for TMI for approximately 55 minutes, one for Mars Orbit Capture (MOC) for approximately 15 minutes, and one for Trans-Earth Injection (TEI) for approximately 10 minutes for a total reactor burn time per full round-trip mission of approximately 80 minutes. Each of the cargo missions is expected to take approximately 350 days to reach Mars. The crewed mission includes an approximately 180-day trip time from Earth to Mars, approximately 500 days of residence time on the Martian surface by the crew, followed by a 180-day return to Earth trip time. The NTP version of DRA5.0 is shown in Figure 1-2 (Figure 2-2 from NASA/SP–2009–566).

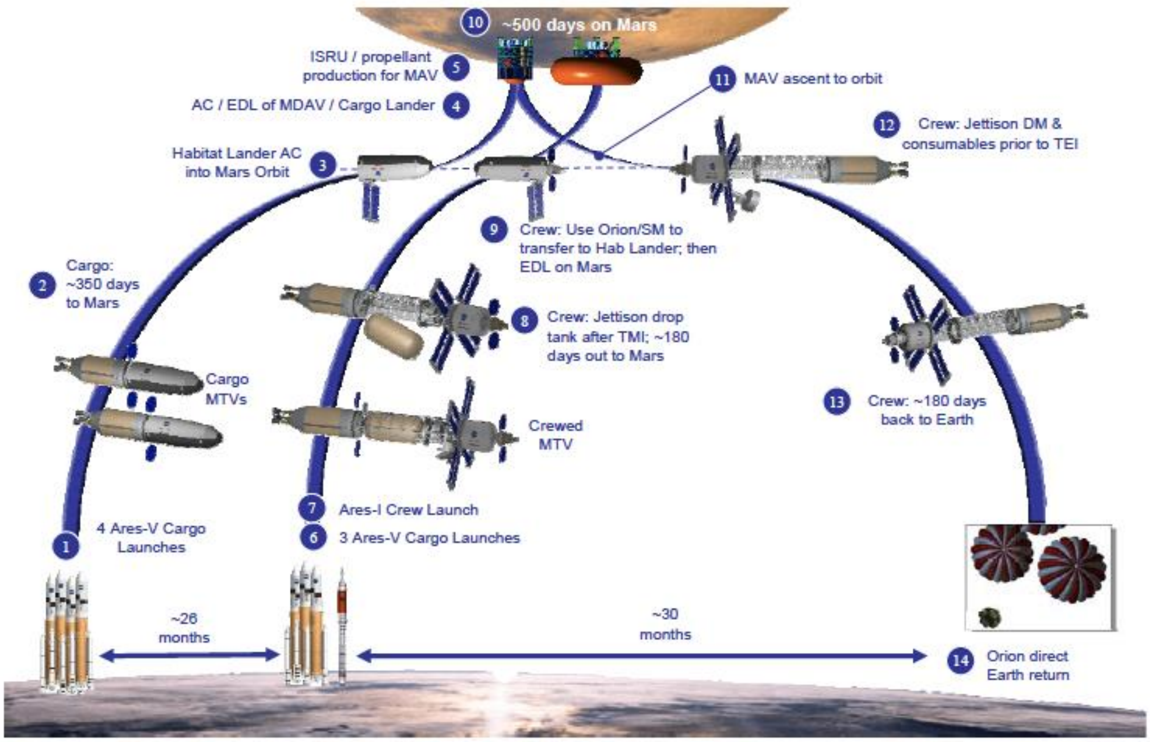

Figure 2-2. Mars Design Reference Architecture 5.0 mission sequence summary (NTR reference).

Figure 1-2. NTP version of Mars DRA5.0 mission.
(Figure 2-2 from NASA/SP–2009–566)

The spent NTP stages for the two cargo flights and their reactor systems would be disposed of after releasing their cargo into Mars orbit and would continue on a flyby trajectory past Mars into the Solar System. End of life for the crewed mission propulsion stage would involve disposal of the reactors into “heliocentric space.” As described in DRA5.0-ADD, “After an approximately 6-month trip time, the crew enters the Orion/SM (service module), separates from the MTV, and subsequently enters the atmosphere while the MTV flies by Earth at a “sufficiently high altitude” and is disposed of into heliocentric space.”[5] It could be important to design the return to Earth flight path on any crewed missions to minimize the probability of an inadvertent reentry of the reactors into the Earth’s atmosphere, while enabling a safe return to the Earth’s surface for the crew.

1.2 Reactor Description

All the reactors considered in this study are assumed to be of the same type, power level, and operational features defined most broadly as “NTP reactors.” Additionally, each of the spacecraft included in the crewed and cargo missions would employ three NTP reactors and each of the three NTP reactor systems included on the spacecraft would be identical to the others. All spacecraft for the two cargo flights and the one crew mission would use a common “core” propulsion stage with three 111-kN (25-klbf) “Pewee-class” NTP reactor systems. The DRA5.0 and addenda describe these reactors as

> “A NERVA [Nuclear Engine for Rocket Vehicle Application]-derived engine uses a “graphite matrix” material fuel element (FE) containing the ^{2,3,5}U fuel in the form of uranium carbide (UC_2) microspheres or as a dispersion of uranium carbide and zirconium carbide (UC_2-ZrC) within the matrix material, which is referred to as “composite” fuel.”

Such a compact fission reactor core utilizing enriched ^{2,3,5} U fuel will generate 100s of MWt to heat the liquid hydrogen (LH_2) propellant to high exhaust temperatures. The “NERVA-derived engine,” shown in Figure 1-3 (Figure 5-32 from Reference 5), is based on decades old, but proven, Rover/NERVA technology.[7] State-of-the-art NERVA designs, along with modern NTP fuels and reactor concepts are currently under research and development, and it is expected that advancements would likely be utilized for the eventually selected core design. However, for the purposes of this deep-dive study on operations, it is expected that while some of the finer operational details may change with better designs and core materials, those can be evaluated when a flight-ready design is actually completed.

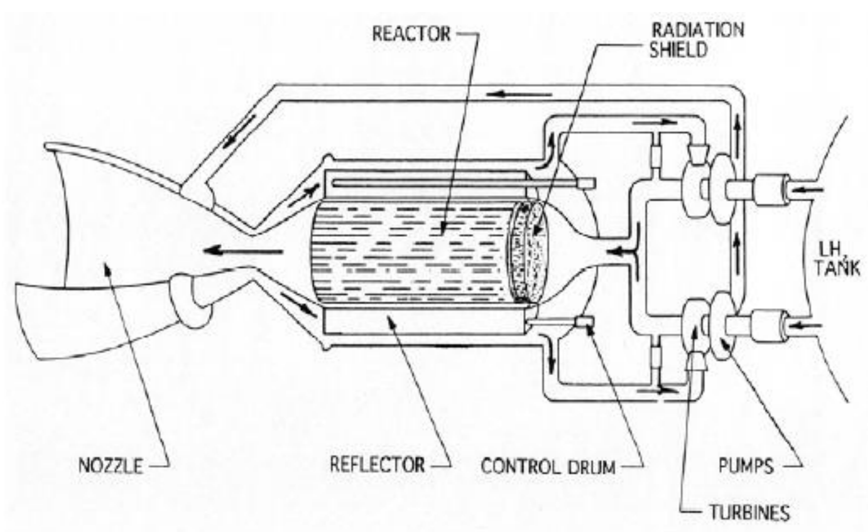

Figure 5-32. Schematic of expander cycle, dual-liquid-hydrogen turbopump NTR engine.

Figure 1-3. NTP engine as described in DRA5.0.
(Figure 5-32 from NASA/SP–2009–566-ADD1)

More detail on NASA’s Mars mission architecture and the reactor configurations are included in a 2009 AIAA Conference Proceedings paper[8] and in a 2014 NASA/TM that describes the capabilities for fast travel between Earth and Mars using NTP.[9] A summary of mission and reactor capabilities and key details of this notional reactor configuration are included in Table 1-1. Figure 1-4 provides graphical detail of the two considered candidate fuel element constructions for the Small Nuclear Rocket Engine (SNRE) considered in NASA/TM—2014-218104.

