

Cross-National TRL Comparison of Fission Surface Power (FSP) for Lunar Exploration

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***Keywords : FSP, Closed Brayton Cycle, Heat Rejection, Power Management and Distribution (PMAD).**

1. Introduction

The U.S. NASA's Artemis program aims to establish a sustainable human presence on the lunar surface by enabling not only scientific missions but also long-duration habitation supported by in-situ resource utilization (ISRU) and in-situ manufacturing [1]. This objective requires a power supply that sustains critical operations through the long lunar night (~14.8 Earth days), when solar availability becomes severely constrained [1,2]. As a result, "power" is not merely a generator-level design problem. It becomes an infrastructure problem that spans habitat-ISRU-communications-mobility functions and includes architecture, deployment, concept of operations (CONOPS), interface definition, and standards and protection concepts [1,3].

Against this backdrop, NASA—together with U.S. government partners (notably DOE) and industry—advances Fission Surface Power (FSP) as a candidate lunar surface power source [1,3]. NASA's Directive on Fission Surface Power (FSP) Development, dated August 4, 2025, explicitly states procurement-driving constraints: (1) rapid release of an industry RFP (Request for Proposal), (2) a minimum electric output of 100 kWe, (3) an assumed ≤ 15 t-class lander, (4) FY30 Q1 launch readiness, (5) adoption of a Closed Brayton Cycle (CBC)-based power conversion system (PCS), and (6) definition and public release of a Standardized Modular Interface (SMI) to support compatibility between the lander and surface assets (including habitats) [4,5]. Collectively, these constraints shift the program emphasis from general "technology maturation" to procurement and flight-system realization under a schedule-constrained framework [4,5].

In addition, a NASA-DOE Memorandum of Understanding (MOU) disclosed in January 2026 delineates roles and responsibilities for core institutional enablers of flight readiness, including authorities for special nuclear material (SNM), responsibilities for the Safety Analysis Report (SAR) and launch safety approval, HALEU fuel supply, and support for ground demonstration, handling, and transportation [6]. This institutional structure indicates that FSP proceeds under the assumption of verification- and certification-oriented system development, rather than performance optimization alone [6].

Meanwhile, China and Russia reference lunar surface nuclear power in connection with the International Lunar Research Station (ILRS) concept, and media reports

suggest potential installation timelines in the mid-2030s (2035–2036) [7–10]. However, publicly available technical detail remains substantially below the level associated with U.S. procurement and verification artifacts.

Public FSP literature also accumulates in fragmented streams: (1) directives and procurement artifacts (requirements, assumptions, schedules), (2) system design and trade studies, and (3) issue- or component-technology-focused studies [3–6,11]. This fragmentation makes it difficult to compare national and institutional priorities and maturity using a consistent lens, particularly in terms of future demonstration and standardization needs [12,13].

Accordingly, this paper will review publicly available information to compare national R&D trends along three areas important to FSP: (A) CBC power conversion, (B) heat rejection, and (C) PMAD, power transfer, and grid integration. A conservative Technology Readiness Level (TRL) assessment for these three areas will be presented by utilizing NASA's Technology Readiness Assessment (TRA) definitions [12–14]. The reason for selecting these three areas for the review are the following.

An FSP system commonly comprises five subsystems: reactor, shielding, power conversion, heat rejection, and PMAD [3]. Because the NASA directive fixes the power conversion approach to CBC, this review defines (A) CBC power conversion as the first area. It defines (B) heat rejection as the second area due to strong coupling with CBC performance, controllability, and operability [4,11]. The third area, (C) PMAD, power transfer, and grid integration, addresses the infrastructure required to deliver 100 kWe-class power to habitats, ISRU facilities, communications nodes, and mobility assets [4,6,11].

Reactor and shielding details face significant disclosure constraints (e.g., security and export control) and are not frozen in detailed geometry by the directive. Therefore, reactor and shielding are excluded from the area-based maturity comparison, which focuses on post-directive trends and open, verifiable artifacts [4,6].

