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ASI Program Update

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Welcome to the twenty-third edition of the Advanced Sensors and Instrumentation (ASI) Program Newsletter. The ASI program has experienced a period of substantial evolution over the past year, marked by changes in program leadership and a strategic refinement of its mission objectives. These shifts are occurring in parallel with recent federal directives aimed at accelerating both terrestrial and space deployment of nuclear reactor technology. In this context, the availability of commercially viable, deployment-ready instrumentation and control (I&C) technologies has become mission-critical for supporting the next generation of nuclear systems.

This edition highlights emerging cross-domain collaborations that bridge terrestrial reactor applications with expanding space nuclear initiatives. Although the U.S. Department of Energy (DOE) and NASA have maintained a long history of technical cooperation, the current momentum reflects a renewed national interest in nuclear propulsion and power systems that can enable sustained exploration and deep-space missions. These renewed efforts underscore the need for robust, radiation-tolerant sensors/systems and autonomous control architectures that remain reliable even under extreme environmental and operational constraints.

ASI continues to advance its core mandate through deep coordination with multiple DOE programs, including the Advanced Reactor Technologies Program, the Advanced Fuels Campaign, the Nuclear Science User Facilities, and U.S. Department of Defense nuclear program partners.

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Through these collaborations, ASI accelerates the development, qualification, and transition of advanced sensing and I&C technologies to industry stakeholders and mission sponsors.

ASI plays a central role in ensuring that the United States maintains technological leadership in nuclear energy innovation—across terrestrial applications, space exploration missions, and emerging defense needs. The research outcomes highlighted in this issue reflect a growing, tightly integrated ecosystem of advanced nuclear R&D poised to meet the evolving challenges of the nation's energy and security landscape.

This issue features a collection of technical contributions from subject-matter experts addressing several priority areas within the ASI mission. The articles examine current challenges and emerging opportunities within the scope of the space nuclear reactor mission, with particular focus on I&C technology gaps that constrain system performance, safety, and long-duration operability. The authors also explore the increasing importance of autonomous and semi-autonomous control architectures for space nuclear systems, highlighting the necessary advancements for ensuring resilience under extreme environmental and mission conditions. This edition also presents a forward-looking assessment of the technical risks associated with space nuclear deployment, offering perspectives on qualification pathways, reliability considerations, and integration with mission-critical subsystems.

Advanced Instrumentation Needs for Space Nuclear Applications

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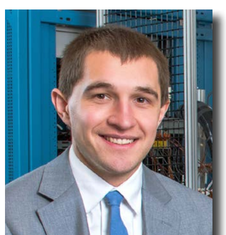

Abstract

As we embark on humanity's next great leap to the Moon and beyond, we will need to bring along many resources to sustain life and accomplish our missions. Chief among those necessary resources is a supply of usable energy, a role for which nuclear technology is spectacularly suited. Regions of our cosmic neighborhood cannot be reached without it.

Integrating reactors and radioisotope sources into spacecraft is no small feat. These compact systems must forego the luxuries of mass and maintainability while also maximizing energy density and associated heat loads. They must also withstand the often-counterintuitive challenges of space environments, as well as the unsettling vibration and acceleration loads needed to leave this planet and land on another. We still have much to learn in this area.

With this renewed interest in space nuclear technology, we must also renew the diligent effort to ensure that these systems can be safely, reliably, and efficiently monitored and controlled. That effort began over a half-century ago, at the dawn of both the space and nuclear ages. But in the interim, and since the early Nuclear Engine for Rocket Vehicle Application (NERVA) and System for Nuclear Auxiliary Power (SNAP) development, there has been limited focus on these unique applications. In today's incoming space nuclear fleet, we require novel development and adaptation of sensors, actuators, control hardware, and autonomous control and fault management approaches to fit the mission, much like the NERVA control actuator depicted in in Figure 1 [1].

Space Nuclear Mission Applications

The space nuclear technology landscape is categorized into two top-level classifications: fission systems and radioisotope systems. Radioisotope power systems (RPSs) and radioisotope heating units (RHUs) are crucial components to the space exploration mission. They have a long legacy of successful operations, and modern developments are likely to see an expansion of these capabilities for both power and heating, ranging from milliwatts to hundreds of watts. The value of these systems cannot be overstated, especially regarding their ability to operate reliably with minimal control input. That same characteristic makes their nuclear instrumentation and control (I&C) requirements and challenges comparatively benign but does not altogether eliminate them.

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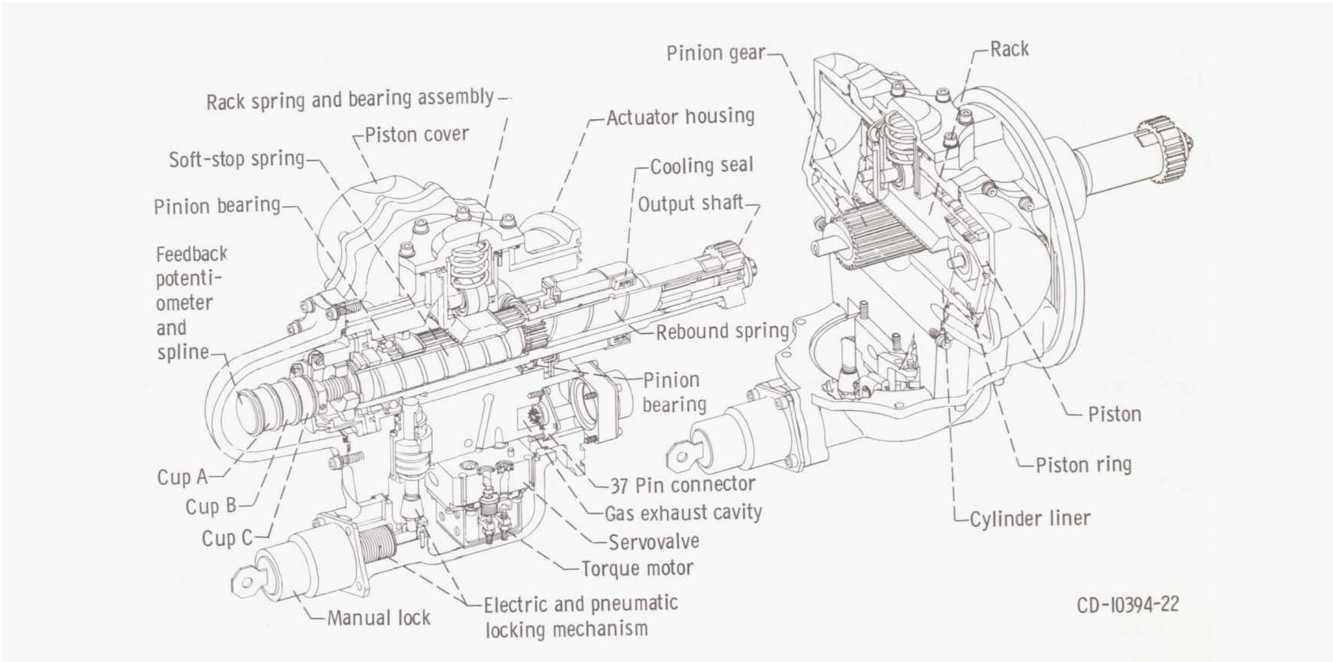

Figure 1. NERVA control drum actuator.

Space fission systems, on the other hand, remain largely underutilized and are now a major focus for technology development. These can be subcategorized into three avenues with significant crossover: fission surface power (FSP), nuclear electric propulsion (NEP), and nuclear thermal propulsion (NTP).