Table 1-1. Notional NTP Reactor Parameters, Assumptions and Attributes.

Reactor and NTP Engine (each)	NERVA/Rover-type engine Greater than 500 MWt for a 25 klbf-class NTP engine High-assay low enrichment uranium (HALEU) or high enrichment uranium (HEU) fuel Either coated particles of uranium carbide (UC_2) or a composite dispersion of uranium and zirconium carbide (UC-ZrC) in graphite Coolant channels coated with niobium carbide (NbC) and zirconium carbide (ZrC) Launch safety control rods are likely to be needed Cylindrical reflector with embedded control drums
Human Rating	System can power a Mars cargo or crew transit vehicle Astronauts can operate on and around spacecraft Human rating may be required on the crewed mission, but not on the cargo missions, though the same human rated engines may be used on both the cargo and crewed missions
Launch and Transport to Lunar Orbit	Reactor stowed until deployed in Earth orbit Multiple launch vehicles are available
Unpacking	A three-engine reactor cluster is delivered to Earth orbit within the launch vehicle shroud Reactor health monitored during all operations Cameras to observe physical damage to the reactor from launch Radiation monitors operational during all operations Sensors indicating equipment interlocks in correct status Unpacking may be done remotely and without astronaut participation Power available from batteries to support deployment and checkout
Startup	Startup managed from Earth and/or by astronauts 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
Operation	Reactor parameters can be monitored from Earth and on board the crewed spacecraft Reactor control and power management to be determined Total burns per engine: 1 to 3 Reactor maintenance could be very limited Astronauts should not generally be present near the reactor NASA radiation limits should determine time and distance requirements from reactors

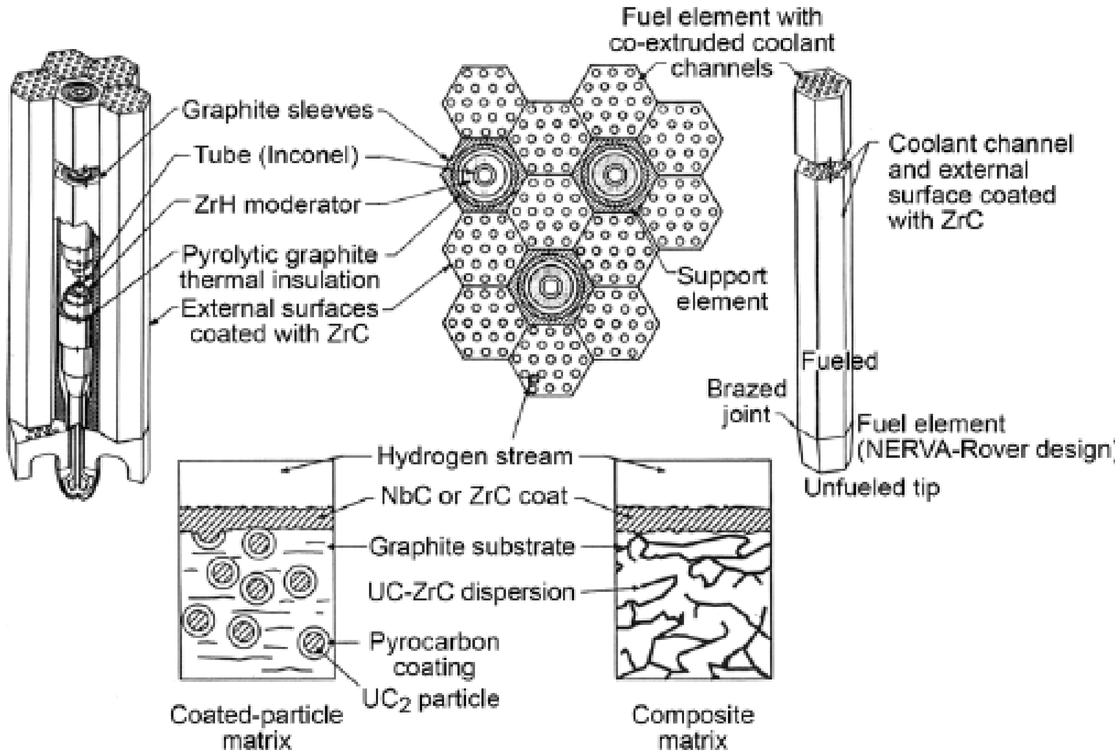

Figure 1-4. Coated particle and composite SNRE fuel element and tie tube arrangement. (Figure 4. from NASA/TM—2014-218104)

2.0 Radiation Exposure Considerations

It is fully expected that the radiation exposures to the crew members on a Mars mission utilizing NTP can be designed and monitored to be kept as low as reasonably achievable (ALARA), within the parameters of the mission. This can happen through the design of the reactor system, the design of the crew quarters on the spacecraft and the monitoring of the local radiation fields in and around the vehicle, both naturally occurring and those introduced by the reactors, and through the monitoring of each crew member's individual exposures. It is most probable that the largest radiation doses received by crew members should come from naturally occurring cosmic galactic radiation or solar particle events, with only a small extra amount of exposure coming from the operation of the NTP engines during the course of the mission. The Mars Design Reference Architecture 5.0 Addendum (DRA5.0-ADD) estimates that the radiation exposure received by astronauts from the NTP engines on crewed missions should be on the order of 5 percent of the overall dose that would be received from natural radiation sources.[5] If the NTP engines are used to reduce transit time the total astronaut radiation exposure should be less than for other options. However, DRA5.0-ADD also concludes that "exposure estimates are well in excess of baselined permissible exposure limits" and that risk mitigation strategies, such as advanced shielding technologies, countermeasures, and individual-based risk assessments can be important to managing these potential risks to the astronauts on these missions. Thus, it can be concluded that minimizing the transit times to and from Mars, as well as the stay times on the Mars surface should help to reduce the potential risk of excessive radiation exposure. It can also be observed that shorter transit times enabled by the use of NTP on crewed missions to Mars should reduce any potential risks to crew members associated with long-duration microgravity exposures.

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 need to be monitored and met by crew members on any space mission[10]. Reference 1 reviewed these radiation exposure limits, and mission designers should be cognizant of the current expectations for radiation protection as they design both the mission and reactor systems.

2.2 Potential Human and Equipment Radiation Exposure Pathways

The reactors utilized in the NTP engines for the mission to Mars should not be operated and should not generate fission products prior to reaching a readiness condition in an appropriate Earth orbit and/or when the spacecraft is already poised to leave Earth orbit on the journey to Mars. Each TMI burn time for the reactors is less than an hour with only a single 39-minute engine burn required for the cargo missions and a 55-minute burn for the crewed mission. It should be during the TMI, MOC and TEI burns that the crew and their equipment should be most susceptible to direct irradiation in the unlikely event of a reactor core malfunction and the possible dispersion of radioactive materials at the rear end of the crewed MTV.

After reactor shutdown, there probably should be few mechanisms available to transport radioactive materials away from the reactor and to a location that could cause a possible radiation exposure to a member of the crew. It may be possible for a crew member on an extravehicular activity (EVA) to inadvertently enter a high-radiation area created by the post-operational radiation emanating from the reactor core, reflector, or any structures that scatter core radiation, but the possibility of this occurring can be minimized with good maintenance and radiation protection practices.

During the course of the mission, the expected radiation fields surrounding the reactor system can be readily calculated for both the direct radiation from the reactor core, reflectors and shield and any scattered radiation off of the propulsion system and any thermal heat rejection radiators. The configuration of the spacecraft, the three reactors, primary radiation shadow shields, and thermal radiators should be taken into consideration during this analysis.

Once the reactor systems are placed in position on the interplanetary spacecraft these calculations can be verified and confirmed through straightforward radiation field measurements as a part of the reactor startup procedures. A full mapping of these radiation fields can be established on the two earlier cargo flights before the crewed spacecraft is sent to Mars.

