Report of the Nuclear Power and Propulsion Gap Assessment Team

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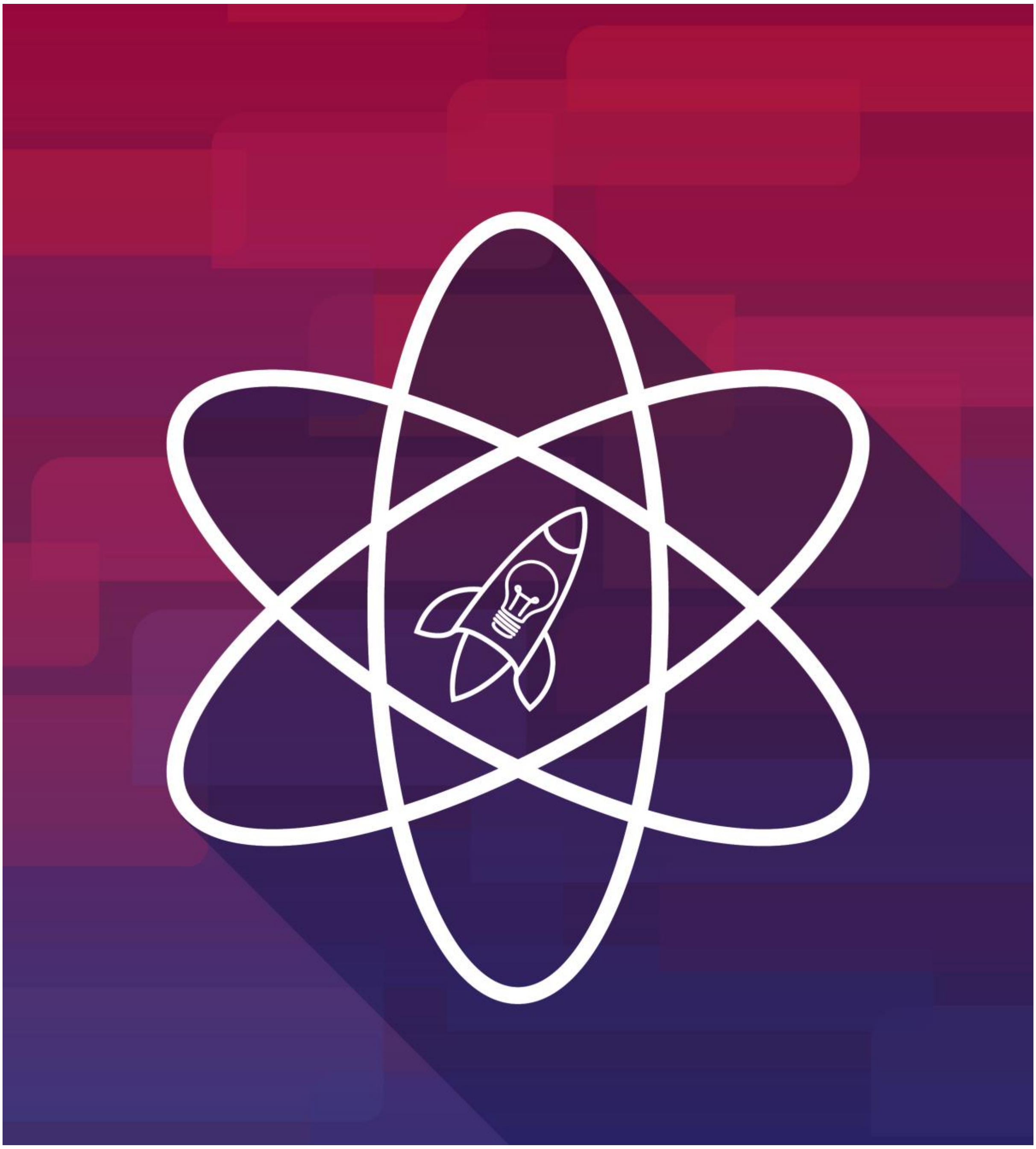

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1 Executive Summary

The international space community is in the process of implementing the first elements of an international architecture to explore the Moon and Mars in the near- and mid-term future. This exploration architecture requires continuous and long-duration human and robotic presence, including operations during the long lunar night or in permanently shadowed regions on the Moon, or on the Martian surface when sunlight is diminished due to extended dust storms, season, or latitude. This makes the implementing organizations - governmental as well as commercial - stakeholders of technology solutions for these challenging mission applications. The absence of continuous solar power allows two viable technical solutions: energy storage that is recharged with solar power, or nuclear systems. Chemical-based energy storage solutions present significant mass penalties resulting from thermal engineering, physical constraints, and environmental conditions - hundreds of kilograms even for small robotic systems designed for surviving the lunar night. Given the significant transportation cost to the lunar and Martian surfaces and the desire to not only survive, but safely operate in these environments, nuclear systems offer a better solution. Similarly, human Mars missions can benefit significantly from the high specific impulse of nuclear propulsion systems, far beyond what is possible with non-nuclear systems.

This report of the Nuclear Power and Propulsion Gap Assessment Team (NPP GAT) describes and assesses gaps in nuclear technology that need to be filled to achieve the objectives of the International Space Exploration Coordination Group (ISECG) Global Exploration Roadmap (GER). The potential nuclear technology solutions are as diverse as their applications: thermal and electrical power needs, as well as power levels between a few hundred watts for small robotic systems to megawatts for industrial exploitation of lunar resources. We classify the solutions in categories: radioisotope systems offer thermal and electrical solutions from a few watts up to one kilowatt, small reactors can generate electricity from a few kilowatts up to 100 kilowatts, large reactors from 100 kilowatts up to one megawatt and beyond. In addition, special reactors can provide large quantities of heat for nuclear thermal rockets or electricity for nuclear electric thrusters.

Key findings from the nuclear gap assessment are as follows:

1. All the member agencies of the NPP GAT have unique capabilities which can be leveraged to advance the technology readiness of space nuclear systems.
2. There is significant mission pull for nuclear systems that spans the range from small science platforms to lunar habitats to industrial-scale mining to crewed Mars transportation vehicles; In-Situ Resource Utilisation (ISRU) was determined to be a major driver.
3. The development of new space nuclear systems presents both technical and geopolitical challenges, which can be facilitated through international coordination and collaboration.
4. At the time of writing, there is no internationally governing regulatory framework for NPP systems in space or on celestial bodies.
5. Nuclear launch safety is a key area for cross-agency collaboration; further efforts are needed to establish common policies that assure safe launch and operating practices for future space nuclear

systems. Benefits include shared/consensus methods to address safety, cross-agency missions, and opportunities for involvement by small agencies.

6. The implementation of nuclear systems in the GER would benefit from a strategy that starts with smaller simpler systems and evolves to larger more complex ones.
7. The categories of large and small reactors for planetary surface applications share many technological characteristics; large-scale production of electricity can be achieved by a modular network of small reactors.
8. There is great potential for space nuclear systems to leverage advances being made in terrestrial nuclear technologies while addressing climate change and providing socio-economic benefits.
9. Low enriched uranium (LEU) could be an alternative solution to address international non-proliferation goals; however, the use of highly enriched uranium (HEU) is discussed in United Nations Resolution 47/68 Principals Relevant to the Use of Nuclear Power Sources in Outer Space [RD03].
10. In general, the shortage of radioisotope and reactor fuel supply for space applications exists at the current time, which can develop to be a major impediment to the development and use of nuclear power and propulsion technologies.

2 Context

The international space community, represented by the participating agencies of the ISECG, are driving forward a coordinated effort to expand human presence into the solar system. This effort is driven by benefits to the nations represented by these agencies in terms of socio-economic impact, inspiration, innovation, and scientific discovery. Based on the agencies' consensus, the GER with its recent addendum lays out a concrete plan to grow human activity beyond Earth orbit to the Moon and Mars.

Reaping the benefits of this renewed push into the yet unknown will depend on our ability to live and work in the harsh environments on the surfaces of the Moon and Mars. These environments are characterised by large temperature variations and unsteady solar illumination conditions. Conventional power systems, and those that have been used in prior lunar and Mars missions are not likely to satisfy future long-duration human exploration goals. Early missions will require 10s of kilowatts; later missions could require 100s of kilowatts or megawatts. The especially challenging aspects of the lunar environment include extreme hot and cold temperatures, the long lunar night (up to 354 hours of darkness), and the cold, dark, permanently shadowed regions that are presumed to be rich with water ice. On Mars, power systems must overcome extended, month-long dust storms as well as diminished sunlight at higher Mars latitudes and during Martian winters. The common issue with these environments is the limited (or non-existing, or unreliable) access to solar illumination.

Most equipment used in human and robotic space activities today relies on solar power generation and rechargeable batteries. In a context with limited access to sunlight, alternatives must be found. Lower power missions on the Moon and Mars have already been accomplished with nuclear power – in the form of radioisotope thermoelectric generators (RTGs). But those systems are limited to a few kilowatts at most. Short-duration human missions can be performed with solar arrays and chemical-based energy storage systems. However, the storage of electrical power in batteries and secondary fuel cells is physically limited by their energy density. For example, a battery designed to store the energy to provide 200 W of power during the 14-day lunar night would need to store approximately 70 kilowatt-hours, implying a battery mass of more than 300 kg.

It is in this context that nuclear technology can enable benefits that are otherwise not achievable. Due to the intrinsic extreme energy density of nuclear systems, thermal and electrical power can be made available to vehicles and habitats in abundance. In all cases, nuclear technologies offer mass advantages over chemical-based energy storage. Radioisotope Power Systems (RPS) rely on the natural decay of nuclear materials to produce heat that can be converted into electricity with static or dynamic power converters. RPS can operate for decades and produce 100s of watts in packages that weigh around 100 kg or less. RPS have been used frequently in space missions since the 1960s. Fission Power Systems (FPS) rely on a nuclear reactor and fuel to supply heat to the power converters. FPS are less mature, although both Russia and the US have deployed small space reactors in the past. Some key advantages of fission technology are its energy density and scalability; there is great potential to exploit fission technology for power levels from 10s of kilowatts to 100s of megawatts. At the smaller scale, FPS can be used to power lunar and Mars bases with growth versions that could satisfy industrial-scale ISRU. At the larger scale, fission technology can be used for Nuclear Electric Propulsion (NEP) or Nuclear Thermal Propulsion (NTP) systems that transport humans to Mars and beyond.