FSP systems seek to provide power to enable an extended human presence on extraterrestrial bodies where alternative sources of electricity are less viable, such as in dark, dusty, or distant environments. For example, on the Moon, night lasts about 14 Earth days, with temperatures plummeting to cryogenic conditions in the absence of direct sunlight. Typical FSP architecture assumes a 1–100 kWe power range and continuous operations for upwards of a decade.

Reactors are also intended to be implemented for both power and propulsion of spacecraft, though only for in-space operation and not for activation on the ground or exiting the atmosphere of Earth.

Much like FSP systems, NEP architecture uses a nuclear reactor to generate electricity, creating power that is then diverted to drive an ion thruster. Electric thrusters benefit from extremely high specific impulse (Isp), which can be considered a rough measure of the spacecraft's fuel economy. However, these produce minimal thrust and must operate for very long durations of time. NEP systems carry the potential to dramatically extend humanity's reach to the outer solar system and afford the added benefit of providing useful electric power during such voyages. They can also support scientific robotic missions at smaller power levels, up to hundreds of kWe, but require much larger power levels (of several MWe) to enable human missions—both of which would require continuous operation for months or even years.

In contrast, NTP engines produce high thrust, similar to chemical rocket engines but with nearly double the Isp of chemical systems, by heating and expelling low-mass hydrogen at extremely high temperatures (>2700 K). For most missions, the NTP engine operates for only a few minutes at a time, but at a thermal power of several hundred MW. Relative to chemical propulsion architectures, NTP vehicle architecture enables Mars missions that include fuel reserves to return home without having to rely on a Martian fuel production capability or needing to rendezvous with a fuel tanker on Mars. It even enables a number of viable abort scenarios in the event of emergency. The improved performance can also increase available life support margins, reduce trip durations, and generally reduce astronaut exposure to the myriad risks associated with the boldest of missions.

Both NEP and NTP technology avenues offer a set of benefits, drawbacks, and technology gaps that could occupy years of technical development and scholarly debate. However, the broad consensus is that both will play some role in our expansion across the celestial neighborhood [2–4].

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Space Nuclear Environment Challenges

Space nuclear systems present a unique set of extreme environments due to the already challenging "natural space environment" as well as the extreme "induced environment" generated by the reactor's operations. Both environments will pose major hazards and technological challenges for the affected systems, especially those associated with I&C.

Modern FSP and NEP system designs typically assume in-core fuel temperatures of around 1100 K, while current NTP designs assume in-core fuel temperature levels of up to approximately 3000 K. In-core I&C will thus need to withstand temperatures ranging from extremely low (cryogenic) values to those maximum design points, although many regions of the system may present more modest thermal conditions. For long-term FSP and NEP, those exposures are developed over continuous operation on the order of years and can see high dose rates, displacement, or burnup in that time. In NTP systems with short total burnup, the challenges instead point more often toward dose rates, transient heating, and repeated thermal cycling. Additionally, I&C that is implemented externally to the core and any pressure boundary will be exposed to the confounding implications of the space vacuum environment. The absence of air pressure causes electric charge potential to behave differently and forces certain materials to off-gas or react in unfamiliar ways. Figure 2 shows a notional layout of the I&C in a reference NTP engine system [5].

The thermal effects associated with the absence of air can challenge the intuitions of even the most seasoned engineers. Without the cooling afforded by convection to air, all objects must reject (or absorb) heat via solid-conduction and thermal radiation only. The common notion of space being cold is inaccurate; in fact, space is not much of anything! However, the components in space are dramatically affected by what they are connected to, or by their view factor toward deep space (cold sink), the sun (hot source), or solar albedo from Earth, Luna, or Mars (warm source). With the addition of a nuclear reactor, a new factor arises in the absorption of high fluxes of gamma and neutron radiation. This internal heating of components near the reactor has the net effect of turning everything into its own heater, and the net flow and buildup of that heat must be accounted for across the entire system. Again, this is no small feat.

The radiation environment emitted from the reactor core as gamma, neutron, and their secondary radiations

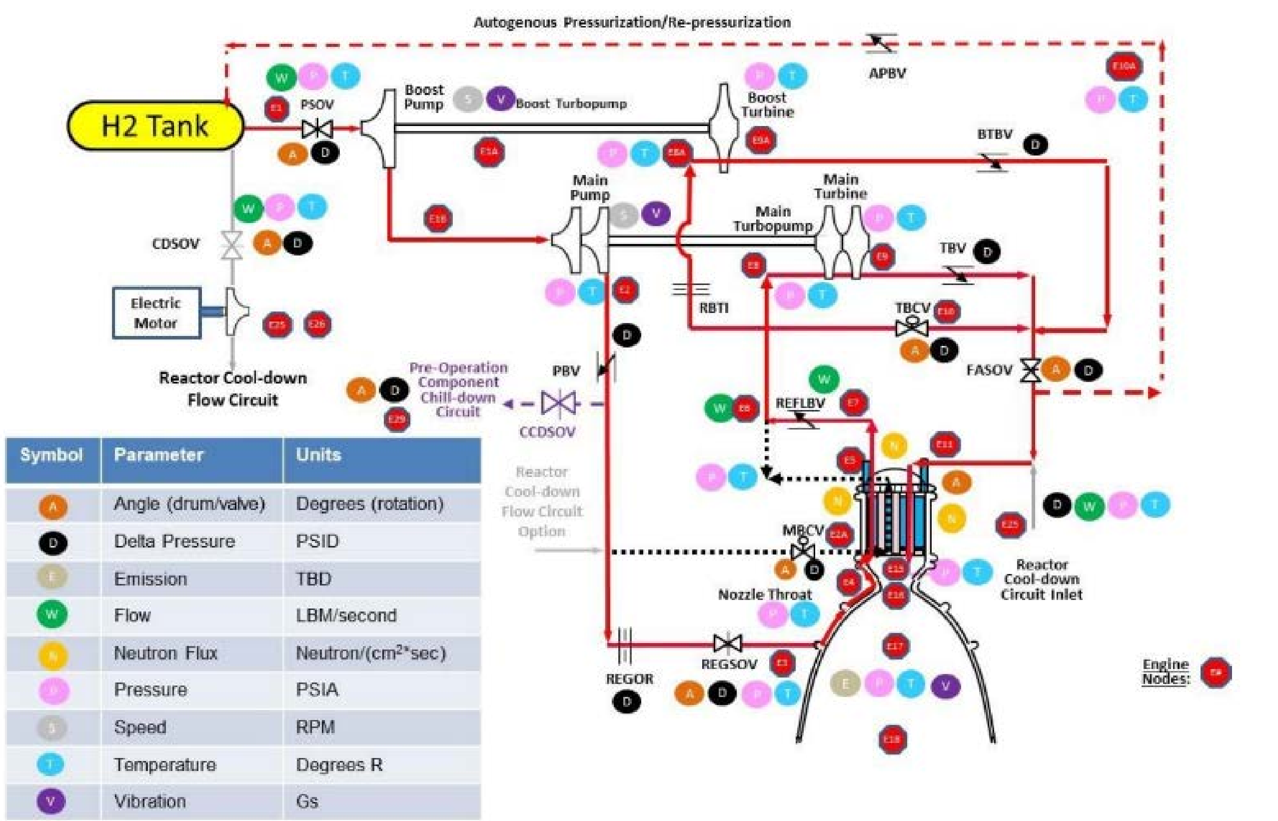

Figure 2. Notional placement of NTP I&C for a reference design.