This paper also presents verifiable deliverables required by NASA's directive instead of a list of required research by the three areas. Using these deliverables as guiding criteria, this paper proposes the research directions that the Republic of Korea should prioritize in each area.

2. Comparative Analysis of National R&D Trends by Area (A), (B), (C)

2.1. (A) CBC Power Conversion System

United States. NASA public materials summarize CBC development history since the 1960s and document ground-test heritage (e.g., BRU/mini-BRU and dual Brayton loop efforts), indicating continued extension of CBC technologies to space nuclear applications including FSP [19]. The FSP Phase 1 report describes a 12 kWe-class CBC power conversion unit (PCU) and provides design specifications and modeling scope, including hot/cold source assumptions, vacuum radiative conditions, subsystem elements (converter, power control, instrumentation and control), and a staged scale-up concept [20].

These document component and subscale level feasibility and provide model-based scaling logic. [20] However, open evidence for direct verification at 100 kWe-class under lunar operating constraints—especially reliability data for bearing/seal life, start–stop fatigue, and FDIR (Fault Detection, Isolation, and Recovery)—remains limited [4,12]. On a conservative basis, the 100 kWe-class CBC PCS corresponds to TRL 4 [12,20].

China. Peer-reviewed literature reports design and optimization methodologies for 100 kWe-class space reactor–CBC systems, incorporating efficiency–mass–reliability metrics and integrated constraints (including heat exchangers and radiator constraints) [15–17]. Additional studies adapt legacy system codes (e.g., RELAP5) for space reactor–CBC applications by implementing compressor/turbine and compact heat exchanger models and by validating selected behaviors through comparisons with design codes, CFD, and historical reports. These results indicate efforts toward transient-capable modeling and verification [18].

Nevertheless, the reference concentrates on model/code-driven optimization, while publicly verifiable demonstrations of long-life durability and degradation behavior remain sparse. This gap limits direct linkage from optimized designs to operational availability [12,13,15]. Consequently, China’s maturity for area (A) is conservatively assessed as TRL 3 [12,15,18].

Russia. Media reporting, including coverage of a Roscosmos–NPO Lavochkin contract disclosed in January 2026 and reporting by Reuters, indicates program level intent toward a lunar nuclear power source for a Russia–China base concept, with notional deployment timelines around 2033–2035 and broader mid-2030s targets [7–10]. However, open technical content (cycle configuration, verification data, endurance testing) remains scarce. Therefore, area (A) is conservatively assessed as TRL 2 [7–10,12].

Republic of Korea. Public Korean literature emphasizes enabling technologies related to space heat-pipe reactor concepts, consolidating knowledge on heat transport, structures, materials, and thermal management, rather than presenting verification artifacts for a 100 kWe-class CBC PCS [21]. Some publications also

survey candidate working fluids and cycle options for space nuclear power conversion [22].

These sources indicate interest and foundational activity, but they provide limited information aligned with NASA’s directive-driven CBC PCS pathway. Hence, Korea’s maturity for area (A) is conservatively assessed as TRL 2 [4,12,21].

2.2. (B) Heat Rejection

United States. The lunar surface imposes vacuum conditions, extreme diurnal thermal cycling, regolith dust deposition, and electrostatic charging, which can reduce radiator performance and constrain deliverable electric power. NASA Glenn’s R2D2 (Risk of Radiator-Dust Demonstration) quantifies radiator degradation by depositing simulant layers under thermal-vacuum conditions and measuring performance change. This work shows that regolith effects require characterization by test rather than treatment as an assumed parameter [11]. Studies on lightweight deployable radiator panels and armoring further elevate environmental and contamination risks to first-order design drivers under the practical assumption that radiators dominate system mass and volume [23].