3 Identification of Key Tasks/Questions

3.1 Objectives of the Activity

The Technology Working Group (TWG) of the ISECG initiates gap assessment teams if and when a critical technology required for the implementation of the GER needs to be better characterised or when new developments make a review desirable. In the cases of nuclear power and propulsion technologies, both criteria are realised. In recent years, the activities of the globe's space agencies in the nuclear technology domain have increased significantly. This creates opportunities, but also makes gaps more visible and more urgent to close.

The objectives of the NPP GAT are to:

- Identify new, enabling capabilities,
- Understand the state of the art, globally speaking,
- Identify gaps, and
- Enable opportunities for partnerships and coordination.

The NPP GAT was formed in 2020 and held the study kick-off meeting in October 2020. The team held monthly meetings from October 2020 through June 2022. Each monthly meeting included an agenda, roll call, discussions, and review of actions that were recorded in meeting minutes. The agenda topics were focused on addressing the objectives above and reviewing the progress on the study deliverables. This report is a product of the Group's activities. An initial draft was submitted to the TWG in January 2023. NASA requested an expanded US review, which was completed in June 2023 prior to the final release of this report.

3.2 Review of GER Critical Technologies

In the current set of the GER Critical Technologies[1] there are three technology gaps that address nuclear power and propulsion as shown in Table 1. These gaps were identified in 2018 and at that time, RPS were not identified as a gap. As this report later shows, there is potential benefit for RPS to support human exploration missions as these missions represent high-benefit activities that also require substantial stakeholder investments. These investments can be justified only if the benefits (scientific results, inspiration, innovation) can be generated over a long period of time, which can be enabled with the use of RPS.

Table 1. Nuclear Power and Propulsion Gaps

Reference Number	Title and Description	Lunar Vicinity	Lunar Surface	Near Earth Objects	Mars Vicinity (Orbit /Moons)	Mars Surface
GER-007	**Nuclear Thermal Propulsion (NTP)** provides the high thrust and high specific impulse needed to significantly reduce launch mass for heavy payloads	N/A	N/A	N/A	Critical Alternative	N/A
GER-013	**Fission Power for Surface Missions** provides abundant continuous power for surface missions	N/A	Applicable	N/A	Applicable	Critical Alternative
GER-014	**Multi-MWe Nuclear Power for Electric Propulsion** provides very high-power electric propulsion vehicle to deliver cargo and/or crew to Mars	N/A	N/A	Applicable	Critical Alternative	N/A

*Critical Alternative denotes that this GER Critical Technology is not flagged as part of the critical baseline.

Since 2018, the ISECG published the GER Supplement[2] in 2020 which delved more into the lunar surface exploration scenario than in past GER publications. For example, Table 4, Chapter 4 of the GER 2020 Supplement indicates ISRU and enabling commercial endeavours later in Phase 2B and Phase 3 that would benefit from fission power. The GER Supplement is agnostic on Mars missions and therefore no updated conclusions can be drawn on the NEP or NTP for Mars transportation. However, the ISECG should decide if a human Mars mission

[1] GER Critical Technology Portfolio (2019) https://www.globalspaceexploration.org/wp-content/uploads/2019/12/2019_GER_Technologies_Portfolio_ver.IR-2019.12.13.pdf

[2] https://www.globalspaceexploration.org/wordpress/wp-content/isecg/GER_Supplement_Update_2022.pdf

should be part of the next GER, which could determine if a change is needed to the NEP and NTP technology gaps.

4 State of the Art at Participating Agencies

4.1 AEM

The Nuclear Energy and Propulsion Report of the Propulsion and Nuclear Energy Gap Assessment Team (Report), derived primarily from the absence of continuous solar energy, requires the study of feasible technical solutions and analysis to close such gaps.

In the context of the Report, among others, the main conclusions of the assessment of the nuclear and propulsion gap and its applications, which are shared by the EEA, However, Mexico has not participated in its applications in the case of deep space missions; however, it has focused on interacting in the study, use and applications of nuclear technology with the scientific community and, above all, with the Government itself. There is an established policy on this, but NOT referring to deep space missions or M2M.

The AEM will assist in the work of the Propulsion and Nuclear Energy Gap Assessment Team (NPP GAT) whose objectives are:

i. Identify new enabling capacities,
ii. Understanding the state of the art, worldwide,
iii. Identify gaps, and
iv. Enabling opportunities for partnerships and coordination.

Mexico could contribute to solutions of access, innovation in excavation and construction and science of extreme environments with support in the scientific community and the Government. As space agencies, it is necessary to ensure the development and rapid achievement of energy-related technologies on an appropriate scale. The entire supply chain of energy production and consumption in Moon-to-Mars missions requires power generation technologies such as Fission Surface Power (FSP) (as the safest and most reliable), adaptive lunar landing matrix systems (to work in tandem) and other technologies such as chemical heat and regenerative fuel cells.

Working from the beginning to achieve these objectives in Mexico, with small tasks and scientific participation, will guarantee not only the success of cooperative missions, but will add additional human capacity on earth and on-site to these power distribution architectures. Mexico hopes to connect with experts and its potential user base, driven by institutional and economic requirements that will set and scale energy demand. It is in the nation’s interest to be part of the short-term needs for immediate priorities, as well as for long-term objectives that could affect initial architectural decisions. It is also of interest for Mexico to frame these needs under an interoperable framework to apply science, innovation and processes with other Moon-Mars ventures.

4.2 AEB

Brazil does not have a major representation on the domain of nuclear power and propulsion applied to space exploration, nor has there been significant participation in deep space exploration missions up to date. Nevertheless, Brazil has an expressive space program that has been in place since the 60's and that has been gaining recent traction due to the incorporation of traditional sectors into its space technology capabilities. In that sense, a domain that has presented powerful development in Brazil, both by the government and academia, is related to nuclear power technology. This can present an opportunity for technology and capability absorption by the space sector, resulting in future space exploration developments and international participation. Brazil's participation in the ISECG-TWG NPP GAT serves as an access to relevant discussions on the state of the art and existing technology gaps. With this newfound view on technology applications and opportunities, the Brazilian Space Agency (AEB) will act to persuade the country's space and nuclear sectors to join future collaborations and developments in the field of space exploration.

4.3 CSA/NRCan

Canada has a long history of innovation and leadership in both the space and nuclear sectors that can support domestic and international efforts regarding the use of nuclear technologies in space. This could include innovations in RPS, radioisotope batteries, and other Space Nuclear Power Systems (SNPS), such as Small Modular Reactors (SMRs). Canada hosts a full spectrum of nuclear capabilities, which includes the Canada Deuterium Uranium (CANDU) reactor technology, the world's largest deposits of high-grade uranium, state-of-the-art nuclear laboratories, and a world-class nuclear safety regime administered by the Canadian Nuclear Safety Commission. Canada is a member state to multiple international nuclear energy fora, including the International Atomic Energy Agency, OECD Nuclear Energy Agency, and the International Framework for Nuclear Energy Cooperation.

Canada has experience designing and commissioning fission reactors in the 20 kW to 10 MW electric power range, including reactor designs that are autonomous with passive safety features. SMRs are being explored in Canada for both on- and off-grid applications including as a source of non-emitting heat and reliable electricity in remote communities and mines. In 2018, the federal government convened Canada's SMR Roadmap to chart a vision for this emerging area of nuclear innovation. In 2020, Canada's SMR Action Plan was launched outlining a series of concrete actions that more than 100 partners are taking to advance SMR technologies in Canada. The SMR Action Plan identifies space exploration as a potential application of SMR technologies and identifies the opportunity to leverage research activities to contribute to international priorities in space.

To this end, the Canadian Space Agency (CSA) in partnership with Natural Resources Canada (NRCan) is studying concepts for SNPS technologies, including fission power systems for the lunar surface in the order of 30 kWe. Through the Federal Nuclear Science and Technology program, the Government of Canada is supporting a project to evaluate current and past Canadian nuclear technologies suitable for space applications in support of identifying Canada's contribution to international priorities in space. Related to RPS, Canada could leverage more than 70 years of experience processing and handling isotopes to support the global supply of suitable radioisotope fuels. For decades, CANDU reactors have been used to produce isotopes for a variety of applications and could also potentially support the irradiation of Neptunium-237 to produce Plutonium-238 for use in RPS technologies. Canada could potentially utilise existing facilities, capacity, and expertise to undertake such supply of radioisotope fuel, subject to regulatory approval of the production activity, applicable export controls, and partnerships related to supply of Neptunium-237. Canada is positioned to leverage existing capabilities and domestic initiatives to support and collaborate on domestic and international efforts related to SNPS and RPS technologies.

4.4 CNES

Since the 1960s, CNES has performed numerous studies on nuclear technology for space in the fields of radioisotopes, small and big power reactors, as well as thermal and electric propulsion. Examples are the early ERATO (1980s) and MAPS (1990s) programs. In the new millennium, CNES has conducted the MEGAHIT (1MWe) study in the frame of the EU HORIZON-2020 framework. Nuclear expertise is well established both for terrestrial as well as space applications.

In general, CNES envisions the use of nuclear devices for the long term via progressive development. While most inner solar system missions could be performed with non-nuclear devices, over 95% of the solar system is only fully accessible with nuclear energy. Nuclear options consolidate when used where they are the most technically and economically efficient. Radioisotope heating units (RHUs) and RTGs are the most affordable nuclear devices, but bear limitations in power and growth potential. Small reactors offer interesting versatility by being compatible with various applications (ground vehicle, base, orbital mission). They also offer growth potential in a modular approach for increased power output. Small reactors also eliminate the need for test and development of new architectures. Large reactors bear constraints that need to be considered: their mass, volume, and lack of flexibility for deployment when considering launch, high development cost, high logistical requirements, high-mass radiation protection, potential need for assembly and lack of flexibility for continuous improvement. Key efforts on reactors conception should be focused on fault tolerance, modularity, and synergies with outer options, recognizing that energy availability is a critical function demanding redundancy.