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are, in more typical fashion, responsible for significant degradation and failure of materials and electronic components. This can include accumulation of total ionizing dose (TID), displacement damage, and an array of neutron-associated single event effects (nSEE) in logic and transistor systems. Note that the dominant effects at any point vary widely across and within each system, due to differences in operating modes (short/pulsed vs. sustained), power levels (kW vs. MW), system architecture (distanced vs. close-coupled), and shielding mass.

The natural space radiation environment is not to be neglected either, and can be categorized largely into trapped particles, solar energetic particles (SPEs), and galactic cosmic rays (GCRs). The relative intensity and spectrum of these electrons, protons, and heavier ions change as a function of location and time. For trapped particles, orbital mechanics play a large role for near-Earth missions or missions to Jupiter and Saturn and their moons, where the spacecraft dips in and out of the intense, trapped electron/proton belts. SPEs arrive as intermittent solar particle events and can envelop a spacecraft from many angles. These short, intense events impose an extreme level of shallow-penetrating radiation that can be lethal to unprotected humans and hardware. Lastly, the persistent incidence of GCRs includes both low- and high-energy particles. The heaviest among these, such as Fe-56, are rare but consequential, creating dense ionization tracks that pummel through shields, spacecraft, electronics, DNA, and anything else. They also create a wake of secondary spallation particles that can collectively be more damaging than the primary ion. Little can be done to stop those high-end extreme ions, short of hiding in the atmosphere and magnetosphere of the planet. However, it is important to note that the overwhelming majority of space radiation is of relatively low energy and scales logarithmically down as energy increases. The consequence is that the thinnest outer layers of a spacecraft or system may seem to experience extraordinarily high radiation doses over a mission, but relatively modest doses can be expected behind a few millimeters of aluminum. However, humans and certain electronic hardware remain especially sensitive to the unusual damage mechanisms of heavy and energetic ions.

Other Operational Challenges

In addition to the novel environments involved, various other operational characteristics impose challenges on space nuclear I&C systems.

I&C must remain reliable throughout long-duration missions with minimal to no maintenance. However, not all failure modes are discrete. For instance, sensor systems are known to drift over time, and that signal drift, offset, or uncertainty must be quantified and corrected without access to a calibration laboratory.

Spaceflight systems are often constrained by size, weight, and power (SWaP). Minimizing these as "low-SWaP" systems is beneficial to the mission across the board. This is further complicated if radiation hardness is achieved through architecture design rather than device fabrication. Shielding, packaging, and redundancy all increase the SWaP factors in the I&C suite.

Signal delays associated with light speed distances, signal intermittency due to orbital mechanics, and data bandwidth limitations due to power constraints and antenna availability are facts of life in spaceflight, necessitating the implementation of autonomous controls in some capacity. To meet that goal, safety-critical controllers with high-level logic, significant data storage, and high-speed processing are needed. These must also be radiation-hardened (rad-hard) in the context of space nuclear environments, which are not necessarily encompassed by existing Radiation Hardness Assurance criteria.

From an operational and safety-basis perspective, there are unique considerations to account for in fault management. For example, in the unlikely event that a reactor incurs damage during a crewed mission, initiating an emergency shutdown (SCRAM) may remove the crew's only mechanism to return to Earth and even put them at more risk than if they were to continue operations, whereas in terrestrial applications, a SCRAM is often the default failsafe action in an emergency. The Department of Energy's (DOE) "safety-critical" lens may not always yield the same action as NASA's "mission-critical" lens. In both cases, crew and public safety are paramount, but different actions may be taken toward that goal.

Another challenge, one that is more programmatic in nature, is the difference between DOE's and NASA's Technology Readiness Level (TRL) definitions. Recent efforts have sought to merge these definitions for level of integration and testing in increasingly representative environments for space nuclear technologies [6].

Past and Future

Space nuclear power and propulsion have a rich history of design, development, and testing that spans over 60 years. Despite this extensive experience, there has been some deprecation in the manufacturing readiness, and thus the technology readiness, of previously demonstrated I&C technologies. Expertise and methods to build and demonstrate technology used in the 1960s has, in many cases, been lost to time [7,8].

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However, the historical insight that they afford remains invaluable. For instance, during the NERVA NTP program, it was found that resolvers were the ideal control drum sensor, as they were observed to maintain precise control drum angle measurements in intense radiation and vibration environments. To monitor vibrations, variable reluctance accelerometers were selected for development over the piezoelectric and strain gauge-based accelerometer alternatives. Linear transformers were chosen for displacement measurements. Thermocouples and resistance temperature detectors were also actively developed, and the best location for radiation detectors, at the time, was determined to be behind the primary shield. Calorimeters, strain gauges, and pressure transducers were also investigated under NERVA, as depicted in Figure 3 [9].

Today, efforts are being made by multi-agency teams to mature technologies that will ensure the success of space nuclear missions. These efforts aim to identify common technology needs across space nuclear systems and to close any I&C gaps. This work includes multipurpose sensors to reduce size and mass; distributed and embedded fibers; temperature, radiation, and pressure sensors that can withstand the in-core thermal and radiation environments; advanced and autonomous controls; anti-criticality and criticality control mechanisms; self-calibration methods, rad-hard signal processing and front-end electronics; and experimental capabilities to facilitate testing of all of the above.

The I&C space nuclear challenge is substantial but surmountable through partnerships with government, national laboratories, academia, and industry. Recognizing commonalities across FSP, NEP, and NTP will simplify the challenge and more rapidly yield a set of viable and cost-effective I&C solutions for imminent space nuclear fleets.

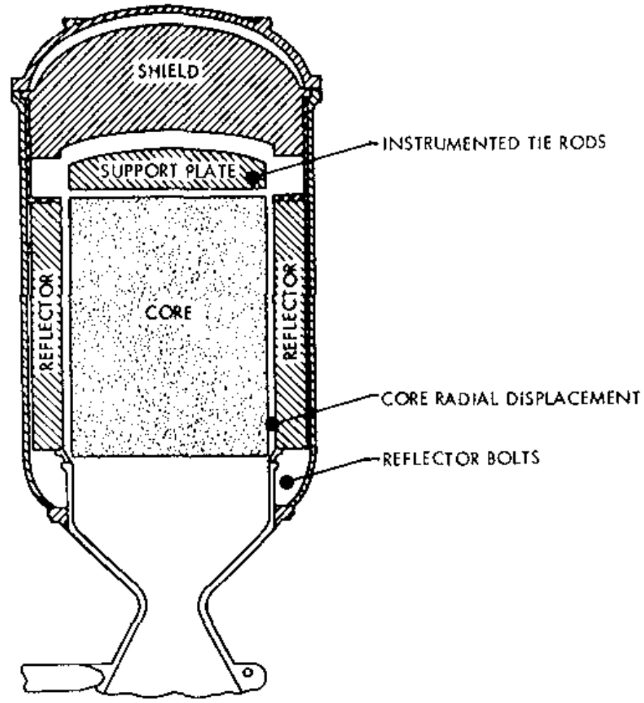

Figure 3. Depictions of specific measurement locations within reactor system were identified under NERVA, including the strain gauges shown here.

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Fission Surface Power Reactor Power Monitoring

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Terrestrial-based reactor power monitoring for commercial light-water reactors is performed via a combination of ex-core and in-core detectors. Ex-core detectors are typically gas-filled detectors such as BF_3 and B-10 ion chambers, and supplemental in-core power distribution monitoring is performed using fission chambers, self-powered neutron detectors, and activation detectors. Recent work under the Advanced Sensors and Instrumentation (ASI) program has been aimed at enabling high-temperature operation (up to 650°C) of in-core detectors and innovating toward real-time neutron energy spectrum measurements for many of the Generation IV advanced reactor applications [1]. The manner in which advanced nuclear reactor applications have progressed in recent months has necessitated the development of novel new sensor types, including sensors that target space reactor applications.