These artifacts support component-level verification in a relevant environment and demonstrate controllable test infrastructure. However, open evidence remains limited for coupled effects among dust, charging, thermal cycling, long-duration degradation, and recoverability. Therefore, area (B) is conservatively assessed as TRL 5 [11,12].

China. Optimization studies treat radiators as design variables influencing mass, efficiency, and control rather than as static sizing outputs [15,17]. Transient-code development work adapts heat exchanger and radiation/convection models to space reactor systems and highlights coupling between transient response and thermal management [18].

While these efforts support modeling-based maturity, publicly verifiable test data reproducing long-term radiator degradation under lunar-relevant conditions remains limited. Accordingly, area (B) is conservatively assessed as TRL 4 [12,15].

Russia. Information on radiator design, dust effects, and environmental testing remains limited beyond program-level reporting; thus area (B) is conservatively assessed as TRL 2 [7–10,12].

Republic of Korea. Korea reports laboratory studies on regolith simulant-bed disturbance control, including disturbance suppression methods and documentation of simulant properties and reproducibility (e.g., *Scientific Reports*, 2021). However, open information for direct radiator degradation and recoverability testing remains limited; therefore, area (B) is conservatively assessed as TRL 2 [12,21].

2.3. (C) Integration of PMAD, Power Transfer, Grid

United States. NASA documents emphasize the need for lunar surface microgrids with evolvability, reconfiguration capability, and common grid interfaces, and summarize demand levels, distribution distances, architecture options, and conversion between high-voltage AC and low-voltage DC [3]. They also report mass trade-offs indicating potential benefits from raising voltage to the ~ 3 kV AC range, balanced against converter mass and insulation constraints [3]. NASA further discloses standardized bidirectional interface concepts using UMIC to connect 120 V DC sources to a 3 kV AC system, including modular, bidirectional, field-replaceable design intent and breadboard-level verification [11,25].

These documents support partial component and lab-scale validation. However, additional verification remains necessary for protection concepts that mitigate partial discharge, arcing, and insulation degradation under lunar-relevant environments (vacuum, dust, charging), including breaker/reclosure logic and converter-based protection schemes [25]. Given the demonstrated maturity, area (C) is conservatively assessed as TRL 5 [12,25].

China. China references infrastructure elements (e.g., pipelines and cables) in ILRS-related contexts, but open verification artifacts remain limited and largely conceptual or model-based. Therefore, area (C) is conservatively assessed as TRL 2 [7–10,12].

Russia. Similar to China, open information remains limited beyond ILRS-aligned intent statements and media coverage; area (C) is conservatively assessed as TRL 2 [7–10,12].

Republic of Korea. Korea conducts research on space power transfer, including wireless power transfer concepts in space solar power satellite (SSPS) studies and ground demonstrations related to Danuri (Korea Pathfinder Lunar Orbiter, KPLO) activities. However, open evidence directly aligned with NASA directive-driven needs—such as SMI- or UMIC-grade interface testing and lunar-environment verification—remains limited. Consequently, area (C) is conservatively assessed as TRL 2 [26,27].

2.4. TRL Comparison Across Areas

Following NASA TRA best practices, this section summarizes TRL evaluation from the publicly available information (test, demonstration, and verification outcomes) [12–14]. When the development remains limited to modeling and code, maturity typically falls within TRL 2–3; when component or breadboard test results are available, maturity aligns with TRL 4; and when functional verification occurs in a relevant environment, maturity aligns with TRL 5–6 [12].

The TRL values reported here represent minimum maturity supported by open evidence, not internal program TRLs [12–14].

Table 1. National TRL levels by area

Country	(A) CBC-PCS	(B) Heat Rejection	(C) PMAD
United States	TRL 4	TRL 5	TRL 5
China	TRL 3	TRL 4	TRL 2
Russia	TRL 2	TRL 2	TRL 2
Republic of Korea	TRL 2	TRL 2	TRL 2

3. Research Gaps and Future Directions

Because the NASA directive emphasizes submission of verifiable artifacts rather than broad lists of technical issues, this review reframes “gaps” as what must be demonstrated and packaged as verification-ready deliverables. These gaps are expressed as verification gates (e.g., the first gate in area (A) is denoted (A)-G#1) [12–14].