4.5 ESA

In the frame of ESA activities, the European member states have engaged in the advancement of nuclear technology for space applications over decades. As a result, Europe has become an important player in this field. At the current time, the three pillars of radioisotope technology for space—fuel production, encapsulation, and launch certification—have advanced to a prototype level. The next logical step is for ESA to engage in a dedicated program to bring this technology to flight readiness. For this purpose, ESA proposes to its member states a multi-domain program named “EuropeaN Devices Using Radioisotope Energy” (ENDURE). In the frame of this program ESA will supply science and exploration missions with nuclear technology capabilities for the survival of cold, dark environments such as the Moon, Mars, and the vast space of the outer Solar System. It is proposed to initially produce a small amount of radioisotope fuel in the form of ^{241}Am at a rate of a few hundred of grammes per year in parallel to the qualification of RHUs and low-power RTGs. The likely first application of a European radioisotope device will be on the European Large Logistic Lander mission in 2029 – if approved. This mission will then be capable of surviving the cold, dark lunar night and provide services to scientists and international partners over an extended period.

Through its decade-long engagement in the development of nuclear technology for space, ESA has accumulated a significant knowledge base of technologies beyond low-complexity radioisotope devices. In particular, the European academic and industrial sectors have studied fission capabilities for planetary surface power and in-space propulsion (thermal and electric). Future engagement of ESA in this mission-enabling technologies will be proposed to the member states in the frame of the ENDURE program.

4.6 ISRO

India has a long legacy in designing and establishing high-quality and reliable systems in both the space sector, as well as the atomic energy sector, with impeccable safety records. There are numerous nuclear power plants spread across the nation, set up with international partners and operated by the Department of Atomic Energy, and together, they generate over 7GW of power for commercial use. Simultaneously, ISRO’s satellite and launch vehicle technologies have reached a level of maturity that has allowed for pushing its capabilities further, with successful missions of sending orbital spacecraft to the Moon and Mars and attempts to land a rover on the Moon. With such forays, nuclear energy for both power generation and propulsion in spacecraft is bound to become inevitable and a viable option for future deep space missions.
Specifically, for interplanetary and lunar missions that require sustained operation of spacecraft components, RHUs and RTGs are currently being considered for design and development, and their realizations at various stages of completion. Fission-based propulsion units are also being explored for interplanetary missions, especially those with electric propulsion.

International collaborations and interactions have been integral to ISRO, with technology transfer right from its inception to international customers for various satellite launches. Along these lines, India is looking forward to collaborating and coordinating with international partners for a safe and reliable nuclear propulsion and power systems.

4.7 JAXA

Regarding crewed lunar exploration and supporting missions, Japan renewed the Basic Plan on Space Policy in June 2020, which states that Japan will support the Artemis program by contributing to the Gateway through habitation technologies and logistic capability and aim to contribute to human lunar surface missions by providing transportation vehicles on the lunar surface so that Japanese astronauts can actively participate in the Artemis mission. A JAXA crew mobility capability could also provide an opportunity to leverage lunar surface activities to simulate and refine plans for the first human Mars surface mission.

Regarding robotic lunar exploration missions, JAXA continues to focus on developing lunar surface capabilities using the Smart Lander for Investigating Moon (SLIM) mission. SLIM will demonstrate pinpoint landing technology and is planned for launch in 2023. JAXA, in cooperation with ISRO, is also planning a Lunar Polar Exploration (LUPEX) mission slated for launch in the 2024/2025 timeframe. The aim of this mission is to obtain knowledge of lunar water resources and to explore the suitability of the lunar polar region for the establishment of a lunar base. JAXA is working towards sending small missions to lunar orbit in the early 2020s to increase industry's capability and maintain the science community's interests. JAXA is also working to develop small-sized and medium-sized landers in the late 2020s and no earlier than 2030 respectively, for technology development and science mission, and also for providing logistics support for human lunar surface missions.

JAXA recognises that the power system is an inevitable element to perform such crewed missions as well as robotic explorations. Although nuclear surface plant could be one of the candidates of the power system to achieve the sustainable lunar exploration scenario, the nuclear power plant study in JAXA is limited to be performed through hearing and collecting information from JAEA (Japan Atomic Energy Agency) and Japanese terrestrial nuclear industries. In Japan, the terrestrial nuclear power plants have been reinforced by strict safety regulatory requirements following the Fukushima Daiichi accident.

4.8 KAERI/KARI

The 3rd Space Development National Basic Plan of Korea includes a plan to launch a robotic lunar lander by 2030 following the Korea Pathfinder Lunar Orbiter (KPLO), which is the first Korean lunar explorer. The Korea Atomic Energy Research Institute (KAERI) was awarded pre-phase development of an RTG which is necessary for night survival of the lander or rover. KAERI has developed two RPS models for space application. They are small RTGs with electric power generation capability of 150 mW$_e$ and 6 W$_e$, respectively.

A 6 W$_e$ RTG is targeted for the robotic landing mission and uses 120 W of heat source. KAERI developed an RTG prototype which generates 6 W$_e$ of electric power in 2020, and the prototype uses an electric heater instead of a radioisotope. KAERI considers Pu-238, Am-241, and Sr-90 as radioisotope heat sources. KAERI is developing the manufacturing process of Sr-90 heat source, which can be extracted from the waste of nuclear fuel. KAERI is also seeking international cooperation for sharing radioisotope heat sources. A highly efficient thermoelectric module was developed with indigenous optimization design and simulation software. Launch safety is critical if an RTG is hosted by the lander. KAERI has developed a carbon composite-based shielding structure which has the capability to protect a radioactive heat source even during aero-braking and impact due to launch failure. A 150 mW$_e$ RTG which uses an electrical heater instead of a radioisotope heat source will be hosted by a test satellite and will be launched by Korea Space Launch Vehicle-II (KSLV-II) in the middle of 2022. The 150 mW$_e$ RTG will be tested in space environment more than one year after launch.

For a small fission power system, KAERI started to develop the heat pipe reactor technologies in 2019. A heat pipe reactor system has been developed to raise the technology readiness level (TRL) for space applications. KAERI has developed the SFR and VHTR technologies to solve the spent fuel and produce hydrogen, respectively.

The non-LWR technologies can be used for the large fission power system. Korea Aerospace Research Institute (KARI), as a designated space development institute of Korea, is continuously seeking applications of developed RTG and nuclear-based energy technologies in lunar exploration such as lunar landing missions, ISRU demonstration, and future space missions.

4.9 NASA

There are four major NASA organizations that influence the agency's nuclear power and propulsion activities. All the NASA activities rely on a strong partnership with the US Department of Energy (DOE), which contributes technical expertise to NASA's space nuclear systems projects and flight missions. The Space Technology Mission Directorate (STMD) develops cross-cutting technologies to support human exploration and robotic science. They are currently leading technology development efforts on NTP and FSP which build on prior efforts like ROVER/NERVA, SNAP-10A, SP-100 and Prometheus. The Science Mission Directorate (SMD) leads the development and operations of space science missions in the solar system and beyond. It is currently leading the technology maturation and flight systems development of RPS. NASA has employed RPS on many past missions including Mars Perseverance, Pluto New Horizons, Curiosity, Cassini, Voyager, Pioneer, Viking, and Apollo. The Titan Dragonfly mission that is currently in development also intends to use RPS. The Exploration Systems Development Mission Directorate (ESDMD) leads NASA's efforts on human missions to the Moon and Mars, and guides NASA architecture studies that determine mission needs for nuclear power and propulsion systems. Future human exploration missions could use FSP on the Moon and Mars, and either NTP or NEP for Mars transportation. Finally, the Office of Safety and Mission Assurance (OSMA) oversees nuclear flight safety including launch safety and approval. A significant update to the US nuclear launch approval process was published in 2019 [RD05] that provides quantitative criteria and a tiered approach for safety analyses and decision making. The US also recently released Space Policy Directive #6 [RD06] which encourages collaboration among NASA, DOE, the US Department of Defense (DOD), and industry to increase the technology readiness and expand the use of space nuclear technologies.

4.10 UKSA

The UK has a strong heritage in nuclear technologies and has participated in many space exploration missions, principally through its membership of ESA. The UK has existing capabilities in nuclear and space systems and an indigenous supply of Americium-241. Development is ongoing for RTG, RHU and Stirling generators for future space exploration missions. The UK has more than ten metric tonnes of Am-241 in nuclear materials stored at Sellafield which is sufficient in principle for several thousand space missions.

The UK National Nuclear Laboratory (NNL) has demonstrated a process to extract around 5g per annum of Am-241 and is considering options to scale up production to meet the requirements of space agencies, with a notional goal of 500g per annum in the next decade and a first deployment of a UK-developed device on ESA's EL3 mission, scheduled for 2029. The UK also participates in and previously chaired the United Nations Committee On the Peaceful Uses of Outer Space Scientific and Technical Subcommittee Working Group on the

Use of Nuclear Power Sources in Outer Space and continues to work to define safe use of nuclear applications in space.

5 Reference Use Cases

5.1 The Global Exploration Roadmap

In 2011, ISECG developed and published the first version of the Global Exploration Roadmap (GER)[3]. The GER reflects the international effort to define feasible and sustainable exploration pathways to the Moon, near-Earth asteroids, and Mars. Beginning with the International Space Station (ISS), the first iteration of the roadmap examined possible pathways in the next 25 years. Updates to the GER were published in 2013[4] and 2018[5] to reflect the latest consensus about the importance of the Moon on the pathway to Mars and adds refinements in each step along this path as agencies continue to make individual and collective progress. Since the release of the GER update in 2018, many ISECG space agencies have set new national priorities and intensified and accelerated lunar exploration plans.