A standoff radiation sensor solution for long-term reactor-power monitoring in a lunar environment requires a proof-of-concept, real-time, neutron-flux monitoring system that employs gas-filled neutron detectors. The population of gamma rays and neutrons emitted from an operating reactor consists of prompt and delayed emissions, as well as the buildup of fission products and the neutron activation of the reactor's structural and support materials [2].

A major concern with radiation detection in a space environment is the differentiation between the radiation emitted by the reactor and the celestial and spallation background radiation experienced at the lunar surface [3]. Idaho National Laboratory (INL) identified two commercially available detectors for testing and experimentation (i.e., ^{3}He- and ^{6}Li-foil-based gas-filled neutron counters), due to their relatively high detection efficiency and good reaction-product energy resolution. Initial testing of these two detectors was conducted in a laboratory setting by comparing (1) detector efficiencies for both high- and low-energy neutron emission spectra, and (2) response rates—meaning the time-to-reporting of increasing/decreasing source emission rates—for incorporation with a reactor control system.

Unlike many terrestrial-based reactor control monitors, all sensors utilized under the Fission Surface Power (FSP) program must adhere to the following considerations:

1. Successful and reliable operation for a period of 10 years
2. Operation in, or nearby, a relatively unshielded nuclear reactor vessel
3. Operation in the harsh radiation environment found on the lunar surface
4. Stability of measurements given the regular temperature cycles on the lunar surface (±200°C)
5. Reliable transmission of measured data over a distance of 1 km.

The transient and steady-state power levels of a nuclear reactor can be directly calibrated to, and correlated with, the radiation emitted by the fission process—typically utilizing gamma ray and/or neutron emissions [4]. Control of a reactor's startup requires measurement capabilities that extend over a broad range of power levels. The difficulty of providing reactor power from 0 W to the proposed 40–100 kW steady-state power of the FSP program's proposed lunar reactor may necessitate multiple detector types/positions. It is imperative that the proper radiation sensors be identified in order to meet this steep requirement in an extremely harsh environment.

Far-edge measurement systems typically comprise one or more high-efficiency detectors designed for standoff measurements of sources or for area monitoring. Detector selection and proper placement are extremely important. Improper selection can lead to weak signal-to-noise output from the device. ^{3}He, ^{10}B-lined, $^{10}BF_3$, and ^{6}Li-based detectors, or otherwise U-based fission chambers dominate the market for terrestrial use. However, because they are designed for terrestrial application by humans, the vast majority of such detectors have a limited environmental operational range. Most notably, the operational temperature of most gas-filled detectors is limited to 100°C–150°C. As far as detector electronics are concerned, serviceability, calibration, and protection from reactor conditions give ex-core radiation monitors an advantage over in- and near-core sensor packages.

Discrimination of background radiation, such as high-energy charged particles from either cosmic or solar origin, is another important aspect of reactor control systems. A background signal can appear to a detection system as a change in reactor power, thereby leading to incorrect adjustment of the reactor power. Energy-discriminating thresholds could potentially be implemented; however, use of "witness" detectors to serve as a form of "coincidence" counter will likely minimize the risk of false signals being sent to the FSP reactor control system.

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Neutron leakage from the lunar surface is also a concern. Spallation neutrons escaping from the lunar surface—as generated from cosmic ray interaction within the lunar regolith—presents a non-zero neutron background flux and must be accounted for.

A series of detectors was tested at INL to determine the feasibility of utilizing multiple detectors simultaneously to monitor the power output of a functioning nuclear reactor. An Li-foil, an Al-foil witness detector, and an ^{3}He detector (Figure 1) were all tested simultaneously against a ^{252}Cf source to gauge their respective responses to changing neutron fluxes (Figure 2), followed by their respective angular sensitivities (Figure 3).

This work performed under the FSP program stands as the prime example of neutron detector development and demonstration being applied to qualify detectors for specific nuclear applications and requirements that follow the strategies employed by the ASI program.

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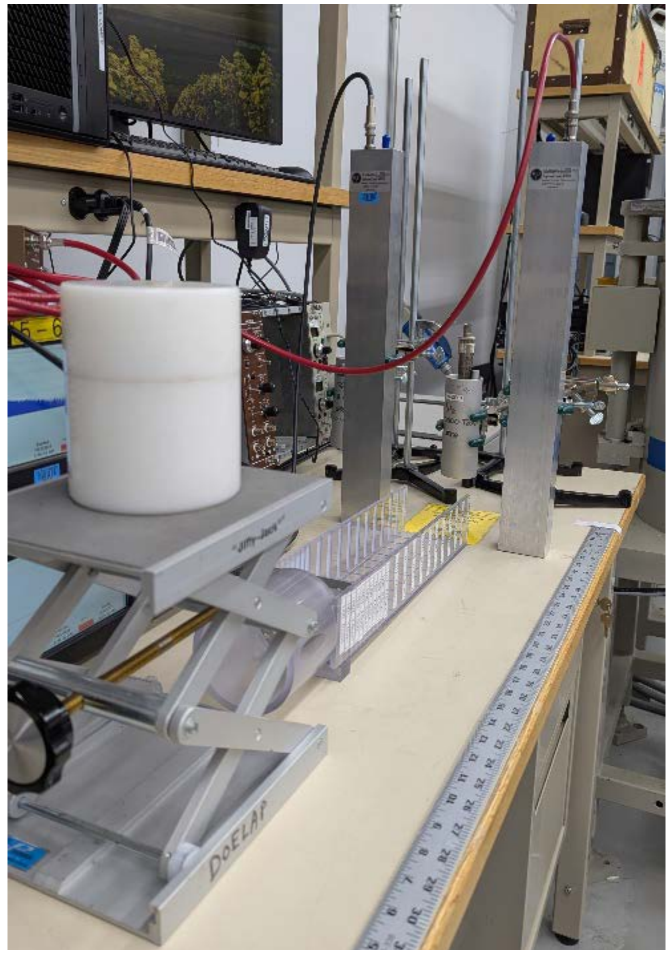

Figure 1. Detector setup for testing ^{6}Li-foil and ^{3}He neutron detectors in tandem with a witness Al-foil detector.

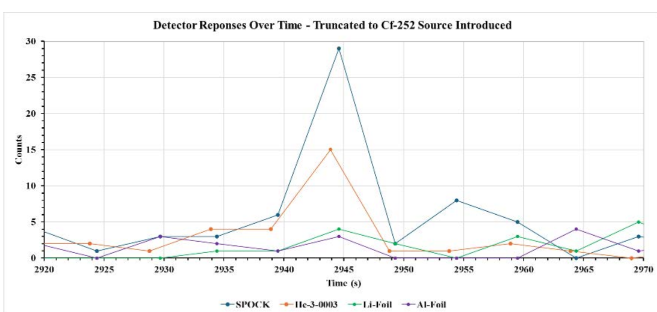

Figure 2. Count rate responses of the HPGe (SPOCK), ^{3}He, ^{6}Li-foil, and Al-foil detectors when exposed to a bare ^{252}Cf source.