The largest possible radiation exposures to equipment during a cargo mission should be during the TMI burn. For the crewed mission, the largest possible crew radiation exposures from the propulsion reactors may come from the final TEI burn as the shielding provided by the LH_2 propellant loading in the core propulsion stage is reduced as the LH_2 is depleted near the end of the burn.

Crew members may also receive radiation doses after a postulated accident that distributes radioactive material away from the reactors. These possible accidents, and the potential for crew radiation exposure, will be addressed in detail in Section 6 of this report. However, it may be expected that the probability of accidents that generate sufficient energy to widely disperse radioactive materials to areas where crew members may receive a radiation dose should be extremely low and thus, these accidents should pose very little risk to crew members receiving significant radiation doses.

Reference 1 also discussed the general means to minimize crew exposures and provisioning for possible crew radiation overexposures. Both of these requirements can be met through sound system design engineering (e.g., positioning consumables around crew quarters), radiation protection practices, and emergency radiation management procedures and training.

2.3 Means to Minimize Crew Exposures

There are a few ways to minimize the radiation exposure for astronauts on the round-trip to Mars. These include the standard means to minimize radiation levels through effective radiation protection design and operation—distance, exposure time, and shielding. The primary design variables within the toolkit of Mars/NTP system designers are lengthening the distance that the astronauts are away from the NTP reactors by extending the boom between the reactors and the crew quarters on the spacecraft and adding additional shielding materials between the reactors and the crew quarters.

With the $1/r^2$ radiation exposure advantage of a longer boom, it is rather straightforward for a designer to achieve lower radiation exposure rates. However, additional boom length needs also to be a design parameter in at least two additional design considerations: (1) the mass determination for the mission; a longer boom translates into additional mass, and (2) the spacecraft system dynamics; a longer boom may distort and complicate the three-dimensional movements and balance of the spacecraft.

Exposure time is the second available variable for the system and mission designers. This was extensively examined in DRA5.0-ADD to compare short and long stays on the Martian surface. The majority of the exposure time is during the long (180 days each way) transit times to and from Mars with the most significant radiation exposure attributed to the natural radiation environment of interplanetary space, and with no more than 5 percent of the exposures coming from the NTP reactors. Thus, it could be advantageous to minimize the mission time, regardless of whether there are nuclear reactors providing the propulsion.

Finally, radiation shielding can be used to reduce the crew exposures. However, increasing the thickness of these shields should probably increase the mass of the system. NASA has and continues to research advanced shielding technologies looking for any improvement of the capability to protect the astronauts.[5] These efforts may yield improvements in the optimization of radiation exposure and system mass.

Most modern habitat designs also incorporate a radiation storm shelter to shield the crew from coronal mass ejection (CME) events. This shelter could potentially be used to further shield the astronauts from the NTP engines during and shortly after the engine burns. Enhanced versions of these shelters contain additional volume and water shielding to protect astronauts from extreme CME events, reduce astronaut dose from the high energy proton component of galactic cosmic rays, and provide additional water for use (nominal or emergency) by the Environmental Control and Life Support System (ECLSS).

Additionally, there may be a limited set of strategies to mitigate the harmful effects of radiation exposure to the astronauts on an NTP mission to Mars.[5] These include countermeasures through the use of radioprotectants and pharmaceuticals, individual-based risk assessments for the selection of astronauts with minimal susceptibility to radiation exposure and damage as well as development of techniques to reduce the uncertainty of both the radiation fields experienced by the astronauts and their individual responses to radiation exposure. NASA contracted the National Council on Radiation Protection and Measurements (NCRP) to examine the radiation resistance genetic characteristics that could be used to select astronauts. The NCRP also examined the regulatory, ethical and legal concerns related to selecting astronauts for long duration missions by considering radiation-related genetic background and previous radiation exposures.[11]

3.0 Managing Approach to Spacecraft and Reactors

One special design consideration for space reactors may be accessibility to the cargo area or other parts of the spacecraft while avoiding any high-radiation areas. Each space reactor configuration includes sufficient shadow shielding to protect the human habitation areas or equipment and payload areas. The crewed mission may contain additional shielding compared to the cargo missions. In both cases, there can be shielding inside the reactor pressure vessel, while the crewed mission may include additional gamma shielding to help protect the entire crew compartment from fission product decay gamma rays following an engine burn.[5] The shielding can be biased toward the spacecraft side of the reactor, effectively producing a safe cone for people and equipment. Putting three reactors on each spacecraft may lead to additional radiation field challenges to be addressed by the designers.

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

3.1 Three-Dimensional Radiation Mapping and Control

For operations in space near the reactors, whether for docking or EVA, radiation control is three-dimensional and should be evaluated that way. In order to plan and manage activities near a reactor, mapping of radiation fields may be required. Detailed mapping can allow the establishment of appropriate exclusion and hazard zones as well as managing necessary activities near the reactors. Initial planning and mapping may be done with models and analyses, but measurements are recommended for validating the expected radiation fields. Measurements can discover damage to shielding or unanticipated scattering paths.

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

The radiation fields around the three reactors may be very intricate and influenced by the reactor internal structures, the shielding design, and the propellant remaining in the tanks at any given time.[12] Radiation fields should be orders of magnitude higher near the reactors on the less shielded side. As the reactors only operate during propulsion maneuvers, docking or maintenance activities are unlikely to occur while the reactor is operating. Analyses indicate that the doses drop very rapidly after shutdown[13]. For example, for a 1575-MWt reactor at 100 ft away on the unshielded side, the doses are predicted to drop to 10 to 20 R/hr 1 day after a burn and to ~1 R/hr after 1 month, depending on the burn time. Therefore, docking and undocking maneuvers with limited dwell time can be carried out soon after a burn, while EVAs and maintenance activities may need to remain behind shielding for a significant time.

3.2 Docking and Undocking Avenues

Docking/undocking operations may occur to transfer cargo or personnel to/from the spacecraft. If the on-board reactors are cold, then there may be little potential hazard to either personnel or equipment. This could be the case during the spacecraft assembly phase in Earth orbit or docking with the MTV after ~500 days on Mars. If the reactors are hot, then operations need to be controlled to avoid direct shine when the docking/undocking spacecraft is in close range. For the purposes of normal spacecraft operations, the NTP engines can typically be considered radiologically "cold" if they are not operating and it has been at least 30 days since significant power operation. For anything other than close approach to the reactor itself, the delay can be reduced based on specific calculations and radiation measurements. The operations of interest and reactor status include:

- Spacecraft assembly in Earth orbit – Cold
- Undocking of the cargo elements at Mars - Cold
- Crew undocking from MTV at Mars - Hot
- Crew docking with MTV for return to Earth - Cold
- Crew undocking upon return to Earth – Cold
- Unplanned docking/undocking – Either Hot or Cold

Note that changes to the mission profile or the need for unplanned burns could change the status of the reactor and potential docking/undocking procedures.

Shadow shielding can be provided to protect the cargo areas and crew habitat areas from radiation emanating from the reactors. For the crewed mission the habitat and docking modules are expected to be more than 50 meters away from the reactors. The shadow shield needs to be designed to accommodate docking spacecraft within the safe cone. When the reactors are hot, docking spacecraft may need to approach and depart within the safe cone, except perhaps for very brief periods or at long distances from the reactors. Given the proposed design and significant distance from the docking location to the reactors, there should be no concerns unless the docking/undocking spacecraft were to maneuver close to the reactors.