These ambitious exploration plans, coupled with new agency participants in the ISECG, created the opportunity to produce a Supplement to the 2018 GER that extends and refines the ISECG Lunar Surface Exploration Scenario[6]. The updated Lunar Surface Exploration Scenario describes a phased approach to implementing infrastructure and exploration on the lunar surface to meet the goals and objectives defined by the ISECG. The updated scenario starts with Phase 1, Boots on the Moon, where space agencies focus on sending humans to the Moon with a goal of landing in 2024 along with robotic exploration missions to support this goal and later phases. Next is Phase 2, Lunar Exploration—Expanding and Building, with an emphasis on completion of the proposed lunar surface objectives by exploring the lunar surface diversely and ultimately settling at the most beneficial site. Initial focus is on lunar surface exploration objectives pertaining to human landing and ascent, logistic cargo landers, and long-range traverses. The later focus is on lunar surface exploration objectives pertaining to long duration habitation, crew health and performance, and ISRU. Phase 3, Sustained Lunar Opportunities, envisages laying the foundation for a sustained and vibrant lunar presence in the coming decades through partnerships with international governments, academia, and industry. During this phase, governments would shift their investment focus to further expand the frontier, including Mars exploration missions.

For Phase 1, likely no space nuclear technologies are required for the surface scenario. For Phase 2A, a target of ~17 kW of power to provide supplemental power generation and storage to localised assets (such as ISRU demonstrations, rover recharge, habitat) on the lunar surface is desired. For Phase 2B, when a longer duration

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[3] https://www.globalspaceexploration.org/wordpress/wp-content/uploads/2013/10/GER_2011.pdf

[4] https://www.globalspaceexploration.org/wordpress/wp-content/uploads/2013/10/GER_2013.pdf

[5] https://www.globalspaceexploration.org/wordpress/wp-content/isecg/GER_2018_small_mobile.pdf

[6] https://www.globalspaceexploration.org/?p=1184

permanent surface habitat is placed on the surface in addition to a focus on ISRU, additional power is required to support operations. A modular power system sized to provide ~10 kW for the lunar day or night is assumed. Multiple units can provide power to meet infrastructure demands. ISRU capabilities of up to ~50 tonnes production of propellant per year is also desired, which would require additional supplemental power. The GER also emphasises the desire for dissimilar redundancy for nuclear power systems in order to ensure the provision of the critical power functions.

From a GER perspective, nuclear propulsion is not assumed for transportation for the lunar missions. Nuclear propulsion would be utilised for future Mars missions. As ISECG has not defined a Mars exploration scenario, NASA's Mars Design Reference Architecture 5 has been assumed for future Mars analyses (see next Section). However, several key nuclear propulsion technologies could be demonstrated and operated in and around the Moon.

5.2 Mars Design Reference Architecture 5.0 (DRA5)

In 2009, NASA documented preliminary studies that defined a reference architecture for human Mars missions and those studies continued through 2014 to refine the mission approach [RD07][RD08]. The results provide a suitable framework to assess potential nuclear power and propulsion requirements for Mars missions. The reference mission architecture includes a six-person crew transported to Mars on an NTP-powered vehicle for a 500-day Mars stay. The 3-year round-trip mission is based on a conjunction class trajectory. The crewed mission is preceded by an NTP-cargo mission that pre-deploys an atmospheric ISRU plant and surface nuclear power system to produce the oxygen propellant needed for the crewed Mars ascent vehicle.

The crew and cargo NTP vehicles use a common core stage with three 25 Klbf engines providing 900s specific impulse with LH2 propellant. An NEP alternative was also studied that uses a 1500K, 2.5 MWe reactor power system and ten gridded annular ion thrusters providing 5000s specific impulse with xenon. NASA continues to study Mars transportation architectures using nuclear propulsion. A 2021 NASA study evaluated both NTP and a hybrid NEP-chemical approach for 2 year-round trip opposition-class missions. The NTP option is similar to the concept developed for DRA5 but uses High Assay Low Enriched Uranium (HALEU) fuel instead of High Enriched Uranium (HEU) fuel. HALEU is below 20% enrichment (usually specified at 19.75%) but above the typical 5% that terrestrial power reactors have used. The NEP-Chem approach uses a 1200K HALEU, 2 MWe reactor power system and twenty Hall effect thrusters providing 2600s specific impulse with xenon. A LOX/CH_4 chemical stage with two 25 Klbf engines is used for the Earth departure and Mars-arrival manoeuvres, while the NEP stage is used for the interplanetary transfers and Earth return. Nuclear propulsion offers advantages for Mars missions compared to all-chemical propulsion systems due to the reduced crew flight time and lower number of launch vehicles for Mars vehicle aggregation and fueling.

The surface mission includes two primary phases corresponding to the cargo and crew missions. The cargo mission departs 26 months before the crew mission and delivers three cargo landers to Mars. Two of the cargo landers include duplicate payloads consisting of crew consumables, science equipment, a pressurised rover, ISRU plant, and nuclear power system. Only one ISRU plant and nuclear power system are required for mission success. The third cargo lander includes the Mars Ascent Vehicle (MAV) with a fully-loaded LCH_4 propellant tank and an empty LOX propellant tank. The ISRU plant is expected to produce approximately 25t of LOX to fuel the MAV and about 2t of crew oxygen in the 19-month period before the crew departs Earth. The notional DRA5 landing site was selected to be 30 deg north latitude with nominal 8hr sun and 16hr eclipse periods. The crew mission includes a fourth lander that delivers the crew, along with a surface habitat and unpressurised rover.

Surface power requirements were dominated by the ISRU plant, estimated to be about 24 kWe continuous or 92 kWe for daylight operations only. Other Mars power users included the crew habitat (12 kW), MAV (1.5 kW), logistics module (1.5 kW), rover recharging (1.5 kW), consumable cache (1.5 kW), and Mars drill (3 kW). Total power requirements decrease to about 20 kWe during the crew phase. Trade studies comparing a 30 kWe mobile nuclear reactor and 100 kWe solar array field (with 10 kWe night power supplied by regenerative fuel cells) favoured the nuclear option. The mobile reactor option was estimated to be approximately 7.8t, or about 35% of the 22.5t solar power option. The nuclear system was mostly unaffected by extended dust storms that were presumed to impair the solar power system for up to 50 continuous days.

NASA studies conducted after DRA5 for the Evolvable Mars Campaign found that the 30-40 kWe surface power need might be better satisfied by a modular approach using four 10 kWe units. The smaller modules provided improved fault tolerance and do not depend on a dedicated mobility platform for deployment. The ability to deploy individual units as needed around the landing site provided greater mission flexibility compared to the DRA5 approach. Additionally, the mass of four 10 kWe units and one spare was considerably less than the mass of delivering the two 30 kWe mobile reactors in DRA5.

6 Challenges and Opportunities

6.1 Safety Ambition: “Safety First”

Nuclear safety is an important subject of international coordination due to the global consequences of safety violations. The Working Group on the Use of Nuclear Power Sources in Outer Space under the United Nations Committee on The Peaceful Uses of Outer Space (COPUOS) Scientific and Technical Subcommittee, discusses advances in knowledge and practice in the standards and use of nuclear power systems in space, as well as promoting and facilitating the use of the Safety Framework for Nuclear Power Source Applications in Outer Space[7] (Safety Framework [RD09]). The safety culture report by the International Nuclear Safety Advisory Group of the International Atomic Energy Agency[8] states that *“safety culture is that assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety*

[7] https://www.unoosa.org/oosa/en/ourwork/copuos/stsc/nps/index.html.

[8] IAEA. (1991). Safety Series No. 75-INSAG-4 International Atomic Energy Agency, Vienna, 1991 Categories in the IAEA Safe. In Safety Series (Issue 75).

issues receive the attention warranted by their significance."

Nuclear power and propulsion technologies for space may pose unique safety and regulatory challenges. The Safety Framework, is a technical consensus of a safety framework for nuclear power source applications in outer space has been developed and jointly published in 2009 by the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) Scientific and Technical Subcommittee, and the International Atomic Energy Agency (IAEA). The Safety Framework provides voluntary guidance for nations exploring the use of nuclear power systems in space.

On 24 January 1978 the Cosmos-954 fission-powered surveillance satellite re-entered the earth's atmosphere in an uncontrolled manner, scattering radioactive debris over a large area in northern Canada. This incident highlighted the importance of safety systems in nuclear reactor powered spacecraft. An example of how safety systems work was the successful containment and recovery of the radioisotope material used in the Nimbus B mission. The mission suffered from a catastrophic launch failure and the spacecraft was completely destroyed. All radioisotope material was contained, successfully recovered from the ocean floor, and re-used on the successful Nimbus-III mission.

There have been two recent updates to U.S. policy on space nuclear systems. Under the Trump administration, the U.S. revised the launch approval process with the release of National Space Policy Memorandum-20 (NSPM-20)[8] providing guidance to *"ensure a rigorous, risk informed safety analysis and launch authorization process."* The document provides quantitative criteria to guide the safety analysis process. It also provides a three-tiered launch authorization process based upon *"the characteristics of the system, the level of potential hazard, and national security."* The U.S. Memorandum on the National Strategy for Space Nuclear Power and Propulsion (Space Policy Directive-6)[9] from the White House establishes a precedent in how principles of the United States will adhere to "*safety, security, and sustainability in its development and use of SNPP systems, in accordance with all applicable Federal laws and consistent with international obligations and commitments*". In its section 3) observes that "*All executive departments and agencies (agencies) involved in the development and use of SNPP systems shall take appropriate measures to ensure, within their respective roles and responsibilities, the safe development, testing, launch, operation, and disposition of SNPP systems. For United States Government SNPP programs, the sponsoring agency holds primary responsibility for safety. For programs involving multiple agencies, the terms of cooperation shall designate a lead agency with primary responsibility for safety in each stage of development and use*."

[8] https://trumpwhitehouse.archives.gov/presidential-actions/presidential-memorandum-launch-spacecraft-containing-space-nuclear-systems/

[9] https://trumpwhitehouse.archives.gov/presidential-actions/memorandum-national-strategy-space-nuclear-power-propulsion-space-policy-directive-6/

In 2019, ESA also released their own document[10] outlining a safety policy on the use of nuclear power sources for ESA space missions. In summary, the document states their intention to implement the guidelines established by UN COPUOS, establish safety-related roles and responsibilities, and mitigate risks arising from the use of nuclear power sources.

A common generality of these principles should be considered by each country and its space agency, and supported accordingly by law and regulations.

6.2 Launch Certification

Certifying spacecraft with nuclear power sources for launch is not fundamentally different from other launches. The safety of the potentially affected population and the work force at the launch site must be ensured within reasonable levels of safety. Important additional aspects for nuclear launches are the aspects of containment of nuclear material and its proliferation control.