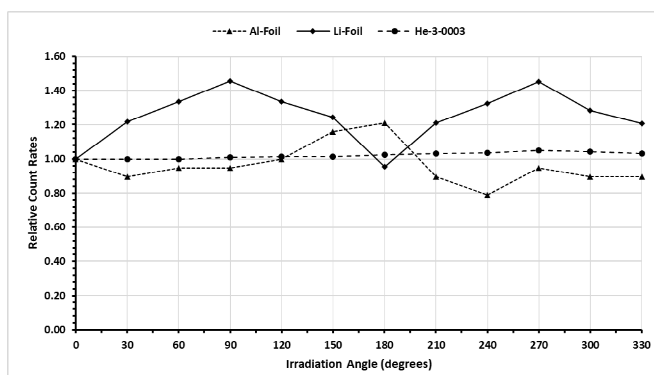

Figure. 3. Angular dependency of the detector response rate when exposed to a ^{252}Cf source as the detector is rotated along its axis. The relative count rates are normalized to each detector's "front" face. The thermalization—and therefore the scattering/deflection—of neutrons from the source indicates a "relative" sensitivity to the neutron incident angle.

Power for Power? The Need for Auxiliary, Backup, and Emergency Power for Space Reactors

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Introduction

Humanity's pursuit of lofty space exploration goals such as a sustained presence on the Moon and eventually Mars has generated a distinct demand for a continuous, reliable, high-capacity power supply that far exceeds anything previous missions have required. Life support systems, in-situ resource utilization (ISRU) facilities, scientific instrumentation, thermal management infrastructure, and surface mobility assets collectively impose power demands on the order of tens of kW per mission. Traditional power sources such as solar photovoltaic arrays are rendered infeasible by launch mass constraints and reliability requirements for long-duration missions conducted in harsh environments.

Fission surface power (FSP) [1] systems, characterized by high energy densities and long operational lifecycles, represent the most credible near-term solution to this challenge. By harnessing power from controlled nuclear fission, FSP systems can provide stable, dispatchable power independent of solar flux, orbital geometry, or diurnal cycles. However, the absence of an external power grid means that planned maintenance outages, unplanned reactor trips, and the startup transient all expose surface assets to potentially mission-ending power interruptions. The robust design of secondary power systems (encompassing auxiliary, backup, and emergency power) is therefore a foundational requirement for any credible FSP architecture. This is an inherently instrumentation and controls (I&C)-intensive challenge. Sensors, actuators, and autonomous control logic are not peripheral to secondary power; they are its operational backbone. This informational article provides an overview of secondary power systems for FSP missions, focusing on relevant functions, design drivers, and systems engineering considerations.

Taxonomy and Requirements

It is important to understand the distinct taxonomy for FSP systems that is used throughout this article. A nuclear fission reactor is the **primary** power source, with power conversion occurring via Stirling or Brayton engines. Heat-pipe microreactors are emerging as the most feasible option for FSP. An **auxiliary** power source is needed to start the reactor, just as a car battery starts a car engine. Additionally, **backup** and **emergency** power are needed to sustain critical loads during planned and unplanned shutdowns, respectively. In most FSP concepts, the same system would provide both backup and emergency power. In this article, auxiliary, backup, and emergency power systems are collectively referred to as the "secondary power system." **Figure 1** describes the key terms pertaining to FSP concepts.

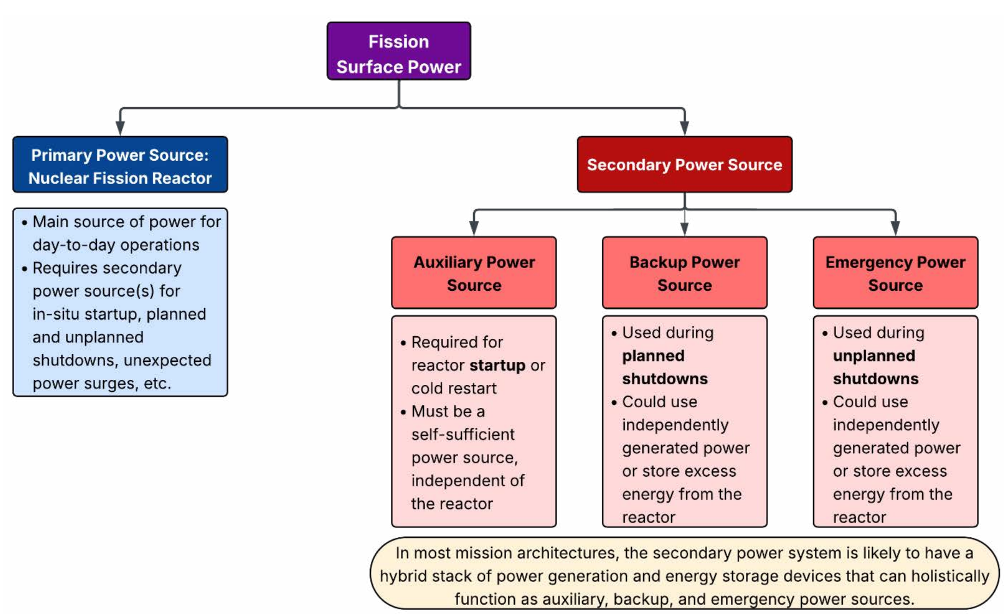

Figure 1. Taxonomy of an FSP system.

The design of the secondary power system is impacted by three broad requirements: it must be able to survive in the mission environment (e.g., the Moon or Mars), execute its designated task (e.g., start the reactor or provide power during shutdown), and maintain a safe operational state at all times. The following sections describe the key design drivers for secondary power systems in FSP missions.

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Designing Surface Systems for the Space Environment

The primary design driver for FSP systems is the harsh environment of outer space. For example, the Moon lacks any substantial atmosphere that can shield engineered systems from cosmic radiation or micrometeorites. The near-vacuum environment creates unique challenges such as extreme thermal cycles. For example, in the equatorial regions, the surface temperature can range from 212°F in direct sunlight to –279°F at night. Many sites encounter long periods without sunlight (e.g., 14-day nights in some areas of interest), and polar craters in which water ice has been detected are permanently in shadow, with temperatures reaching as low as –410°F. Lunar gravity is about 1/6th that of Earth. The light regolith (dust) can accumulate in and cause damage to mechanical and electronic components. Similarly, Mars entails its own unique challenges, including occasional planet-wide dust storms and significant communication latency with Earth. These factors impose several design limitations on FSP systems. NASA's 2024 Fission Instrumentation and Controls (FICS) Workshop identified the key attributes required for FSP I&C technology: compact form factor, multi-sensing integration to reduce mass and volume, radiation hardening for both in-core and ex-core placements, high-temperature durability, and long operational life [2]. These types of requirements can seldom be met by simply adapting commercial off-the-shelf components. Instead, they necessitate purpose-developed solutions.

Auxiliary Power for Startup and Cold Restart

While the reactor is the primary power source in FSP concepts, reactor startup requires a power source independent of the reactor itself—a classic chicken-and-egg problem. The auxiliary power system must operate all components necessary for startup: the reactivity control mechanism (control rods/drums), sensors (pressure, temperature, neutron flux, etc.), heat extraction components (valves, motors, preheating systems, etc.), power conversion system (Brayton, Stirling, or thermoelectric), power management and distribution (PMAD) system, and safety shutdown mechanisms. Equivalent loads are expected during cold restarts following extended shutdowns. Since the auxiliary system must be fully independent of the reactor, feasible options are limited to stored energy or alternative generation sources such as lithium-ion batteries, solar cells, or Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs).