3.1. Long-Life, Maintenance-Free, and Autonomous CBC Operation

NASA adopts CBC for risk reduction and scalability, but for a 100 kWe-class system the dominant risks relate less to cycle efficiency and more to: (1) long-life performance of rotating machinery (bearings and seals in turbine–compressor–generator trains), (2) fatigue and performance degradation under repeated start–stop and part-load operation, and (3) sensor drift and autonomous recovery via FDIR [4,12,19,20]. Under TRA principles, TRL advancement requires verified artifacts in the required environment. Moreover, the NASA–DOE MOU explicitly positions ground demonstration and safety approval pathways, implying that PCS maturity must be supported by integrated demonstration evidence [6].

A schedule-credible program therefore defines baseline requirements not only for power and efficiency but also for availability targets, allowable maintenance actions, autonomy levels, and fault coverage. This step freezes PCS requirements and the verification plan ((A)-G#1) and produces an artifact package aligned with System Requirements Review (SRR) expectations. Next, a PCU integrates rotating machinery, heat exchangers, and controls to verify functional operation and demonstrate performance and stability across start–stop and part-load regimes ((A)-G#2). Finally, after integrated non-nuclear loop verification, a surrogate-heat-source integrated loop supports long-duration operation, degradation tracking, and experimental validation of autonomous FDIR scenarios, yielding packaged reliability and availability evidence ((A)-G#3).

3.2. Heat Rejection Operability and Recoverability in Lunar Environments

R2D2 results show that dust-driven radiator degradation directly reduces deliverable power, and

NASA roadmaps emphasize systematic definition of dust environments, standards, and investment priorities [11,24]. However, dust effects do not reduce to an average thermal-resistance increase; they can alter emissivity/absorptivity, reduce control margin, and emerge as coupled phenomena involving dust deposition, electrostatic charging, thermal cycling, and surface optical-property evolution [24].

Accordingly, standardized contamination metrics, charging conditions, thermal-cycling definitions, and deployment/armoring profiles must be fixed as test standards, along with protocols, metrology, and performance metrics ((B)-G#1). Using these standards, thermal vacuum dust deposition tests generate reproducible degradation datasets ((B)-G#2). The program then establishes combined dust charging thermal cycle protocols with multi-simulant comparison data ((B)-G#2, extended). Finally, these protocols support operability and recoverability demonstrations under representative operational scenarios (including deployment and thermal-contact variations), supported by FDIR testing and CONOPS-informed optimization ((B)-G#3).

3.3. Converting Generation to Usable Power via PMAD, Protection, and Standards

The directive's emphasis on defining and releasing the SMI reflects schedule risk: even if the reactor, CBC-PCS, and radiator mature, delayed interface standards and protection/distribution architectures can prevent FY30-aligned deployment [4]. NASA studies also indicate that UMIC/PMAD designs require early choices on voltage type (DC vs AC, including ~3 kV AC), frequency, and topology (radial/ring/mesh), because these choices drive cable mass, insulation constraints, converter mass, and late-stage risks such as arcing and insulation failure if interfaces remain unfrozen until late design phases [28,29].

Therefore, the program freezes grid voltage/frequency selections and protection design principles (breaker-based vs converter-based protection, reclosure logic, and fault isolation zones) early ((C)-G#1). With these definitions, UMIC/PMAD validate baseline conversion/distribution performance, efficiency, losses, and thermal management, followed by arcing and insulation-degradation testing and protection-coordination validation ((C)-G#2). Finally, a ground demonstrator using microgrid hardware-in-the-loop (HIL) evaluates converter control under injected faults, fault detection performance, insulation timing constraints, and stable recovery behavior, culminating in a qualification test plan (QTP) and certification-ready test planning artifacts ((C)-G#3).