Docking/undocking spacecraft may need to be designed to tolerate the radiation fields that may exist either outside or within the safe cone. If the reactor is shut down prior to docking, which would be the norm for a NASA Mars mission, the radiation fields can be greatly reduced, depending on how long the reactor has been shut down. In any case the shield design, docking spacecraft design, and physical approach profile all need to be developed with the anticipated radiation fields in mind. The commonly used ALARA principle is appropriate for developing docking/undocking strategies that minimize radiation exposure from on-board reactors.[14]

3.3 EVA Approach to Reactors

For the most part, space reactors for propulsion should be designed to avoid the need for maintenance or other activities near the reactors. Should the need for such an EVA occur, then the ALARA principle applies. Much as for a docking operation, astronauts need to remain within the safe cone and at a maximum possible distance from the reactors. EVA considerations should factor into selecting the radius of the shadow shield. The reactors should be shut down as long as possible before the EVA. As with any EVA, planning to simplify the procedures and minimize the exposure time may be important. NASA's Human Integration Design Handbook[15] provides guidance on design of EVA translation paths and the need to avoid exposing astronauts to unnecessary hazards. Radiation needs to be included along with other potential hazards that could adversely impact the astronauts. Physical constraints that prevent movement into high radiation zones should be considered, e.g., limits to tether length. Radiation should be continuously monitored during the EVA. Precautions should be taken to ensure that no contamination is transported back inside the spacecraft. These precautions may include procedures for decontamination. Lastly, the use of robots as substitutes for the human crew should also be considered if emergency work is required in a high radiation field area.

3.4 Multiple Reactors

With three reactors present on each spacecraft, the radiation shielding may become a little more complicated. There may be multiple shadow shields, or one larger shield, that should account for both direct shine and scattering. Any EVAs or docking approaches should account for the combined effects. For this mission, the reactors are all located together on one end of the spacecraft, thus simplifying the problem and allowing docking and EVA activities to be managed in a manner similar to a spacecraft with a single reactor, i.e., within a designed safety cone. 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. Propellant tanks can also be utilized to provide shielding, up to the final NTP engine burn when only a small amount of unused propellant may remain.

3.5 Design Considerations and Positive Controls

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

- Minimizing the time needed to carry out planned operations, e.g., simplify tools and procedures
- Providing physical controls and barriers to prevent inadvertent entry into a hot zone, e.g., restrict tether lengths during an EVA
- Providing the means to construct temporary shielding
- Including simple dosimetry and warning systems
- Establishing safe paths for ingress and egress
- Creating decontamination zones.

3.6 Radiation Monitoring

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

- Changes in the operating characteristics of the reactors, e.g., power level and flux profile
- Buildup of activation products in surrounding structures and materials
- Changes or degradation in the shielding configuration
- Changes to surrounding structures influencing the scattered radiation

While such changes are likely to have a minor impact on radiation fields, they warrant the need for 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 should remain in place around reactors to provide warnings of possible problems. In addition, portable monitoring equipment and personnel dosimetry may be required whenever humans approach a reactor for maintenance or other purposes.

4.0 Managing Reactor Maintenance

Some general maintenance requirements for space reactors were discussed in Reference 1. The maintenance requirements can 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. To date, there have been no crewed space missions involving a nuclear reactor, and un-crewed missions have not allowed for maintenance. The focus here is on maintenance activities that are a result of failures after launch. Some components would most likely not be amenable to any maintenance. It may be possible that the reactors and key components could be located in an area difficult for astronauts to access. Maintenance may only be possible robotically or not at all in those cases. When maintenance is possible, planning should minimize the potential risks to astronauts, including expected radiation doses.

For the two cargo missions, maintenance should be unlikely after departure from Earth orbit, and for the crewed mission, manual maintenance activities may incur a number of potential risks to astronauts. There may be increased potential for radiation exposure, along with the normal risks of astronauts performing activities outside a spacecraft. In the discussions below, it is assumed that all components are properly designed for the loads and environments associated with launch and other phases of the particular mission. The focus here is on the nuclear aspects of operation and maintenance.

For cases where maintenance may be possible, it is important to distinguish between planned maintenance and the capability for maintenance. The former should generally 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.[16] As with most design matters, this may lead to trade-offs. Providing the capability for maintenance may add intricacy 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 need to be developed, increasing the potential burden on astronauts.

4.1 Precluded Maintenance Items

There are a number of items for which maintenance can be precluded for either the cargo or crewed missions for practical reasons. Such reasons can include

- Mass penalty associated with replacement components
- Large, complicated tools needed to affect the repair
- Difficulty of performing the repair operation in space

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

Passive system components, including piping, vessels, and some instrumentation are not amenable to maintenance activities, either planned or unplanned. This includes the passive components associated with the LH_2 storage and piping system. These components should be designed such that no maintenance is necessary. The design should allow for expected radiation levels, thermal loads and possible meteoroid strikes.

For those components and systems where maintenance may not be possible, there are still strategies than can be implemented to ensure system reliability, including:

- Redundancy, e.g., in sensors
- Quality and reliability standards
- Design margins

Redundancy in sensors should be carefully managed, as having multiple sensors can lead to conflicts regarding which one to believe. Such a conflict contributed to the accident at Three Mile Island when operators chose to believe the wrong instruments. NASA standards can be found at https://standards.nasa.gov/nasa-technical-standards. For example, Reference 17 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.

4.2 Maintenance for the Mars NTP Cargo Mission

For the cargo mission, maintenance should be unlikely after the vehicle leaves Earth orbit. While still in Earth orbit, operations in and around the reactor to prepare the vehicle for departure are possible. There are no radiation concerns prior to the departure burn. An example where maintenance might be practical is the locking mechanism on the reactivity control systems that render the reactors safe during launch. If the mechanism fails to unlock, a repair mission might be undertaken. In this case the reactor should 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 should be designed to allow access
- The astronauts should practice the repair on Earth per typical NASA training requirements
- Appropriate tools should be provided
- The drive motors should be disabled to prevent rod or drum motion subsequent to unlocking
- Radiation levels should be verified prior to approaching the reactor
- The astronauts should move to a safe distance prior to moving the control rods or drums

Other components that fail upon initial reactor startup, including valve actuators in the LH_2 system or other accessible components, may be repaired while the spacecraft is still in Earth orbit. As noted above, the cargo mission does not anticipate any planned maintenance activities and has 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 4-1.

Table 4-1. Maintenance Strategy for Cargo Mission

	Planned Maintenance	**Unplanned Maintenance Possible**	**Reliance on Standards and Design Margins**
Reactor Core and Passive Reactor Components	No	No	Yes
Active System Components	No	In Earth Orbit for Accessible Components	Yes
LH_2 System	No	In Earth Orbit for Accessible Components	Yes

4.3 Maintenance for the Crewed Mars Mission

The reactor designs for the crewed mission are the same as for the cargo mission. Like the cargo mission, these reactors are intended to avoid any planned maintenance. One significant difference is that these reactors should be human rated, and emergency maintenance possibilities need to be considered. The availability of three reactors provides significant advantages for mission-level fault tolerance. That is, a failed component does not need to be repaired if the remaining two reactors can complete the mission.

4.3.1 General Maintenance Considerations in Design for Human-Rated Systems

There are a number of components in a fission reactor system that are not very amenable to maintenance, either due to radiation levels or practical considerations. In some cases, this limitation can be addressed through redundancy and diversity of system components that mitigate single failures. According to NASA requirements for human ratings, systems should be single failure tolerant.[15] Certain items are excepted from this requirement:

> *"a. Failure of primary structure, structural failure of pressure vessel walls, and structural failure of pressurized lines are exempted from the failure tolerance requirement provided the potentially catastrophic failures are controlled through a*

defined process in which approved standards and margins are implemented that account for the absence of failure tolerance.

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

Certain reactor system components, such as the fuel, reactor internals, and parts of the LH_2 flow systems are likely to be potential single failures and not amenable to maintenance activities. Therefore, the quality control and design margins are likely to be particularly important for these components.

4.3.2 Maintenance While in Earth Orbit

While still in Earth orbit, the maintenance possibilities are the same as for the cargo mission. As noted previously, there are no radiation concerns prior to the departure burn. Repairs to locking mechanisms on the reactivity control systems or other repairs may be undertaken in a manner similar to any other repairs that might be attempted for the spacecraft system. The only nuclear concern is to ensure that the repair activities do not damage the reactor system or controls or include activities that might induce an inadvertent criticality by inducing control drum motion or bringing a neutron reflector close to a reactor.