Out of the community of participating agencies today, only the US Government has an established nuclear launch authorization process. Scope and details of the process can be found in [RD05]. The general approach is to engage in a flexible process that is commensurate with the risk posed by the mission at hand. For example, a lower-risk and proven interplanetary mission on a mid-sized launch vehicle is authorized by the launching agency, while missions with higher quantified risk or missions with high-enriched uranium are authorized by the Executive Office of the President.

ESA is actively pursuing the definition and implementation of a legally binding launch certification process for the European Ariane launch vehicle family. The process started in 2016 and is expected to be fully applicable in Europe in general and in national law of the European launching state France in time for the first application of radioisotope technology on a European mission in 2029. This process is specific to European launch vehicles and not applicable to other nations.

6.3 Common Regulatory Constraints

6.3.1 Proliferation of Highly Enriched Uranium

Governments represented by the participating agencies are concerned about nuclear proliferation. In particular, the utilisation of highly enriched uranium would be contrary to commitments made by several states during the Nuclear Security Summit process. In the frame of our discussion, we were able to obtain governing statements that will be useful for the further discussion. We quote these statements here for this purpose.

1. From [RD06]: "*All agencies involved in the development and use of SNPP [Space Nuclear Power and*

[10] Implementation of the guidelines provided for in the international safety framework for nuclear power source applications in outer space for ESA space missions — The ESA safety policy on the use of nuclear power sources

Propulsion] systems shall take appropriate measures to protect nuclear and radiological materials and sensitive information, consistent with sound nuclear non-proliferation principles. For United States Government SNPP programs, the sponsoring agency holds primary responsibility for security. For programs involving multiple agencies, the terms of cooperation shall designate a lead agency with primary responsibility for security in each stage of development and use. The use of highly enriched uranium (HEU) in SNPP systems should be limited to applications for which the mission would not be viable with other nuclear fuels or non-nuclear power sources. Before selecting HEU or, for fission reactor systems, any nuclear fuel other than low-enriched uranium (LEU), for any given SNPP design or mission, the sponsoring agency shall conduct a thorough technical review to assess the viability of alternative nuclear fuels. The sponsoring agency shall provide to the respective staffs of the National Security Council, the National Space Council, the Office of Science and Technology Policy, and the Office of Management and Budget a briefing that provides justification for why the use of HEU or other non-LEU fuel is required, and any steps the agency has taken to address nuclear safety, security, and proliferation-related risks. The Director of the Office of Science and Technology Policy shall ensure, through the National Science and Technology Council, that other relevant agencies are invited to participate in these briefings."

2. From [RD10]: *"Canada remains dedicated to minimizing highly enriched uranium (HEU) and other sensitive nuclear materials, as a means of further enhancing our security."*
3. Collective statement by Argentina, Armenia, Australia, Canada, Czech Republic, Chile, Denmark, Finland, Georgia, Indonesia, Mexico, Netherlands, Nigeria, Norway, Philippines, Poland, Republic of Korea, Romania, Singapore, Sweden, United Kingdom, and the United States from the 2016 Nuclear Security Summit; to make every effort to achieve further progress with regard to minimizing and eliminating the use of highly enriched uranium (HEU) in civilian applications [RD11] "… *avoid to the extent practicable the use of HEU in new civilian facilities or applications, including in research reactor facilities, critical assemblies, subcritical assemblies, pulsed reactors, fast reactors and civilian propulsion and power production reactors as well as for production of radioactive isotopes.*"

6.3.2 Transportation of Nuclear Material

The transportation of nuclear material is highly regulated to achieve a high level of safety. No nuclear transportation accident has been recorded for ground shipments containing hazardous quantities of radioactive or fissile material. However, at the same time, the associated cost, risk, and schedule impact limits opportunities for partnerships. For example, the separation of the production of ^{238}Pu into individual steps performed at different international partner locations will be constrained with regard to which isotopes can be transported.

6.4 Bidirectional Terrestrial Technology Transfer

Space nuclear systems, unlike terrestrial systems, require engineering solutions to safely and effectively operate in the harsh space environment. Specific challenges include extreme temperatures, vacuum or unfamiliar atmospheres, launch and landing loads, zero or reduced gravity, space radiation, and others. In addition, special accommodations must be made in the system design for waste heat rejection in space and long-duration operation with limited or no human intervention. Despite the differences, there is great potential for space nuclear systems to influence terrestrial nuclear systems, and vice versa.

RPSs were developed for spacecraft, satellites, lunar probes, space probes, and lunar/mars rovers. As shown in Figure 1, they are also used for naval vessels, buoys, lighthouses, autonomous power sources within nuclear power plants, and arctic monitoring sites [RD24]. Recently, a large RPS was considered as the electricity source for a remote military base [RD25]. To expand the application range, RPS technologies have been enhanced to increase their power and efficiency. As an additional consideration, the irradiation and production of suitable isotopes for use in RPS systems has the potential to overlap existing processes to produce radioisotopes for medical applications.

Figure 1. Spin-in & Spin-off of Radioisotope Power System (source: DOE, NASA, INL, KHNP)

Coated particle fuel, which is a robust, carbon and ceramic fuel for encapsulating small spherical kernels of fissile material, was developed to increase the high temperature resistance for nuclear thermal propulsion in the NERVA project [RD26]. After the 1960s, it was used to raise the operating temperature of the gas-cooled reactor [RD27]. Many countries have developed coated particle fuel as the fuel for High Temperature Gas-cooled Reactors (HTGR) for hydrogen and process heat production as depicted in Figure 2. In December 2021, the first generation IV HTGR started to supply electricity to the grid in China [RD28]. Recently, the US government recommended coated particle fuel for space and military applications. The US DOD plans to demonstrate the transportable gas-cooled reactor for the military base by 2024 and the nuclear thermal propulsion spacecraft by 2025 ([RD29], [RD30]). US and UK nuclear industries will demonstrate various high temperature reactors by 2030 ([RD31], [RD32]). Their fuel will be the coated particle fuel.

Ongoing efforts to advance small and modular nuclear fission power systems for off-grid applications on Earth could potentially be leveraged for lunar surface applications. While fission surface power technologies are expected to have unique design characteristics to operate successfully in the lunar environment, the underlying principles and components will have overlap with terrestrial designs. The Kilopower reactor [RD33] concept utilises alkali metal heat pipes to transport fission energy from a core to Stirling engines. Presently, this reactor concept is a promising candidate for the lunar base. It was pioneered by LANL in the 1960s. In the 1980s, US DOD developed the heat pipe reactor for the radar base in north Canada [RD34].

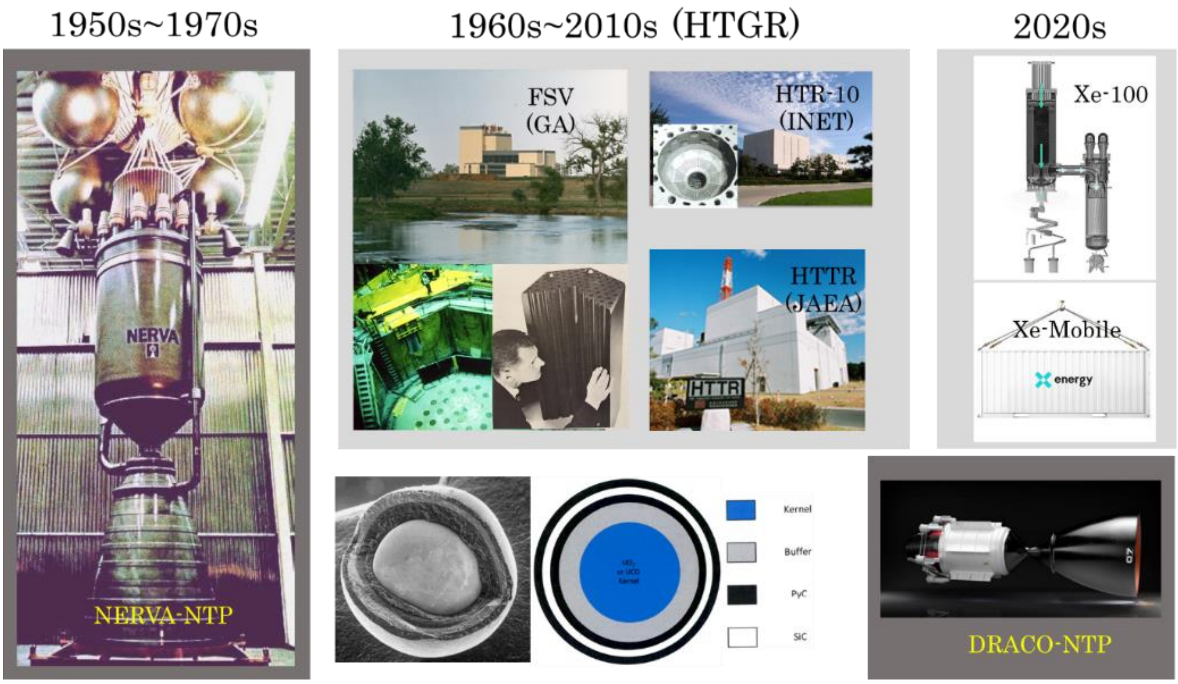

Figure 2. Spin-in & Spin-off of Coated Particle Fuel (NASA, ANS, INET, JAEA, X-energy, DOD)

After the conclusion of the SP100 project, the heat pipe reactor was noted as the alternative reactor concept for pump-driven liquid metal cooling. Apart from the Kilopower project, several nuclear industries are developing mobile heat pipe reactors in the 1 to 10 MWe range for remote special purposes [RD35] shown in Figure 3. The development of Earth-based micro reactors is expected to have a synergistic effect with the development of a large power systems for space, including to drive innovation related to portability, flexible and remote operations, and passive safety systems.

Existing nuclear sector supply chains may therefore be able to support design development, component testing, prototyping, and manufacturing for a variety of space nuclear power system concepts. Further, many terrestrial nuclear technology developers and operators worldwide are familiar with robotic operations in high radiation environments and employing high-end or exotic materials. This expertise could potentially support international priorities in space beyond power production, including materials science and radiation safety management.