Backup/Emergency Power for Off-Nominal Conditions

Despite all built-in safety measures, backup and emergency power are essential for scenarios in which the reactor cannot produce power. This can happen as a result of planned maintenance, component failures, meteorite impact, solar storms, and so on. Backup and emergency power systems must sustain all critical loads: nuclear safety functions (sensors, actuators, and controllers for safe reactor shutdown), the Environmental Control and Life Support System (ECLSS) for crewed missions, and monitoring and communications for Earth-based mission support. Thermal loads like freeze protection, electronics temperature management, and radiator loop control dominate the energy budget for uncrewed missions. Unlike auxiliary power, backup and emergency systems may leverage the reactor by storing excess energy in batteries or ultracapacitors during normal operations. System sizing is governed by critical load power requirements and the expected durations of planned and unplanned outages, which vary from one mission to another.

Autonomous Control and Fault Management

Perhaps the most demanding requirement for FSP systems is autonomous operations, as necessitated by Earth-communication latency and the difficulty of rapid human intervention. Autonomous health monitoring involves constantly checking sensor calibration, reducing measurement uncertainty, and providing sensor validation. Techniques such as cross calibration between redundant sensors, empirical neural network modeling, and physics-based modeling can be combined under a modular signal processing platform to enable continuous system health assessment [3]. For unplanned shutdowns, anomalies, and emergencies, a robust fault detection, isolation, and recovery (FDIR) strategy must ensure that the integrated system can autonomously detect faults, initiate controlled shutdown, and transition to emergency power with minimal or no human intervention. Provisions must nonetheless be made for astronaut override and remote troubleshooting by Earth-based mission control during communication windows. The control architecture must therefore support both fully autonomous and human-supervised operational modes, with appropriate interlock logic in place to prevent unsafe states in either configuration.

Candidate Technologies and System Sizing

Nearly seven decades of space exploration have produced a range of power technologies suitable for FSP secondary power applications. Radioisotope power systems (RPSs), or "nuclear batteries," have supported 17 long-duration NASA missions. The Multi-Hundred Watt Radioisotope Thermoelectric Generators (MHW-RTGs) aboard Voyager 1 and 2 have continuously operated for over 45 years [4], while the latest variant, the MMRTG [5], currently powers the Curiosity and Perseverance Mars rovers at approximately 110 We at beginning of life. With no moving

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parts, no refueling requirement, and proven performance in extreme environments, MMRTGs are a strong candidate for FSP auxiliary and backup power. Solar photovoltaic cells are also viable for secondary power in sunlit locations on the Moon or Mars. In locations where water ice is accessible, such as the lunar south pole (e.g., Shackleton Crater), Martian polar ice caps, subsurface glaciers, and craters (e.g., Korolev), regenerative fuel cells (RFCs) [6] represent an innovative dual-use solution. RFC electrolyzers split ISRU-derived water into stored hydrogen and oxygen, which the fuel cell later recombines on demand to generate electricity. Key advantages include high energy density, low mass, long-term storage capability, and potential integration with crew life support systems.

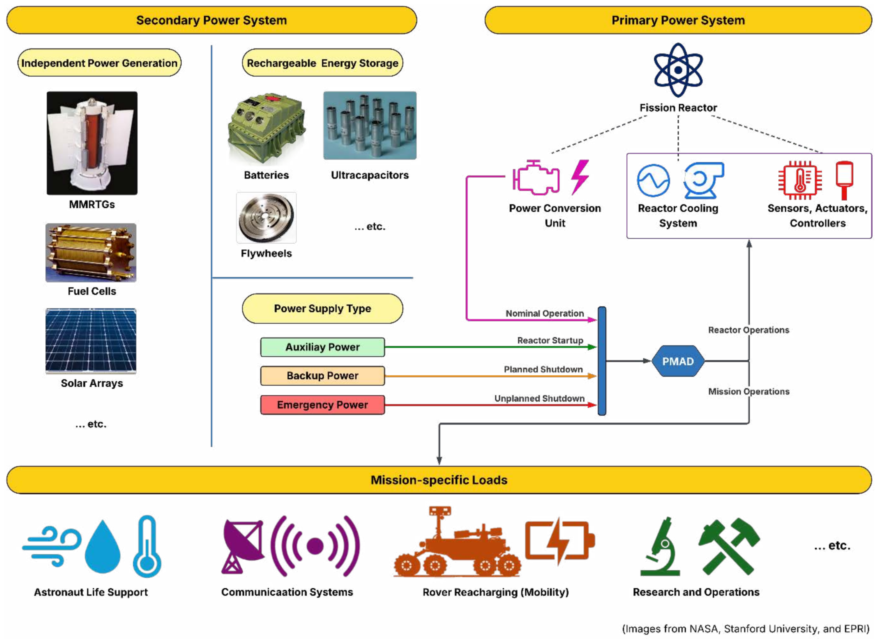

Figure 2. Architecture of fission power systems.

For shorter-duration backup and emergency needs, energy storage devices are promising options. Lithium-ion batteries are mature; flight-proven across satellites, orbiters, and rovers; and readily scalable. Solid-state batteries offer improved energy density and safety for space environments. Solid-state ultracapacitors [7] excel at millisecond- to second-scale high-power transients (e.g., actuator surges, voltage drops during fault events), thanks to their rapid charge/discharge capability, high power density, and low-temperature operability. However, their low energy density makes them unsuitable for sustained outages. Flywheels [8] offer high power density and an extremely long lifecycle in vacuum, but generally have higher mass and volume relative to batteries.

In practice, FSP architectures will likely employ a hybrid energy stack: ultracapacitors for instantaneous transients, batteries for hours-long outages, and fuel cells for multiday scenarios. Because every kilogram of redundancy displaces mission payload, system sizing must be governed by a risk-informed framework that accounts for mission duration, crew presence, critical load inventory, acceptable outage duration, and practical considerations such as start-surge currents, duty cycles, conversion losses, radiation-induced efficiency degradation, and margins for longer-than-expected outages.

Sensors for Secondary Power Systems

The secondary power system requires a dedicated instrumentation layer. For example, battery state-of-health monitoring (e.g., tracking of the state of charge, cell voltage, temperature, and internal resistance throughout a decade of operation) is essential for ensuring that backup energy reserves are available when needed. For regenerative fuel cell systems, sensors must monitor hydrogen and oxygen storage pressures, electrolyzer and fuel cell stack temperatures, and membrane integrity. Ultracapacitor arrays require voltage balancing electronics and discharge monitoring for fast transient loads, such as control actuators during emergency shutdown sequences. For radioisotope power systems used as auxiliary power sources, decay heat output is predictable but declines over time. Accurate long-term power budget management requires temperature monitoring and output tracking against expected degradation curves.

System Architecture, Integration, and Operation

The generic system architecture and operational concept for power generation and storage in FSP missions is illustrated in Figure 2. The key components are the reactor core (primary energy source), cooling system, power conversion unit (Brayton/Stirling/thermoelectric), secondary power system (auxiliary, backup, emergency), PMAD, and mission loads.

It is important to account for electrical and thermal integration of the power system in the mission design phase. Key considerations include connection and compatibility of PMAD buses, switches, controllers, and

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isolation systems with all the various load systems such as astronaut habitats, laboratories, rover charging stations, and ISRU plants. It is also necessary that the system be designed to protect against faults, overcurrent, and single-event effects, and to ensure that the secondary power system does not become a common-cause failure path into the reactor plant. The tradeoff between mass and safety means that fault-tolerant redundancy patterns should be judiciously used for risk-prone or mission-critical components. In missions with a high-power demand, multiple microreactors may be cross-strapped to form a "microgrid" to provide adequate power while also ensuring redundancy. In such configurations, the multiple fission units could be connected in modular fashion, thereby creating a backup power strategy.