4.3.3 Maintenance after Earth Orbit Departure

While no maintenance is planned for the reactor systems after Earth orbit departure, human rating requirements allow for unplanned maintenance to be considered. Most passive components, such as fuel, piping, and vessels are not be amenable to maintenance. Neither should the internals of many active components, such as turbopumps, valves or control rods, or drums. However, maintenance may be considered for a number of components depending upon their accessibility in the design. Active components external to the reactor vessel and LH_2 system may be considered. For example, while valve bodies and internals may not be accessible, a valve actuator may be. Components to consider include the external parts of reactivity control systems, turbopumps, valves, and sensors. If maintenance is attempted for these components, there may still be high radiation levels present, and the potential risks to astronauts could be significant. Further, parts and tools should be available and safe procedures need to be developed. It may be preferable to design with sufficient redundancy and reliability to minimize the likelihood of unplanned maintenance.

4.3.4 Robotic Maintenance

Robotic maintenance should be considered if any activities are envisioned in a high-radiation environment or to reduce the overall potential risks to astronauts performing EVAs. Robotic maintenance capabilities can be sent with the mission at a cost of additional mass in robotics and spare parts. The system designs need to consider such activities and robotic systems need to be designed for the anticipated environments. If the systems are not autonomous, then the astronauts may need appropriate training and preparation.

4.3.5 Maintenance Performed by Astronauts in Space

Maintenance needs by astronauts should be minimized in all cases, particularly in space. Section 3.3 discussed some of the topics surrounding EVAs and reactors. If maintenance is required, it should be as simple as possible and require minimum time outside the spacecraft. Normally, it is preferable to wait a significant time after reactor shutdown before beginning maintenance operations. If maintenance can be delayed for a few weeks, the radiation doses to the astronauts from the reactor may be greatly reduced.[12] If maintenance cannot be delayed, then shielding may be necessary for any maintenance operations. The astronauts can approach the reactor from behind the shadow shield that should be located between the reactor and spacecraft. Additional, temporary shielding may be needed to support maintenance operations, and time near the reactor needs to be minimized by simplifying the operations as much as possible. Procedures and training can optimize the operations to achieve minimum times and doses.

The radiation fields around the three reactors may be very involved and influenced by the reactor internal structures, the shielding design, and the propellant remaining in the tanks at any given time.[12] Radiation fields should be orders of magnitude higher near the reactors on the unshielded side. As the reactors only operate during propulsion maneuvers, maintenance activities probably can never occur while the reactor is operating. As noted in Section 3.1, the doses drop very rapidly after shutdown.[12] Maintenance activities within the safe zone could begin soon after shutdown, while activities outside the zone may require extended cooldown times. Operations adjacent to the reactors may be precluded for several months or longer.

For all maintenance activities, the following considerations may apply:

- The reactor should be confirmed to be in a safe, shut down state
- The components to be repaired should be designed to allow access
- Sufficient time should be allowed after reactor shutdown to reach safe radiation levels
- Shielding design, including portable shielding, should minimize radiation doses to astronauts
- Radiation levels should be verified prior to approaching the reactor
- Both in-place and portable radiation monitoring should be provided
- The astronauts should practice possible repairs on Earth per typical NASA training requirements
- Appropriate tools and spare parts should be provided
- Astronaut exposure time should be minimized
- Appropriate keep-out zones should be implemented to restrict maintenance activities to safe areas, supplemented as appropriate by physical controls and barriers
- Decontamination procedures should be included, if necessary, prior to reentering the spacecraft

The overall maintenance strategy for the crewed mission is summarized in Table 4-2.

Table 4-2. Maintenance Strategy for Crewed Mars NTP Mission

	Planned Maintenance	**Unplanned Maintenance Possible**	**Reliance on Standards and Design Margins**
Reactor Core and Passive Reactor System Components	No	No	Yes
Active Reactor System Components	No	Yes, for unlocking control systems, repairing drive systems or accessible external parts	Yes
LH_2 System	No	Yes, for sensors, actuators, or accessible external parts	Yes

5.0 Reactor Control and Health Monitoring

The control of the NTP reactor and propulsion system was an integral part of the early Rover/NERVA systems development.[18] Early studies involved developing the methods to control and operate these high-performance reactors.[19, 20, 21, 22] In 1993 Gunn, Savoie, and Hundal provided a very useful summary and description of the operation and control of NTP systems.[23]

Recently, Sikorsky, and Wood have reviewed the state-of-the-art for nuclear thermal rocket control systems and have found that there is insufficient recent research and development activity in this area.[24] They propose an approach for the development of a control system for NTP systems including the utilization of control theory, digital electronics, modeling, and autonomous systems advances since the end of the Rover/NERVA program, plus a highly robust testing and development regime leading toward the availability of fully autonomous NTP engines.

Probably the most comprehensive and detailed development of a control system for an NTP system was for the last engine developed for the Rover/NERVA program, the XE-PRIME engine. NASA reviewed and summarized these early reactor/engine tests in 1991.[25] The XE-PRIME was the last NERVA development engine tested and was the only nuclear thermal propulsion engine to be tested with components in a "flight-type close coupled arrangement." The engine was fired downward at the Nuclear Reactor Development Station in Nevada. It was operated successfully through a total of 24 separate startup sequences over a 9-month period from December 4, 1968 and September 11, 1969. The engine was rated at 1,140 MW, 3,861 kPa (560 psia) chamber pressure, and 2,272 K (4,090 R) chamber temperature and operated at full power for a maximum of 3.5 minutes on June 11, 1969. A full summary of the testing objectives, experimental plans and results of the test series are discussed in Reference 24 including:

> "The XE-PRIME engine control system (ECS) provided several modes of automatic operation, as well as various manual modes of operation. The purpose of the multiple modes of control was to obtain performance information for guidance in the development of the NERVA engine, and to obtain additional information for confirming and improving methods which were used to analytically model the engine. The control drums regulated reactor power while the TPCV (turbine power control valve) regulated the gas flowing to the turbine. Normally, the objective was to obtain desired engine chamber temperature and pressure conditions. However,

there were interactions between the two control parameters which made them interdependent in terms of controlling chamber temperature and pressure. In the automatic modes of control, these interacting effects were automatically regulated to maintain the desired operating condition. In manual control, operator action was required to maintain control parameters at the desired operating point.

The ECS provided the following operating modes: 1) manual drum control, 2) reactor power level control, 3) chamber temperature control, 4) manual TPCV control, 5) chamber pressure control, and 6) program control. In addition, control of startup and shutdown operations was provided. Startup and shutdown could be accomplished either manually (with the operator supplied with feedback information from console meters) or automatically. Startup could be made on nuclear power, or on temperature without the use of nuclear instrumentation."

Though the full details need to be established during the design of the mission and the NTP engines to be used to transport cargo and astronauts to Mars, the system control during operations, including during startup, full thrust, and shutdown can be achieved by coordinating the liquid hydrogen flow with the reactor power level through the use of the multiple control drums, encircling the reactor core to regulate the neutron population and reactor power level over the reactor's operational lifetime.[8] Clearly, the effective control and monitoring of these NTP reactors during all operational phases, including startup, operation, hot shutdown, cold shutdown, and engine dormancy should be necessary.