3.4. Proposal of Research Directions for Republic of Korea

Given Korea's lack of an Artemis-style procurement pathway, an effective strategy emphasizes verification-

leverage niches aligned with directive needs rather than duplicating full-system integration efforts. Instead, Korea should prioritize verification-leverage niche areas that directly map to the NASA directive's CBC-fixed architecture and its emphasis on verifiable artifacts (test data, standardized protocols, and qualification-oriented documentation). This strategy positions Korea to contribute packageable evidence that reduces integration and certification risk, rather than competing through full-system replication.

For area (A): CBC power conversion, the near-term priority is to freeze CBC-PCS requirements and a verification plan that explicitly targets long-life, maintenance-free operation and FDIR-relevant behaviors. Korea already reports foundational capabilities that can be re-scoped toward this objective, including helium Brayton turbomachinery conceptual design, working-fluid and cycle candidate assessments for space heat-pipe reactor power conversion, supercritical CO₂ compressor/loop research, and predictive methods for gas-foil bearing performance and life [30–33]. Building on these assets, Korea should focus on non-nuclear integrated-loop partial testing and model-test evidence for rotating-machinery degradation and fatigue under start-stop/part-load duty, linked to FDIR performance metrics, rather than pursuing immediate full-scale CBC-PCS demonstration. In other words, Korea's differentiator is not a complete 100 kWe-class CBC-PCS prototype, but a verification package that quantifies reliability-limiting mechanisms (bearings/seals/rotor-dynamics, thermal mechanical fatigue, sensor drift) and connects them to availability and fault-recovery requirements in a qualification-oriented test plan.

For area (B): heat rejection operability and recoverability in lunar environments, the key capability is dusty thermal-vacuum testing that yields reproducible degradation and recoverability evidence. Korea's prior work on KLS-1 development and its engineering/geotechnical characterization, together with studies that establish criteria for controlling regolith disturbance during depressurization in dusty thermal vacuum chambers, provides an enabling basis [34–36]. Korea should convert KLS-1 property/reproducibility datasets and dusty thermal vacuum operational know-how into a radiator contamination test standard, producing dust deposition degradation curves as verifiable artifacts. This roadmap requires fixing a combined dust charging thermal cycling protocol and defining radiator degradation and recoverability KPIs that are traceable to CONOPS-level operability (e.g., allowable performance loss, restoration procedures, and repeatability).

For area (C): PMAD, power transfer, and grid integration, Korea should re-target its microgrid testing strengths toward space-relevant protection and standardization challenges (long-distance distribution, high-voltage operation, and modular interfaces). Existing research on microgrid HIL development and DC microgrid PHIL testbeds support a test-driven

pathway to validate converter control, fault detection, and reclosure/protection coordination under fault injection, when reframed for space-like architectures and interface constraints [37,38]. In addition, KPLO operational design/lessons and deep space antenna based wireless power transfer research can inform surface power infrastructure operation and transfer concepts, but impact requires translation into SMI/UMIC-compatible verification tasks (standardized interface test procedures and protection-coordination logic validation) [26,27,39].

Collectively, these area-specific efforts allow Korea to deliver qualification-oriented evidence packages—protocols, datasets, and protection/interface verification results—that directly reduce risk for Artemis-aligned FSP integration.

4. Summary and Conclusions

NASA's August 2025 directive reframes FSP as a procurement-driven development program grounded in fixed assumptions— ≥ 100 kWe, CBC-based PCS, public SMI definition, and FY30 Q1 launch readiness. The January 2026 NASA–DOE MOU further specifies institutional requirements for SNM authority, SAR responsibility, fuel supply, and ground demonstration. Together, these documents shift the primary success criterion from performance optimization to verification- and certification-ready evidence packages.