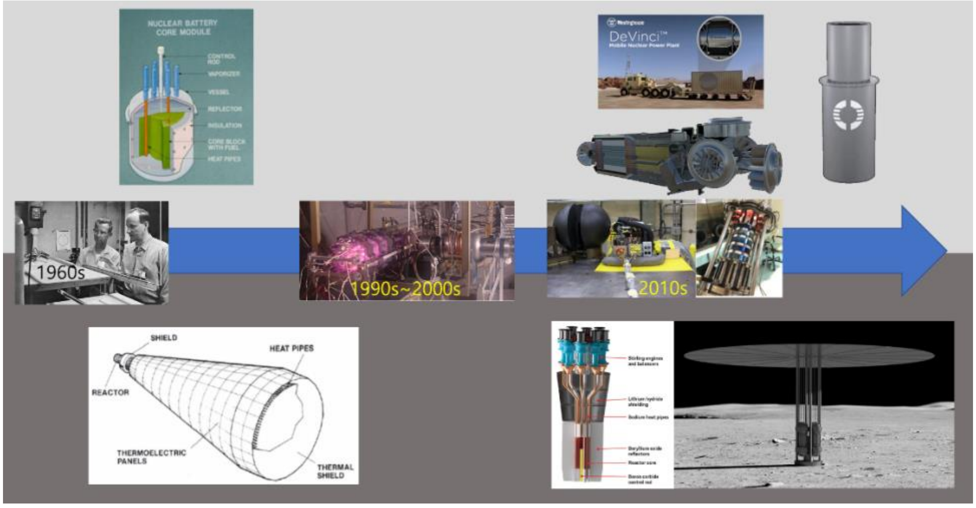

Figure 3. Spin-in & Spin-off of Heat Pipe Reactor (LANL, DOD, NASA, Westinghouse, Oklo)

6.5 Public Private Partnerships

The dynamic evolution of space activities in the private sector over the last decade, supported and facilitated by government agencies, opens opportunities in nuclear technology development and provision. For example, private sector players could engage in the provision of mission-enabling nuclear systems. Also, public-private partnerships for development and delivery of RPS to business partner/customer can be envisioned. Another opportunity would be a public-private partnership with the private launch or system provider directly, in which the government contributes the RPS in return for a service, consistent with the applicable Nation's laws. Also, international public and private organizations may fit into previously unexplored partnership models.

7 The Domains of Space Nuclear Technology

Nuclear technology represents a diverse class of engineering solutions that rely on the physical properties and interactions of atomic nuclei. We categorise nuclear technology according to the technologies used to serve the demanded function. Mainly, this categorization can be achieved as a function of the power levels provided by typical systems using the technology. This leads to three categories: the low-power regime below 1 kW, medium-power regime between 1 and 100 kW, and the high-power regime above 100kW. At power-levels below 1kW, the system design regime is below the threshold that makes control and complex conversion subsystems unattractive from an engineering point of view. This leads to the exploitation of decay heat of inert nuclear material for direct thermal output or electrical output using simple conversion methods.

The material used in this category is typically mid-lifetime alpha emitters such as ^{238}Pu and ^{241}Am. This category of systems is referred to Radioisotope Power Systems (RPS). The second power-category is the 1 kW - 100 kW regime, in which small, simplified fission engines are the most attractive engineering choice. In this category, solid reactor cores of highly or moderately enriched fissile material are the typical choice for the underlying nuclear technology, and it is therefore referred to as the "small fission reactor" category. Since small reactors can be combined in a modular network, it is related to the small modular reactor (SMR) approach for terrestrial systems. The third power-category comprises large systems that output more than 100 kW. Typically, this third category of large fission reactors (LFR) is employed to supply industry-scale operations on planetary surfaces.

In addition to the three power categories, we add a fourth category: nuclear technology for propulsion. We separate this out due to the different technical approaches used here. The propulsion category contains nuclear thermal solutions and nuclear-electric solutions. Nuclear thermal solutions comprise high-power reactors in the GW regime that are specialised to use propellant as coolant so that the thermal expansion of the propellant can be exploited to create very high exhaust velocities and thus highly efficient reactive thrust propulsion. Nuclear-electric solutions utilise more conventional electrical power reactors optimised for providing electrical power in the 10 to 100 MW range to electrical propulsion systems that accelerate ions to very high velocities to achieve even higher efficiency (yet lower thrust) reactive thrust propulsion. Table 2 presents a summary of nuclear technology by category.

Table 2. Nuclear technology listed by category

Category	Description
RPS	<1kW systems with radioisotope heat source material, thermoelectric or Stirling power conversion, and passive thermal management.
Small fission reactors	10kW - 100 kW systems with enriched uranium fuel, moderator (if needed), neutron reflector, primary heat transport, high-efficiency power conversion, and active thermal management.
Large fission reactors	> 100kW systems use larger version of the small fission reactor - or a network of small fission reactors.
Nuclear propulsion	Nuclear thermal propulsion systems use high-temperature thermal reactor (100-500 MW) and hydrogen propellant; Nuclear electric propulsion systems use moderate-temperature power reactor (10kW - 10MW) and electric thrusters with xenon propellant.

8 Radioisotope Power Systems

Radioisotopes, i.e., radioactive isotopes of chemical elements, have been used in terrestrial and space applications for decades. The natural effect of heating due to radioactive decay is well documented in planetary cores, including Earth's core. The technological application of this effect goes back to the 1960s when the radioactive isotopes became abundantly available due to the peaceful use of nuclear power from terrestrial reactors.

The physical principle of Radioisotope Power Systems (RPS) is the interaction of emitted radiation (mostly α-radiation) with the solid-state material embedding the isotope. As the radiated particles collide with nuclei and electrons in the material, they impart kinetic energy that ultimately manifests itself as thermal energy in the material. On a macroscopic level, a piece of radioisotope material appears naturally warm due to that effect. The temperature of the material depends on the activity and concentration of the radiators as well as the thermal environment in which the material is kept. RPS thus naturally provides a source of heat (thermal power). Since this heat cannot be controlled (as in a fission reaction), the external thermal control system (passive or active) requires the function of providing the proper temperature ranges. In addition to thermal power, a suitable power-conversion subsystem can be attached that utilises the flow of thermal energy from the hot side (radioisotope material) to the cool side (space radiator) to generate electricity. Normally, either thermoelectric (Seebeck effect) or a thermodynamic engine such as a Stirling generator is used to perform this function. In this fashion, RPS can also provide electricity independent from solar illumination.

The utilisation of RPS devices normally yields mission-enabling results in small-to-medium space systems operating in cold and dark environments such as the Moon, Mars, and the outer Solar System. We can envision three programmatic categories of mission application: first, near-term missions with programmatic backing or approved projects with, second privately funded missions, and third medium- to long-term strategic mission architectures and large science programs.

In the first category, missions such as the European Large Logistic Lander (EL3), the Mars Sample Fetch Rover, and the Volatiles Investigating Polar Exploration Rover (VIPER) are found. While EL3 has baselined the use of RPS, Mars Sample Fetch and VIPER currently do not foresee them on their design baseline. We have evidence from Mars rovers and many deep space probes that mission life extension well beyond the design and planned/expected duration is possible by utilizing RPS. This suggests that future Moon or Mars mission projects can mitigate operational or development risk by using RPS: operationally, impediments such as the arrival of lunar night or Martian dust storms can be managed in the frame of the nominal mission without the need for heavy batteries or new, unproven energy storage technologies. However, the significant use of RPS for Moon and Mars missions may require additional production of radioisotope material to fully address these impediments.

In the second category, missions such as the NASA Commercial Lunar Payload Services (CLPS) program (the VIPER mission mentioned above will use this service) by the private companies in the United States are evident. It is likely that private entities have limited access to nuclear technology and thus could benefit from government-furnished equipment for lunar night or Martian dust storm survival. By reducing mission risk, RPS technology could help in closing the business case for some commercial service providers, e.g., by offering lunar night survival and thus mission extension beyond the 14 Earth-day lunar day.

In the third category resides the human lunar architecture described above in the section on the GER, as well as long-duration science missions to the outer Solar System. Missions in this category represent the high-benefit activities that also require substantial stakeholder investments. These investments can be justified only if the benefits (scientific results, inspiration, innovation) can be generated over a long period of time. Past missions in this category are the Apollo surface science experiment packages (ALSEP) or the Voyager and Cassini missions to the outer Solar System, just to mention a few.

ESA has conducted preliminary studies on the implementation of missions to Saturn to investigate the level of mission constraints because of the availability of RPS (see Table 3). These studies find that Saturn missions (and to a lesser degree Jupiter missions) are severely constraint if RPS are not available. For the desirable "high energy profile mission", the use of an RTG is required, implying the need for tens of kilograms of radioisotope fuel per mission.

Table 3: ESA assessment of Saturn missions and their need for RPS

Technology Used	Low energy profile mission • Spacecraft operating on solar power up to Saturnian distance • Short active science phase or operation of low power science payload, potentially supported by RHU, small RTG, or fuel cells	Medium energy profile mission • Spacecraft operating on solar power with support of RHUs or fuel cells • Medium term operation of scientific payloads or short-term operation of payloads with high power needs)	High energy profile mission • Spacecraft operating on solar power with support of RTGs or nuclear reactor • Long term operation of scientific payloads with medium (RTGs) to high power needs (nuclear reactor)
Photovoltaic assembly with high-efficiency cells	• Beneficial for Jupiter (standard cells suffice) • Mission enabling for Saturn • Not sufficient for beyond Saturn	• Beneficial, but not sufficient (either RTG, Stirling generator, or fuel cells needed in addition)	• Beneficial, but not sufficient (multiple medium-size RTGs, Stirling generators, or nuclear reactor needed)
Solid oxide fuel cell	• Beneficial for e.g., landing assets	• Beneficial for e.g., landing assets or high-power science modes • Enabling if no RTG or Stirling generator available	• Beneficial for e.g., landing assets • Not sufficient if no RTG or Stirling generator available (energy density ≈1000Wh/kg)
Radioisotopic heater units (RHU's)*	• Beneficial • <2kg nuclear material	• Beneficial even in combination with RTG • → <2kg nuclear material	• Beneficial even in combination with RTG • → >2kg nuclear

			material
RTGs or Stirling generator*	• Beneficial • → 40-50 Watts electrical • → >2kg nuclear material but < 7.88kg	• Beneficial • → 50-150 Watts electrical • → >7.88kg nuclear material	• Mission enabling • → 2-3 times 200W electrical • → >7.88kg nuclear material

*Values shown are approximate.