One design choice that may need to be made early in the design process for NTP reactors is the uranium enrichment of the fuel. The total startup reactivity for a cold reactor at the beginning of life can vary greatly depending upon the uranium enrichment, the neutron energy spectrum chosen, and the degree of neutron moderation required. The fuel enrichments may range from HEU, as was used in the Rover/NERVA program (greater than 90 percent), down to HALEU at approximately 20 percent. Much of this required startup reactivity variation should be due to the neutron spectrum, uranium enrichment, and fuel loading. Any reactor should first need to have enough reactivity to overcome the temperature deficit of reactivity as it heats up from near ambient space conditions to the approximately 2700 to 3000 K reactor temperatures expected during full power operation, taking into account multiple factors including the reactivity effect of hydrogen propellant being simultaneously injected into the core. The engine design and startup sequence should ensure that the positive reactivity from increased hydrogen concentration in the core and reflector is balanced by the negative reactivity from Doppler feedback (which can be stronger in reactor cores fueled with HALEU), core expansion, and other factors. Ideally, reactivity effects can be balanced such that a small amount of control drum rotation should be adequate to bring the engine from a cold critical condition to full thrust operation. Additionally, in the event that one engine "scrams" during the startup sequence it may be desirable that instrumentation be devised to allow that engine to be successfully started even with adjacent engines operating at full thrust.

For moderated reactors operating in a thermal neutron spectrum with an average lower ^{235}U loading than is needed in a fast neutron system, there should be a need for additional reactivity to overcome burnup effects. These reactors can also have greater sensitivity to reactor poisons that may occur in a moderated system. As an example, moderated, thermal spectrum reactors require additional available reactivity to overcome Xenon poisoning if a restart is required within 48 hours of shutdown from full thrust. This should not be a problem for unmoderated fast reactors. Excess reactivity requirements should be considered early in the design process. If not, total excess reactivity for many HALEU fueled, moderated thermal spectrum designs could be greater than $10. Hydrogen, acting as moderator, propellant and reactor coolant, can provide a significant amount of positive reactivity to compensate for the negative temperature coefficient effects, but may not be sufficient to compensate for all of the necessary startup and restart requirements, unless the system and startup sequence are designed appropriately. In general, moderated HALEU NTP engine startup and operation can benefit from the NTP reactor being undermoderated and utilizing fuel with minimal parasitic neutron absorption.

NTP reactor systems are required to startup rapidly (typically taking only about 30 seconds to go from around 10 kWt to greater than 100 MWt) to reduce the amount of hydrogen expended during startup. For a HALEU fueled and moderated reactor, the reactor should be designed, and the startup sequence devised to minimize control drum movement required during startup. During startup the system should come up to operating temperature at the same time the hydrogen gas is rapidly changing density. Both of these rapid changes, along with the large temperature and Doppler reactivity changes occurring in the approximately 80-weight percent of ^{238}U in the fuel, can pose a significant control challenge that has not been demonstrated in the past. This can place new, and unique challenges on the control system including the rate of data collection from the sensors and the reactor controller. Past Rover/NERVA systems that were designed with HEU inserted less than $5 worth of reactivity during startup, and a similar limit, or preferably lower limit, should be set for moderated HALEU systems. An accurate and robust control system could be needed to adjust the reactivity of the system in very short periods of time, typically on the order of seconds, and therefore these commands cannot be executed from Earth. This could require a great deal of engineering and testing to ensure performance and avoid catastrophic failure of the reactors.

5.1 Impact of Multiple Reactors on Spacecraft

The mission plans in DRA5.0 include three clustered NTP reactors on each flight to Mars. The propulsion plans, including the need to balance the thrust of the three engines, could dominate the matters related to the power management of the three reactors. Additionally, care should be given to the clustering of the reactors so that they do not neutronically interact with or affect each other, making their control challenging.

Fortunately, clustering of engines does not appear to be a significant design or operational concern. To better understand the neutronic aspects of clustering nuclear rocket engines, a series of tests was conducted by Los Alamos National Laboratory in 1964.[26] In these tests, two reactors were placed in close proximity to each other. The first series of measurements had one reactor, KIWI-B4, fixed and the other movable, a zero-power reactor, PARKA, was placed 16, 9, and 6 feet away. The second series of tests included a piece of neutron absorber in between the two reactors to eliminate the transfer of neutrons between the two reactors. The result of these tests demonstrated that neutronic coupling between these two reactors had only marginal effects and did not appreciably affect reactor control or operation. The reactivity effects were measured to be $0.03, $0.12, and $0.24 at 16, 9 and 6 feet respectively. These relatively small reactivity changes show that clustering of the engines should pose no significant effects on reactor operations. Any neutronic coupling could be reduced even further by adding a thin layer of strong neutron absorber on the radial surface of each pressure vessel on the side facing the other engines.[27] Instrumentation may need to be designed to allow an engine to start even if a high radiation field is present due to an adjacent reactor already operating at full thrust.

Balancing the thrust of the three NTP engines could add difficulties to the design of the control systems for the integrated spacecraft. As seen above, the Rover/NERVA program had developed effective reactor and engine control systems, but never operated or controlled multiple NTP engines at the same time. NASA propulsion designers have extensive experience with accurately controlling and balancing the thrust from multiple liquid-fueled rocket engines during the development of the Saturn, and other rocket systems[28, 29], so this concern may be manageable.

5.2 Dynamic Operations and Restarts

According to DRA 5.0, the NTP engines used on cargo missions only need to be fired once for 39 minutes for TMI to leave Earth orbit and place the spacecraft on its way to Mars. Once the spacecraft reaches the vicinity of Mars, the cargo would be inserted into a suitable Mars orbit by chemical propulsion. Thus, multiple engine restarts should not be needed for the NTP engines used on the cargo missions. On the other hand, the crewed mission is anticipated to include three separate NTP engine burns, the first one for TMI would be planned to last for approximately 55 minutes, the second one for MOC would last for approximately 15 minutes, and the final one for TEI would last approximately 10 minutes for a total reactor burn time per full round-trip mission of approximately 80 minutes. The time interval during which the reactors would likely be placed in cold shutdown between TMI and MOC would be approximately 180 days and the time interval for the reactors to be placed in cold shutdown between MOC and TEI would be approximately 500 days. These long times need to be accounted for and the reactor components tested during the long shutdown periods to ensure that the reactors can restart when the engines are needed.

The XE Prime reactor, the final test reactor operated during the Rover/NERVA program, was fired on 24 separate startups during a 9-month period of time from December 4, 1968 through September 11, 1969, demonstrating that multiple reactor startups could be accomplished.[24] However, most of these tests were not aimed at extended full power operation. One full-power test was conducted on June 11, 1969 where the engine was operated essentially at full power for only 3.5 minutes. The times between startups during the test program ranged between minutes with some longer periods of down time as long as two and a half months. These tests demonstrated the capability for multiple engine restarts, though the period of time between starts did not approach the times needed under the DRA 5.0 crewed scenario. Though considerable and significant testing was done to understand the operations, control, startup and shutdown of NTP engines in the Rover/NERVA programs, it is clear that much more remains to be developed and modernized to startup, control, monitor, shutdown, restart and understand these systems.

All of the Rover/NERVA NTP engine design and testing utilized HEU fuel. If lower fuel enrichments are considered for future Mars missions, then the startup and control of NTP engines may be different and additional design and testing could be required to accommodate solid neutron moderator materials within the core. Most moderated thermal nuclear rocket concepts use a metal hydride moderator (such as a ZrH) for moderation. This material has a temperature limit and duration for which the hydrogen in the moderator could be lost or degraded. Long-term use above approximately 1000 K causes gradual hydrogen loss, and temperatures above that may cause short term loss. During the cool-down phase of an NTR mission where the reactor may be restarted and right after the first, or subsequent burns, hydrogen gas from the propellant tank is used to cool down the reactor from operating temperatures to cold standby conditions. For a fast spectrum NTP system with no moderator and no structural materials within the core, the core only has to be cooled to just below the peak fuel temperature of approximately 3000 K, with the reflector, pressure vessel, and other non-refractory structural materials cooled to around 1000 K. For a moderated system, the moderator should also be cooled to approximately 1000 K to prevent hydrogen loss and damage to the moderator. Depending on the decay heat removal scheme employed, the amount of heat conduction between the fuel and moderator, and other factors, extra stored thermal energy in the moderator may need to be removed to reduce the temperature of the moderator from operating temperatures down to approximately 1000 K. This means that additional hydrogen may be required to provide decay heat cooling for a moderated system. If more than one restart is planned during the mission, then even more hydrogen for multiple full cooldowns would probably be needed, increasing the total hydrogen mass required to be launched from Earth and carried along for mission completion. For the DRA 5.0 mission scenario, including two full-power planned restarts for MOC and TEI, a significant amount of cooldown hydrogen may be needed.