Looking to the Future: FSP on the Moon, Mars, and Beyond

The development of robust auxiliary, backup, and emergency power systems for FSP is not merely an engineering subtask, but rather a foundational investment in the resilience of humanity's long-term spacefaring capability. The absence of an external grid, the severity of the space environment, and the operational autonomy demanded by communication latencies together necessitate careful and intentional design of secondary power systems. With NASA's Artemis Program [9] reinvigorating lunar exploration, an opportunity has arisen for using the Moon as a proving ground for FSP technologies. The operational data collected from lunar FSP missions, along with the opportunity to rapidly validate key technologies, will enable risk-informed system design for Mars missions, in which the power challenge is more acute, mass-volume constraints are stricter, and autonomous fault management is a necessity. Novel concepts like multi-reactor microgrid topologies, advanced regenerative fuel cell systems, and scalable radioisotope auxiliary sources can be matured in the lunar context and translated naturally to Mars, and then eventually to more distant destinations. The decisions made today in designing secondary power systems for the lunar FSP will echo across the entire trajectory of future space exploration.

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Autonomous Operations for Space Nuclear Systems: A Perspective

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Introduction

Autonomous systems have always been integral to space exploration, evolving in tandem with the increasing complexity of missions and the rapid advancement of technology. Growing interest in space nuclear systems for both propulsion and power generation has spurred the need to explore integration of autonomy early in the design process for instrumentation and control (I&C) systems, especially ones intended for demanding environments in which human access will be limited or impossible. Design and development of I&C systems that feature integrated autonomy informed by the design requirements of the space fission system would enable reliable, resilient, and cost-effective nuclear systems for use in space exploration.

NASA expects there to be two distinct use cases for space fission systems: nuclear propulsion and surface power [1]. Nuclear propulsion uses the heat generated from the reactor to generate thrust, either by directly utilizing nuclear heat to accelerate a propellant, or by using it to generate electricity that in turn ionizes a gaseous propellant and accelerates it electromagnetically to produce thrust (i.e., nuclear electric propulsion).

Space fission systems, particularly fission surface power (FSP), provide constant, reliable power generation regardless of the environmental conditions found on the Moon and Mars. FSP design and deployment cannot rely on any external power or robotic support, nor on astronaut involvement for system startup, shutdown, operation, and maintenance. Therefore, autonomous systems will be necessary to meet the operational requirements for FSP and to deploy integrated power systems on the Moon and Mars. This article will focus on lunar FSP.

The I&C systems for space reactors must meet broad requirements. Autonomous controls and operations technologies are specifically needed as part of the solution to address many of the design requirements and goals for space reactors. Additionally, situational awareness technologies—including technologies that provide an understanding of the health of reactor structures, systems, and components (SSCs)—will be needed as part of other design requirements and goals. One specific need is for sensor longevity in conjunction with redundancy, though it is important to realize that redundancy will not help in cases when the sensors only last a few years under radiation (including the baseline radiation environment of space) but the system has a longer mission lifetime. Sensor, instrumentation, and actuator longevity is critical, as it enables foundational insights into the state of the reactor and other associated systems for power conversion/propulsion, and into the ability to change the system state as needed to maintain mission capabilities. In addition to selecting long-lived I&C components, the optimal number and locations of sensors are needed to ensure that redundancy is maintained and that the desired system state information is available throughout the lifetime of the system. Optimal quantities, placement, and shielding of sensors and associated systems must therefore be considered early in the design process in order to ensure redundancy, longevity, and seamless reactor integration. Selection of components should emphasize the use of hardware that can be calibrated digitally or mitigated through algorithmic/software compensation, thereby increasing the longevity of space systems when faced with partial component failure. Early I&C development also improves mass allocation efficiency and reduces overall deployment costs.

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Autonomous Systems and Key Considerations

Several definitions of "autonomous system" have been developed, encompassing different levels of automation (also referred to as levels of autonomy). For example, The U.S. Nuclear Regulatory Commission (NRC) Artificial Intelligence (AI) Strategic Plan [2] defines full autonomy as "fully autonomous AI in systems where the algorithm is responsible for operation, control, and intelligent adaptation without reliance on human intervention or oversight that could affect plant safety, security, and control." A complementary NRC definition from SECY-24-0008 describes autonomous systems as being able to "perform their task and achieve their functions independently, perform well under significant uncertainties for extended periods of time with limited or nonexistent communication, with the ability to compensate for failures, all without external intervention."

Le Blanc et al. [3] discuss different definitions of autonomous systems in the nuclear context, identifying three converging attributes: systems must be (1) independent (free from outside control), (2) adaptive (able to respond to changing conditions), and (3) self-governing (exercising control over their own affairs). These considerations are particularly salient for space nuclear applications, in which communication delays, radiation environments, and the practical impossibility of human intervention make autonomous operation not merely desirable, but a fundamental mission requirement. The second attribute, "adaptive," could be "anticipatory" (i.e., able to predict changing conditions and prepare the system to respond appropriately). AI could benefit autonomous systems in terms of predicting future operation states.

For fission systems, including space fission systems, autonomous operations can be broadly categorized into five levels [2]. Degrees of automation range from the operator having full control to a fully autonomous system in which the computer makes all decisions and the operator provides backup if necessary. Fully autonomous control would theoretically eliminate the need for any sort of operator altogether; however, in reality, even a fully autonomous control system is expected to need a human operator that can interact with it and direct goals and actions if necessary. This approach would also allow software updates that account for component failures, drift, and other issues. Other categorizations of autonomy levels exist but are largely finer-grained divisions of the levels identified in [2] and [3].

Technical Gaps and Research and Development Needs

Achieving autonomous operation in space nuclear systems requires integration across system health management, activity planning, and scheduling and execution; multi-unit coordination (for multi-unit space nuclear systems); and automated data analysis for decision-making [4]. Given the strict size, weight, and power design constraints that are expected to limit onboard computation and data storage, as well as the number of sensors deployed to monitor the state of the system, solutions for these technological areas will need to be computationally efficient as well as able to function in the face of limited observability of the system. Development of deployable space nuclear systems will require research in two major areas: improved intelligence of control systems to handle a wider range of operating scenarios under uncertain conditions, and a more robust nuclear technology and sensing infrastructure that inherently reduces the failure modes. Given the state of current autonomous operation technologies that may be applicable to fission power systems and the remaining challenges in achieving autonomous operations in space fission systems, maintaining a safe and reliable fission power source will require technological development that addresses the following elements:

- Control architecture and decision-making framework to include not only autonomous operation of a single reactor but also activity planning, multi-unit coordination, and scheduling. The decision-making tool must be able to diagnose the given situation and identify and select a viable course of action or sequence of actions that will enable transition to a safe state. Given the expected small-sized reactor cores for space nuclear systems and the consequently limited number of sensors that can be included, the supervisory decision-making methods will need to use limited sets of sensors. The supervisory control (a system architecture in which a supervisory controller oversees and influences the operation of other controllers) will also need to handle and mitigate errors that arise from component-level failures.
- System models that can inform decisions, based on system reliability and mission requirements. These models, sometimes referred to as "digital twins," must allow for autonomous evaluation of alternate control actions to make a recommendation on which control action to take. While AI- and machine learning–based solutions are being extensively researched for terrestrial reactors, such solutions are not anticipated to be widely used for space reactors, due to the expected computational and storage limitations on board and the limited amount of data available to

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represent multiscale system dynamics at the proper dimensionality while being subjected to known constraints and other parameters.