8.1 Gap Analysis

NASA, KAERI and ESA have shared high-level information regarding their respective existing and near-term capabilities in the provision of RPS as shown in Table 4, Table 5 and Table 6, respectively.

Table 4: NASA existing and near-term RPS capabilities

RPS name	Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)	Lightweight Radioisotope Heater Unit (LW-RHU)	Next-Generation Radioisotope Thermoelectric Generator (NG-RTG Mod 1)	Dynamic Radioisotope Power Systems (DRPS)
Funding Authority	NASA	NASA	NASA	NASA
Thermal or electrical?	Electric	Thermal	Electric	Electric
Date of availability	2009	1977	2028	2030+
Mass per unit (kg)	44 kg	.042 kg	56 kg CBE	~115 kg CBE
Power output per unit W_e/W_t	110 W_e BOL	1 W_{th} BOL	245 W_e BOL, 177 W_e EODL	~300 W_e BOL
Specific power (W/kg)	2.4 W/kg	23.8W/kg	4.3 W/kg CBE	~2.6 W/kg CBE
Power degradation rate %/yr	3.2%/yr	~1%/yr	1.9%/yr Target	1.3%/yr Target
Fuel isotope	Plutonium-238	Plutonium-238	Plutonium-238	Plutonium-238

Constraints coming from e.g., fuel quantity	System performance limited by PbTe-TAGS thermoelectric technology. No fuel availability issue.	No fuel availability issue.	System performance limited by SiGe thermoelectric technology. No fuel availability issue.	Stirling power conversion. No fuel availability issue.
Remarks	2 units have flown.	Hundreds have flown. New production in development.	Under development based on GPHS-RTG that flew on Ulysses, Galileo, Cassini, New Horizons. SiGe technology on Pioneer & Voyager.	Power conversion technology under development.

Table 5: Korean RPS Existing and near-term capabilities

RPS name	Korean Radioisotope Heat Source (KRHU)	Korean RTG1 (K-RTG1)	Korean RTG 2 (K-RTG2)	Korean Radioisotope Stirling Generator (K-SRG)
Funding Authority	Korean Government	Korean Government	Korean Government	Korean Government
Thermal or electrical?	Thermal	Electrical	Electrical	Electrical
Date of availability	2025	2022	2028	2030
Mass per unit (kg)	0.5	0.7	7 for ^{238}Pu / 8 for ^{241}Am	10
Power output per unit W_e/W_t	29	0.2)[1] 0.1)[2]	6 for ^{238}Pu / 6 for ^{241}Am	20
Specific power (W/kg)	58	0.29	0.86 for ^{238}Pu / 0.75 for ^{241}Am	2.0
Power	2.45%	0.79%	0.79%/0.16%	0.79%/0.16%

degradation rate %/yr				
Fuel isotope	^{90}Sr	^{238}Pu	^{238}Pu/^{241}Am	^{238}Pu/^{241}Am
Constraints coming from e.g., fuel quantity	Fuel availability <100g/year starting not earlier than 2027	Discussion with VNIIEF in Russia for ^{238}Pu	Discus with VNIEFF in Russia for ^{238}Pu Discuss with NNL for ^{241}Am	Discus with VNIEFF in Russia for ^{238}Pu Discuss with NNL for ^{241}Am

)1 w/o launch vibration

)2 launch vibration to 19 grams

Table 6: ESA RPS Existing and near-term capabilities

RPS name	European Radioisotope Heat Source (ERHU)	European Large Heat Source (ELHS)	European RTG	European Radioisotope Stirling Generator (ESRG)
Funding Authority	ESA+UKSA	ESA+UKSA	ESA	ESA
Thermal or electrical?	Thermal	Thermal	Electrical	Electrical
Date of availability	2025	2025	2028	2030
Mass per unit (kg)	0.2	7	10	70
Power output per unit W_e/W_t	3	200	10	100
Specific power (W/kg)	15	30	1	1.5
Power degradation rate %/yr	0.16%	0.16%	0.16%	0.16%
Fuel isotope	^{241}Am	^{241}Am	^{241}Am	^{241}Am
Constraints coming from e.g., fuel quantity	Fuel availability <500g / year starting not earlier than 2025	Fuel availability <500g / year starting not earlier than 2025	Fuel availability <500g / year starting not earlier than 2025	Fuel availability <500g / year starting not earlier than 2025
Remarks	-	-	Modular: can be stacked	-

Given the need for RPS in the frame of near- and mid-term exploration activities described in the introduction section to this chapter and the near- to mid-term capabilities available from ESA, KAERI, and NASA listed above, we find a clear capability gap that poses a potential technology and programmatic risk for envisioned missions.

While it is currently not possible to quantify the need for radioisotope fuel, the situation is that existing and near-term capabilities to produce radioisotope material are carefully designed to only serve existing demands. For example, in the US Pu-238 is produced at a rate commensurate with the demand from approved projects – currently mainly robotic Mars and outer solar system missions. The initial production rate of Am-241 in Europe is designed to address the needs of the first few missions of the European Large Logistic Lander (EL3). With the conservative assumption that the human exploration architecture described in the GER, private sector lunar missions, and large science missions to the outer solar system will become approved programs in the not-too-distant future, we conclude that a potential gap of tens of kilograms of suitable radioisotope fuel (^{238}Pu or ^{241}Am) exists today. This gap will become apparent once the programs are approved and we predict a need date to be in the late 2020s (2028/2029). Such a gap can be closed in an on-demand manner (as, e.g., is done in the US) in the time frame of five to ten years (see section on gap closure below). At the current time, the providing nation retains ownership of the radioisotope material. For example, in the case of the US providing Pu-238 for the Ulysses mission in partnership with ESA in the 1990s, the US Department of Energy (DoE) remained the owner of the Pu-238 on board the spacecraft. While this approach provides a well-established governance scheme for the use of radioisotopes, some entities are concerned it might constrain mission planners and project managers in the utilisation of radioisotopes in terms of launch approval and certification process and launch vehicle selection. These constraints may pose a potential barrier to the utilisation of RPS and can thus be considered a gap in the RPS capabilities of the international community.

In terms of gaps for devices the situation is less severe: both radioisotope-based heating systems as well as low-power electricity systems are available or will be available in the not-too distant future. This assessment, however, assumes that proposed development programs (e.g., the proposed ESA ENDURE program) will be approved. Also, a gap for high-efficiency power conversion systems exists if higher-power (i.e., electrical power devices in the 1kWe class) are desired.

Finally, we consider potential gaps in the safety and launch approval process for launch vehicles to carry radioisotope-bearing payloads. While today in Europe the launch certification process is under definition, it is likely that a certification of Ariane 6 for the launch of radioisotope-bearing payloads will be achievable in the second half of this decade. The US employs a risk-oriented approach, in which the launch approval authority is determined based on a combination of mission risks and national security risks. The authorization of robotic missions using launch vehicles that have been used previously with radioisotope-bearing payloads (e.g., ULA Atlas V) can be relatively straightforward using well-established methods and tools. At the other end of the spectrum, a first-time launch of a nuclear fission reactor for the lunar surface on board a commercial heavy-lift launch vehicle would require new and specialized safety methods and tools that are still under development. We observe that nuclear launch approval is an experience-driven capability, i.e., project managers, safety officers, and mission planners following a well-defined process. Therefore, countries and space agencies that lack this experience must overcome the nuclear safety analysis and launch approval gap in order to plan and execute RPS missions.

8.2 Options for Gap Closure

Given the gaps identified in the previous section, the team encourages the ISECG member agencies to consider measures to mitigate or close these gaps. Such measures could be:

- Production of suitable radioisotope material (^{238}Pu or ^{241}Am)
- Coordination and mutual recognition of certification of launch vehicles and spacecraft to carry radioisotope material
- Improvement of the communication safety elements of radioisotope systems to stakeholders, including the public.

More specifically, the team has formulated a vision in which radioisotope material is abundant, and in which the ISECG member agencies have the capability to launch radioisotope devices on launch vehicles and spacecraft that are not necessarily under the responsibility of the same agency as the one producing the material. In this vision, the ISECG member agencies would benefit from a less self-limiting utilisation of the mission-enabling capability to operate longer and more effectively on the surface of the Moon, Mars, and in the outer solar system. Also, new emerging initiatives driven by the private sector will be able to offer more profitable services due to longer mission times, an expanded operational environment, higher payload, or lower operational risk.

The ISECG member agencies are already engaging in measures to close or mitigate radioisotope technology gaps: NASA considers investing in maturing higher-efficiency radioisotope power systems to conserve the limited supply of ^{238}Pu, and ESA proposes to its member states the ENDURE program, the objectives of which are a steady supply of ^{241}Am, the certification of Ariane 6 for RPS utilisation, and the development of heat and electrical power devices.

8.3 Direct Partnership Opportunities

The three following areas represent potential for collaboration: recondition, target production, and irradiation steps could be developed in a partnership scheme. However, one constraining factor is transportation (see earlier section on regulatory constraints).

There are several US companies that are actively pursuing commercial RPS, including some that are considering alternative radioisotope materials. Among the benefits proposed by these commercial entities are lower system costs and greater availability of nuclear material to serve a larger spectrum of missions. Continued attention is warranted to monitor the progress of these efforts, and partnership opportunities between suppliers and mission users should be explored. However, given the complexities of designing, building, qualifying and safely launching RPS, some restraint should be exercised in accepting all the claims that are advertised for systems that have yet to be fully developed.

Relying on more than 70 years of experience processing and handling radioisotopes, Canada's nuclear supply chain has the capacity to help close the fuel shortage gap for RPS systems. Given their large size, neutron energy spectrum, and on-line fuelling capability, Canada's CANDU reactor fleet is uniquely well suited to irradiate Np-237 to produce Pu-238 while concurrently producing electricity. As Canada does not have an identified stockpile of Np-237, Canada would need to work with international partners to secure a supply of Np-237 feedstock to realise this gap closure process. Experience in Canada related to materials and thermal hydraulics research in high radiation environments could also support the development of heat conversion systems for RPS or fission systems.