5.3 Impact of Autonomous Control and Health Monitoring

The autonomous control and monitoring of NTP engine operation may be essential for both the cargo and crewed missions to Mars because of the distance involved between the Earth-based mission controllers and operators. The crewed missions may include some form of astronaut control override; however, the astronauts should not expect to be included in the control of the rocket engines, except under dire emergency situations.

Significant efforts were conducted during the Rover/NERVA programs to understand and conduct automatic or programed engine startups.[30] Automatic startup techniques were first demonstrated and successfully tested on the Kiwi-B-4D Rover program reactor in May 1964.[24]

- While there have been considerable improvements to the development of autonomous controls in general, none have been developed specifically for or tested on NTP engine configurations.[31] Thus, significant efforts may be needed to develop, modernize and test these technologies.

6.0 Reactor Accident Scenarios

Numerous tests of reactors and systems during the Rover/NERVA development programs, plus numerous reactor design studies over the past 25 years were all aimed at developing NTP engines that could be used on space missions. The development programs of the early years focused on reactor design and testing with reactor safety being approached from a "deterministic" view of analyzing safety, which was similar to the design and safety testing approach that was utilized in all of the early terrestrial reactor programs. The Rover/NERVA flight safety considerations started with a philosophy that utilized the design process to provide solutions that were built into the engines. The program had very detailed specifications and criteria for the safe use of nuclear rocket reactors.[32]

However, since 1975 the approach to terrestrial reactor safety has taken a decidedly much more "probabilistic" approach to safety. This has resulted in the deep development of probabilistic risk assessment (PRA) techniques, tools and approaches to reactor safety that are driven by building the probabilistic safety analysis (PSA) approaches that are well defined within the terrestrial reactor world. While the approach to launch safety has become more probabilistic in nature[33], there apparently has been little to no probabilistic safety development for accidents involving

NTP engine safety during that time. Preliminary probabilistic design and failure modes and effects analyses (FMEA) utilized in the Rover/NERVA program in the early 1970s focused on providing sufficient component redundancy to eliminate a number of identified failure modes in the design. An example is the incorporation of dual turbopumps and four valves to replace individual valves to eliminate single point of failure opportunities. If no reasonable design solutions could be found for credible single or multiple failures that could threaten the crew, then abundant countermeasures and large safety margins were installed.[34] Examples of the types of events that need to be considered include:

- Component failures, i.e., pumps and valves in the LH_2 system
- Abnormalities in LH_2 flow rates
- Failures in reactivity control systems and reactivity excursions
- Failure to balance reactivity and LH_2 flow
- Insufficient cooling of the reactor during operation or cooldown
- Meteoroid impact

Going forward, there is a critical need to develop the techniques and tools necessary to perform full PRA for NTP reactors as regular part of the reactor and mission design activities so that they are coordinated and provide value to each. Terrestrial reactor designers and operators have incorporated the techniques of PRA into the design and operation of all reactors for over 20 years and such an integrated approach may be required of the designs for future NTP reactors. As part of this approach and as NTP reactor and systems designs become solidified, in-depth sequence of events analyses should be needed, including a full exploration of the initiating events that can happen during startup, full-power operation, shutdown, and dormancy periods. Some beginning efforts have been considered to explore the safety and reliability of NTP systems, but they have a long way to go before they can be considered effective and useful.[35,36]

6.1 Accident Progression and End States of Failure Modes

Many accident scenarios during startup and operation of the reactor in space have end states that lead to either the core melting or to thermal shock leading to reactor disassembly. These accidents have a low probability of causing harm to the Earth depending on the orbit at which these activities occur and how long after the accident Earth impact occurs. After a few weeks to a few months, the radiological hazard to the Earth should be negligible. The public impact may be low, but the destruction of the reactor may be a reliability matter that could endanger astronaut lives and the mission. The loss of the reactor could lead to catastrophic failure of the mission and loss of life for the astronauts who could be stranded in space. If only one reactor is affected by the accident, the spacecraft may still be functional, and the astronauts may be able to return safely. Quality assurance and the elimination of single-point failures, where practical, can be the primary means of controlling these accidents.

6.2 Radioactive Material Transport Mechanisms

Reactor accidents in space should, in general, not provide a dose to any astronaut or member of the public. Unless the reactor were in an orbit that allowed for accidental re-entry of the reactor, the public should not be impacted. The loss of the reactor or the thermal disassembly could cause harm to the astronauts, but primarily from shrapnel or a shock wave impacting the astronaut capsule. Radioactive aerosols could be sent out into space and some might have enough velocity to impact other surfaces, but none should make it into a sealed capsule. Existing shielding could be enough to prevent direct ionizing radiation from impacting the astronauts.

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.[37,38] There is very little guidance about the need to avoid radiological impacts on destination bodies. In part, this is because radiation environments are pervasive in our solar system, and any radiation impacts from a fission reactor should likely be incremental. While planetary impacts on destination bodies are not expected to be a major concern for nuclear reactors, it still may be appropriate to consider the requirements.

7.1 Planetary Protection Requirements for Mars Missions

NASA Procedural Requirement 8020.12D describes the planetary protection categories of solar system bodies and how they should be treated.[37] A Mars mission can be in Category III, IV, or V, depending on the nature of the mission. Flyby or orbiter missions are Category III, lander missions are Category IV and Earth return missions are Category V. The Mars NTP mission evaluated here includes landers and Earth return, although the nuclear propulsion systems are not intended to land on either Mars or the Earth. However, by being attached to landing and return systems, the clean room, assembly, and other requirements may be driven by the higher-level requirements per NPR 8020.12D. The biological decontamination procedures may be complicated by the need to simultaneously observe nuclear safety procedures.

In addition to biological safety requirements, the probability of a spacecraft or launch vehicle impacting Mars should be controlled. From NPR 8020.12D, Chapter 5:

> *5.1.3 For all launch vehicle elements leaving Earth's orbit, the probability of impacting Mars shall be less than $1x10^{-4}$ for a period of 50 years. The probability of impact assessment should be provided in the Planetary Protection Plan.*
>
> *5.1.4 For all spacecraft crossing Mars orbit en route to other targets, the probability of impacting Mars shall be less than $1x10^{-2}$ for a period of 50 years. The probability of impact assessment should be provided in the Planetary Protection Plan.*

The likelihood of inadvertently impacting Mars should be calculated for each of the nuclear propulsion missions. Whether the probabilities are to be treated individually for each mission or summed over all of the related missions is not clear. These probabilities are not expected to be difficult to achieve; however, if that cannot be demonstrated, then additional measures such as trajectory biasing may need to be considered. Such methods can significantly impact the mission profile.

7.2 Treaty and Operational Impacts

Planetary protection is addressed in the Outer Space Treaty, Article IX.[39] 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."

Since none of the propulsion reactors in this mission are intended to land on Mars, the only possible way to interfere with the activities of other nations may be an inadvertent NTP reactor impact on Mars at a site of interest to other nations. Such a probability should be vanishingly small and should require no additional analysis. If an NTP reactor inadvertently impacts Mars (e.g., in the case of failed cargo landing and dispersal of its carried cargo), the location should be clearly marked and communicated to other countries of interest.