- Efficient anomaly detection and fault diagnosis techniques to assess and monitor system health, supported by optimization of observables (which determine sensor needs) to increase fault tolerance. Diagnostics may be conducted to identify process irregularities and assess the condition of equipment or components. Given the limited amount of data from all possible conditions, along with the expectation that fault conditions will be somewhat rare, a strategy is necessary for diagnosing, assessing, and addressing rare faults.
- Testing as well as verification and validation (V&V) of the autonomous controls and operations logic in a representative space environment.

To address the need for testing and V&V, along with the other identified research gaps, appropriate testbeds that can be configured to represent a space environment are needed. Capabilities available at Idaho National Laboratory (INL) and Oak Ridge National Laboratory (ORNL) are being used for this purpose, to address these R&D gaps.

Available Capabilities

Test beds capable of testing/validating reactor components, sensors, and control strategies for space applications are being developed at ORNL and INL. Among them are the ORNL mock reactor, INL's MAGNET, and the Microreactor Automated Control System (MACS) and ViBRANT, to give a few examples.

The ORNL mock reactor "Big Red" (Figure 1) [5] platform uses hardware-in-the-loop (HITL) simulation in tandem with physical control actuation, heated core feedback, and coupled fluid flow dynamics to represent surface nuclear power applications. A modular Docker container-based software design creates an interchangeable environment for applying control signals and reading sensor feedback data over I^2C (Inter-Integrated Circuit) communication with the hardware. MQTT (Message Queuing Telemetry Transport) for internal communication provides a language-agnostic platform that allows for third-party development of control strategies and reactor models deployable in real-time HITL simulation tests. A similar modular approach for I^2C communication board selection streamlines the process of incorporating additional sensors for hardware testing and validation.

The Microreactor Agile Non-nuclear Experimental Testbed (MAGNET) at INL (Figure 2) is a state-of-the-art facility that provides a controlled, non-nuclear environment in which to evaluate structural performance under thermal

Figure 1. ORNL mock reactor "Big Red."

Figure 2. MAGNET testbed.

stress, strain, creep, and deformation, using instrumented test hardware with advanced sensors and I&C systems [6]. MAGNET supports thermal energy storage and hydrogen production integration and features a closed Brayton cycle Power Conversion Unit [7]. Together, these capabilities make MAGNET a relevant testbed for validating space nuclear hardware and control systems prior to deployment.

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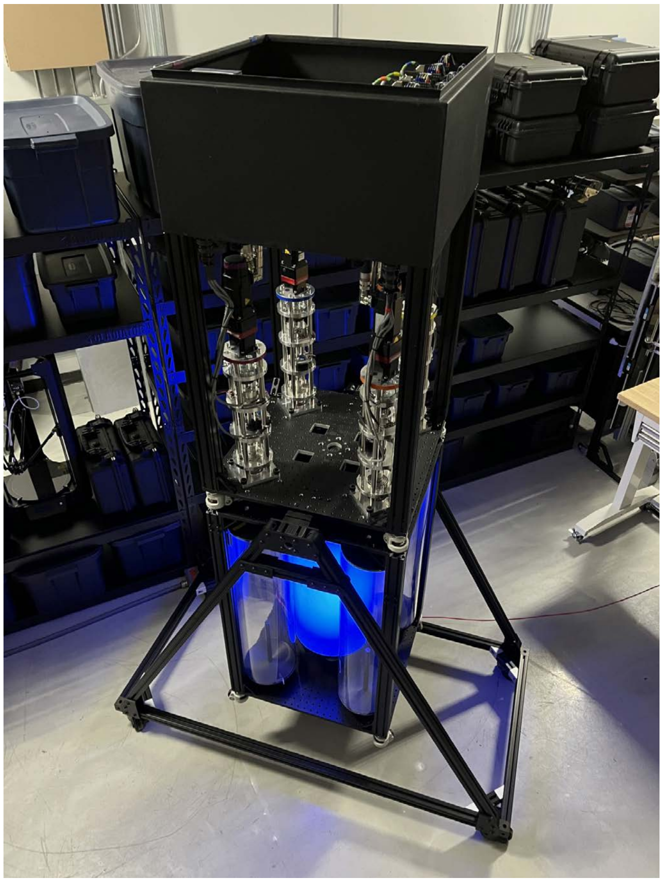

Figure 3. MACS with actuator cell and surrogate reactor cell.

MACS [8] (Figure 3) was designed and constructed at INL under the DOE Microreactor Program. It is a real-time HITL testbed for non-nuclear testing of microreactor control system automation. MACS is a modular platform comprised of a control box, actuator cell, and reactor cell. The control box houses motor controllers, power supplies, and data acquisition equipment. The actuator cell houses the four control drum motors, position sensors such as encoders and limit switches, and control drum clutches. The surrogate reactor cell contains the control drums and the Visual Benign Reactor as Analog for Nuclear Testing (ViBRANT) Barrel light-based reactor core physics simulator and visualizer. The ViBRANT Barrel core physics simulator uses light-emitting diode (LED) arrays to represent reactor core physics (e.g., power, reactivity, or temperature) [9]. Together, MACS and ViBRANT provide a core simulation through light intensity feedback with physical control actuation for HITL simulation and closed-loop control studies.

In addition to testbeds, several advanced controls and decision-making algorithms have been developed under different U.S. Department of Energy (DOE) programs. Specifically, under the DOE Nuclear Energy Enabling Technologies (NEET) Advanced Sensors and Instrumentation (ASI) program, the Control and Optimization Modular Modeling Application for Nuclear Deployment (COMMAND), a Python-based open-source platform, was developed [10]. The COMMAND platform was designed to integrate advanced control technologies such as digital twins, machine learning, and optimization to support development of autonomous operations in advanced nuclear reactors. The platform was coupled with the MACS hardware testbed to display reactor power levels and spatial core power distributions by using LED lights, thus bridging the gaps between hardware and simulation performances of achieving advanced controls [11, 12]. Research was performed on developing a hierarchical supervisory control system to enable autonomous operation of advanced reactors during flexible load-following transients [13-15], and this system was demonstrated on representative testbeds [15, 16] under the NEET ASI program. Other research into advanced control algorithms, with a specific focus on predictive control, utilized an anticipatory control approach by taking advantage of linear and nonlinear model predictive control [17, 18]. There has also been research on developing control algorithms to support operational decision-making and recovery in the presence of SSC degradation [19, 20].

Each of these control algorithms addresses different control strategies to achieve automation in reactor operation under different conditions. These control algorithms with testbeds lay the groundwork for autonomous operation of space nuclear systems. The limited HITL demonstration of these advanced control algorithms suggests the need for more rigorous V&V of control algorithms under a representative space environment.

Summary

Autonomous operations of space nuclear systems is a fundamental mission requirement driven by the harsh environment of space, where it is infeasible to deploy systems reliant on human oversight. This article provided insights into the key considerations that need to be addressed early in the design phase in order to enable a reliable, resilient, and cost-effective autonomous nuclear system in support of space exploration. The R&D needs suggest a holistic and integrated approach, with rigorous HITL V&V being carried out by leveraging and expanding the existing testbeds at INL and ORNL. Realizing the full potential of autonomous space nuclear systems will ultimately require a coordinated, multidisciplinary effort that bridges reactor physics, I&C engineering, and autonomous systems research, laying the groundwork for reliable, long-duration fission power on the Moon, Mars, and beyond.

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