Publicly available information suggests that the U.S. benefits from prior CBC PCS heritage and provides component- and subscale-level feasibility evidence with model-based scaling arguments. However, open-domain evidence remains limited for long-life operation, degradation behavior, and autonomous FDIR. For lunar heat rejection, tests in relevant environments support component-level validation, yet verification gaps persist for coupled effects that include dust contamination, electrostatic charging, thermal cycling, and life-limiting degradation mechanisms. For PMAD and microgrid integration, laboratory demonstrations support partial component validation, but additional verification is required for protection philosophy and coordination, partial-load operation under lunar conditions, and high-voltage risks such as arcing and insulation aging.

China has published studies on optimization and transient analysis for 100 kWe-class CBC–space reactor systems, but publicly verifiable information remains limited for long-life performance, operational availability, and FDIR capability. In many integrated studies, heat rejection and PMAD appear primarily as system-level design variables, and verification evidence beyond parametric treatment in system models remains insufficient. Russia provides limited publicly accessible technical verification artifacts beyond program-level reports that state an intent to deploy a lunar surface power station in the mid-2030s.

In the Republic of Korea, open literature supports foundational work in space heat-pipe reactor technology and power transmission, but the emphasis remains on

enabling technologies and concept alignment rather than cross-subsystem verification that directly maps to NASA's directive and its flight-driven assumptions.

Overall, lunar FSP competitiveness likely depends less on cycle efficiency than on: (1) CBC long-life, maintenance-free, autonomous operation; (2) heat rejection operability and recoverability in lunar environments; and (3) conversion of generated power into usable power through PMAD, protection, and standardization. To meet the NASA directive's FY30 launch-readiness objective, the program should first freeze system requirements and interface definitions and conduct prototype testing of key subsystems in relevant environments. It should proceed to an integrated non-nuclear loop demonstration and FDIR verification, followed by an end-to-end ground demonstration of the integrated system and preparation of the Safety Analysis Report. Only after these verification milestones have been completed can launch readiness be credibly established.

This review conservatively assesses maturity using open, verifiable information across three areas and proposes verification gates and research directions for Republic of Korea.

The Republic of Korea has limited capacity, at present, to execute end-to-end demonstrations of an integrated FSP system. However, Korea can still provide meaningful contributions to the Artemis program by leveraging its existing enabling technologies to deliver procurement-relevant verification assets, including standardized test protocols, validated datasets, and evidence packages for protection and interface compliance. Such contributions address schedule-critical needs that are often underrepresented in open literature yet directly influence system qualification and integration readiness.

Even if Korea does not assume a leading role in near-term Artemis FSP system integration, establishing these verification-oriented capabilities creates a strategic pathway toward leadership in the development of nuclear surface power systems for future crewed Mars habitation. Because Mars surface power will similarly depend on long-life autonomy, environmental robustness, and grid/interface standardization, early investment in verifiable protocols and qualification evidence enables Korea to play a proactive and potentially leading role in the next generation of planetary nuclear power infrastructure.

This review addressed only three of the five major FSP subsystems; therefore, its contribution to establishing a procurement- and verification-driven development framework for the overall FSP system, as envisioned by the NASA directive, remains inherently limited. This limitation does not primarily arise from insufficient technology maturity of individual components, but from the central challenge of system-level verification of an integrated architecture.

Future works should extend the scope to include the reactor and shielding subsystems and systematically

identify, for all five subsystems, both (1) the technology maturity supported by publicly verifiable evidence and (2) procurement-relevant verification deliverables that can be credibly audited. On this basis, country-specific research priorities should be defined according to the gaps revealed at the current stage. In addition, integrated system demonstrations should be conducted in environments representative of lunar surface conditions to verify safety, performance degradation behavior, and resilience/restorability of the end-to-end FSP system.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No.: RS-2024-00436693).

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