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 activities should not interfere with planned activities of other nations. Previously, radioisotope thermoelectric generators (RTGs) or other small radioactive sources have been left in place on the Moon or Mars without any particular disposal strategy. None of the nuclear propulsion systems proposed for this mission are intended to impact either the Earth or Mars. The cargo mission provides for the NTP system to fly on past Mars, while the crewed return mission provides for the NTP system to fly on past the Earth. As noted previously, the probability of an inadvertent NTP engine impacting Mars should be shown to be appropriately small for at least 50 years following the completion of the mission. This requirement may need to be considerably longer for an impact of the reactor on the Earth's surface. The options for final disposal include:

- Intentional impact into the Sun or other body that should have benign consequences
- A final trajectory into deep space
- A final orbit around the Sun, which does not intersect the Earth or Mars in the timeframe of interest

8.1 Missions Not Requiring Specific D&D Plans

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. Although the reactors in question are not intended to ever impact the Earth or Mars, it may be appropriate to ensure shutdown after final use. Once shut down, the radiation levels drop rapidly, and even if a subsequent reentry were to occur, it should pose little threat. Therefore, it is recommended that the reactors be shut down and verified to be in a safe state. This could be accomplished by reengaging the control rod/drum locking mechanism used during launch. 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.

8.2 Missions That May Require D&D

The discussions above assume that a fission reactor mission is terminated normally. In the event of an abnormal termination, e.g., a reactor accident or an impact of the Earth or Mars, other measures may be necessary for D&D. Potential impacts of the Earth are addressed in launch safety assessments. If one of the reactors were to impact Mars, it may not be practical to clean up the area and dispose of the fission products. As noted previously, the location of impact should be noted and communicated to interested parties. In any case, the radiation levels around the impact area should be relatively benign within months of the impact.

If a reactor accident occurs during the mission such that the reactor is destroyed, it may only be of concern if the reactor were to impact the Earth or Mars soon after the event. Otherwise, the radioactive decay should render the reactor benign with a few weeks to several months. For the case of a reactor failure during the crewed mission return to Earth, the most likely time for this to happen probably would be when the TEI burn is conducted. If, for some reason, this created an immutable trajectory that could cause direct return of the spacecraft into the Earth's atmosphere, it is noted that reentry could occur approximately 6 months after the reactor was last shut down. The reactor should be fairly benign at that point, unless the reactor became critical upon impact with the Earth, an event of extremely minimal probability following an accident in which the reactor was destroyed.

9.0 Conclusions

This report identifies the implications associated with the operation of space nuclear power reactors utilized for NTP missions to Mars. There is a significant amount of planning, mission, and reactor design activities, including testing, that should be accomplished before the complete conclusions on the operations of NTP reactors can be drawn. However, there are a few direct conclusions that can be identified from this study.

With respect to the radiation safety of the astronauts who participate in missions to Mars, it is possible to conclude that the radiation exposures from natural space sources including galactic cosmic radiation and solar particle events may be very high and considerably greater than those that the crew might receive from the NTP engines. It can also be concluded that potential risk mitigation strategies, such as advanced shielding technologies, countermeasures, and individual-based risk assessments may be important to managing these potential risks to the astronauts on missions to Mars. It can also be concluded that minimizing the round-trip time for a human Mars mission utilizing NTP, including the surface stay, can reduce the overall risk of radiation exposure complications to the astronauts.

The primary potential direct radiation hazards to the crew and equipment on the Mars-bound spacecraft from the NTP engines should be during the reactor burns or from the dispersion of radioactive materials due to a reactor malfunction. Since the total engine burn time should be very short in comparison to the mission length, it can be expected that these radiation exposures should be fairly manageable by normal radiation protection procedures of minimizing exposure time, increasing the distance between the radiation sources and the astronauts, and by the effective placement of radiation shielding.

The radiation fields around the three reactors may be very complicated and affected by the reactor internal structures, the shielding design, and the propellant remaining in the tanks at any given time. Thus, it can be important to map these radiation fields and monitor any changes in them. Additionally, docking and undocking maneuvers with limited dwell time should be able to be carried out relatively soon after an engine burn; however, EVAs and maintenance activities may need to remain behind shielding for a significant time after the burn.

For the most part, space reactors for propulsion should be designed to avoid the need for maintenance or other activities near the reactors. For the two cargo missions, maintenance should be unlikely after departure from Earth orbit. Prior to NTP engine operation, there are no radiation exposure concerns. For the crewed mission, manual maintenance activities may be possible, but they could incur a number of potential risks to astronauts. There may be increased potential for radiation exposure if the astronauts venture outside of the normal radiation shielding areas, which could be compounded by the normal risks of astronauts performing activities outside a spacecraft. Robotic maintenance can be considered if any activities are envisioned to be needed in a high-radiation environment or to reduce the overall risks to astronauts performing EVAs. Robotic maintenance capabilities might need to be sent with the mission at a cost of additional mass in robotics and spare parts.

Effective control, monitoring, and management of NTP reactors during all operational phases, including startup, operation, hot shutdown, cold shutdown, engine dormancy, and engine restart, could be necessary. While considerable engine design and testing was accomplished during the Rover/NERVA development programs, modern instrumentation and control methods could be applied to any advancements of NTP engine technology. The full development of effective control methods should be needed for NTP systems including the utilization of control theory, digital electronics, modeling, and autonomous systems advances since the end of the Rover/NERVA program, plus a highly robust testing and development regime leading toward the availability of fully autonomous NTP engines. The impact of fuel material choices should also be analyzed and their impact on NTP engine operational details should be well understood.

Because the Rover/NERVA development programs were conducted prior to the advent of modern probabilistic safety analysis and probabilistic risk assessment techniques, there is a significant need for the development of the tools necessary to enable the application of these safety analysis techniques to be applied to NTP systems and missions. Activities such as full sequence of event analysis, failure mode and effects analysis, detailed levels 1 through 3 probabilistic risk assessment and other techniques now common within the terrestrial nuclear facility safety analysis world need to be developed and conducted to fully understand these complicated and rapidly changing NTP systems.

The likelihood of inadvertently impacting Mars and the Earth both during and after the mission is complete should be determined for both the cargo and crewed nuclear propulsion mission scenarios. These possibilities should not be challenging to determine and avoidance measures such as trajectory biasing may need to be considered. Options for final disposal include directed impact into the Sun or other body that could have benign consequences (although both of these options may require additional propellant loading to accomplish the significant ΔV required for accomplishment) and final trajectories into deep space or final orbit around the Sun which do not intersect the Earth or Mars.

As with any large-scale mission or technology, there exist a number of significant ambiguities that need to be resolved during system development. Some of the uncertainties identified in this report include:

- Uncertainty regarding the applicability of the DRA 5.0 mission architecture, which utilizes HEU reactors based upon the Rover/NERVA nuclear rocket engine development programs from the 1960s and 1970s.
- Uncertainty regarding the use of HEU, as was assumed for the DRA 5.0 mission architecture, versus the possible use of HALEU for future NTP missions. The full ramifications of the utilization of HALEU are yet to be completely understood, determined and tested.
- Uncertainty related to the application of modern probabilistic safety analysis and the availability of valid engine and component reliability data needed to support these analyses.
- Uncertainty related to the likelihood of the NTP reactors inadvertently impacting Earth or Mars needs to be determined for each of the nuclear propulsion missions. Whether the probabilities are to be treated individually for each mission or summed over all related missions is not clear. These probabilities are not expected to be difficult to achieve; however, if that cannot be demonstrated, then additional measures such as trajectory biasing may need to be considered. Such methods can significantly impact the mission profile.
- Detailed design studies, of both the mission and reactors should be completed to reduce the uncertainties regarding the operations of these NTP reactors for Mars missions. It is recommended that NASA and the Department of Energy perform the detailed design, safety and operability analysis necessary to eliminate these uncertainties.

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14. ABSTRACT

This report is aimed at identifying the implications associated with the operation of space nuclear power reactors that would be utilized for Nuclear Thermal Propulsion (NTP) missions to Mars. The objective of this study is to evaluate the operational features of reactors that could provide propulsion and possibly electrical power for future crewed and cargo missions to Mars. This report follows upon an initial report looking at the generic considerations for operating fission reactors in space applications and is intended as a deeper dive into the operational features related to specific Mars NTP applications.

15. SUBJECT TERMS

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