9 Small Fission Reactors

Small fission reactors are electrical power generators based on the principle of nuclear fission that converts the heat generated by the fission process into electricity. In the space environment, these reactors need to perform all their high-level functions: control, containment, and conversion based on the same principles as terrestrial reactors, but differently in terms of engineering implementation. In the space environment, much of the engineering of small fission reactors is driven by the need to efficiently reject the waste heat of the conversion process. Since in deep space and on the lunar surface the main environment is the thermal vacuum of space, only radiative cooling is available. For Mars, atmospheric heat convection is available, but to only very limited extent. Therefore, most fission reactor concepts today rely on high-temperature cores to benefit from the T^4 relationship of radiative cooling, i.e., the thermal flux being proportional to the fourth power of the temperature difference between the hot and cold end of the heat exchanger. Due to the overlap between the aspects of large and small fission reactors, some of the reactor concepts are also explained in the section on large reactors below.

Small fission reactors can provide electricity at desirable levels (few kilowatts to tens of kilowatts) largely unaffected by the harsh environmental conditions that are present in space and on planetary surfaces. This feature makes them highly desirable elements of a lunar or Martian infrastructure. The goal to achieve sustainable exploration architectures drives the pursuit of local resources (ISRU) instead of transportation of materials from Earth. If such a level of sustainability is indeed required, processing of large quantities of local material is necessary. Without a constant, reliable source of electrical power such industrial activities will not be feasible.

Today's concepts rely on enriched uranium cores with beryllium reflectors used to maintain the neutronic conditions for the fission reaction. The criticality is controlled by a neutron absorbing rod - typically boron carbide. The heat generated by the fission process is transferred to the power converter by heat pipes or pumped fluid loops. Due to the high-power levels compared to RPS, fission reactors will likely rely on high efficiency dynamic converters, such as Stirling (or Brayton, Rankine) engines to avoid excessive heat rejection requirements.

The most recent example of technology advancement in low-power fission systems is the Kilowatt Reactor Using Stirling Technology (KRUSTY) experiment [RD33]. KRUSTY included a prototype space reactor using high-enriched UMo fuel and BeO neutron reflector coupled to eight Stirling engines via Na heat pipes, all contained in a vacuum chamber to simulate space conditions. The nuclear test was conducted in 2018 at the Nevada National Security Site, Device Assembly Facility under a partnership between NASA and the DOE National Nuclear Security Administration. A primary objective was to demonstrate that a space-compatible reactor could be designed, built and tested in a short time (~3 years) without an enormous investment (<$20M total budget). The 28-hour test profile included reactor operation at full-power (~4 kWt) and temperature (~800 deg C), as well as numerous off-design excursions to demonstrate robust reactor performance under adverse operating conditions. A key outcome of the testing was data that verified controlled reactor load following under varying Stirling power draw without any control action—based solely on negative-temperature reactivity feedback. The successful KRUSTY test verifies the maturity of reactor technology for space flight development and paves the way for future mission uses.

Operationally, fission reactors are launched "cold", i.e., with the virgin core that contains only low-radiation fuel and no fission products. Only after reaching initial criticality (e.g., after landing on the surface) will the reactor become "hot", i.e., emitting hazardous amounts of radiation from fission products. From this time on, shielding is needed for crew to approach the reactor even when the system is not operating. During operations, highly penetrating neutron radiation prevails, which is either mitigated by additional shielding—potentially with locally sourced material—or by keeping crew at a safe distance.

9.1 Gap Analysis

While the basic engineering of fission reactors for planetary surfaces and deep space has achieved a high level of maturity, the major gap that remains is to develop a qualified flight system and utilize the reactor in an actual space mission. Many previous projects have been cancelled prematurely due to loss of funding, change in mission priorities, or slow technical progress. The mission itself may present gaps for the new fission system including adequately sized landers to deliver the large payload and equipment to offload and deploy the system on the surface. A new technical gap has emerged with the policy goal that encourages the use of high assay low enriched uranium (HALEU). By constraining the small fission system to use HALEU over HEU, designers must incorporate advanced moderator materials that require additional technology development in order to achieve comparable reactor mass with HEU systems that can be designed without moderators. A final gap that was highlighted by this ISECG gap assessment are the tightly controlled export restrictions in place for nuclear fission technology which presents constraints for sharing information between ISECG member agencies and establishing common standards for system design and launch certification. The gap between the lunar surface mission demands and the power provision by small fission reactors comprises mainly the following aspects:

- Technology development programs beyond TRL 5 aimed at delivering flight systems,
- Mission accommodations for launching, landing, and deploying fission reactors,
- International cooperation and establishment of shared standards for design and safety.

9.2 Options for Gap Closure

The most important step to close gaps on the roadmap to achieve the capability of small fission reactors is to proceed forward on a technology development program that culminates with a flight mission. Success will depend largely on coordinated efforts by the system developer and the mission user. Early definition and mutual agreement on mission interfaces and operating features will be crucial to assuring a positive outcome. Equally important will be a sustained and unwavering commitment (including adequate funding) to complete the development and deliver the flight system. In parallel, it is important to establish an international framework, to allow sharing of ideas between agencies and development of common standards for nuclear fission reactor payloads. High-level guidelines exist in the form of high-level principles [RD03] and national policies [RD04], but further cooperation could expedite technology advancement and minimize geo-political impediments to using nuclear systems in space. This could be achieved in existing fora, such as the UN COPUOS and supported by the ISECG community.

We especially encourage the continuation of development programs beyond TRL 5 by the ISECG participating agencies, as well as by private sector players. Such an engagement could provide a timely closure of the gaps to achieve a feasible fission solution for sustainable missions on the Moon and Mars.

9.3 Direct Partnership Opportunities

The U.S, has begun technology development on a 40 kW lunar Fission Surface Power (FSP) flight system with plans to complete the development before the end of the decade. NASA and DOE are collaborating with industry to develop viable concepts that leverage terrestrial microreactor technology. Current design studies are underway with three different contractor teams that were selected in part based on partnerships established between established aerospace companies (with expertise in space systems) and terrestrial nuclear energy companies (with expertise in nuclear technologies). This model embodies the policy direction outlined in Space Policy Directive-6 and presents an attractive approach to the development of a low-risk flight system using established nuclear technologies.

Canada could potentially support the development of small fission reactor systems by leveraging more than 70 years of experience in advancing nuclear innovation. The Atomic Energy of Canada Limited (AECL) has developed and installed SLOWPOKE research reactors at six universities and laboratories across the country, in the 20kW to low MW power range. Each SLOWPOKE reactor has compact fuel assemblies and refuelling timelines on the order of 40 years. The AECL-developed SLOWPOKE technology is possibly the only reactor design currently in operation that has a license to run for unattended operation for a specified period.

The Canadian Space Agency has begun a Lunar Surface Exploration Initiative, with the goal of preparing a major Canadian contribution to infrastructure to be utilised on the lunar surface. One of the areas under consideration for this is 'Power Generation & Distribution', with a nuclear power system as a potential deliverable.

South Korea is willing to participate in the development of a small fission reactor using Korean nuclear technologies. Korean 5th comprehensive nuclear energy promotion plan (2017-2021) included the promotion of challenging R&D to meet future needs, cultivating new nuclear applications through innovative technology convergence and graft. Space application is one of the future needs. The next plan will include more detail on the space applications of nuclear technology. Korea Atomic Energy Research Institute (KAERI) has developed heat pipe reactor technologies for small fission reactors.

10 Large Fission Reactors

In this section, the gap assessments are described for Large Fission Reactors (LFR). These reactors cover power outputs greater than 100 kWe, which is a relatively high-power range compared to Small Fission Reactors.

10.1 Gap Analysis

Technology gaps for LFRs are identified through the following definition steps. Detail of the studies on each step are described in the following sections.

i) Mission definition and power requirement

LFRs defined the following mission and corresponding power requirements as follows.

a) **Full success:** With the coordination of agencies and other international stakeholders (e.g., safety and regulatory authorities), lunar surface electrical power supplemented by high energy nuclear power solutions (typical power: 100 to 1,000 kWe) is supplied to meet the demands for international space agency missions on the Moon.

b) **Extra success:** Power provision capability for a commercial service is not necessarily provided by government agencies, but the extra power could be provided with the system. In addition, commercial power service may be utilised for government agencies.

Note regarding above:

- For item a), it should be considered on a conceptual study for not only performance or end of life but also from the nuclear safety viewpoint.
- For item b), it is difficult to predict the accurate power requirement for commercial service. As a concept to respond to the requirement, it is a plan to work collaboratively with commercial providers to develop options that assure safe and reliable operations, potentially serving both commercial clients and government agencies, as well.

Based on the mission scenarios from the GER and the other references, power requirements are identified for ISRU missions on the Moon based on GER and Mars missions with crew and ISRU based on NASA Design Reference Architecture 5.0, as shown in Table 7.

Table 7. Power Requirement for Moon/Mars Exploration

Required items	Moon –Phase 2; ISRU Pilot Plant	Moon –Phase 3; Commercial-scale propellant production	Mars –Phase 1; ISRU Pilot Plant	Mars –Phase 2; Crewed Mission
1) O_2 production in ISRU pilot plant	20 kW	N/A	30 kW	30 kW (Same as Phase 1)
2) Liquid H_2 and O_2 production for fuel in ISRU plant	N/A	300 kW (Estimated value for single-LH2 and LOX production system.)	N/A	N/A
3) Human Exploration Missions	60 kW (10kW/person up to 60kW continuous consumption)	60 kW (Same as Phase 1)	N/A	20 kW
Total	**Appx. 100 kW**	**Appx. 400 kW**	**Appx. 30 kW**	**Appx. 50 kW**

ii) Expected combination for the Large Fission Reactors

Based on the power requirement, it is expected that large surface power system options are relevant, especially for Moon Phase 3 in Table 7. The GAT analysis for LFRs considered a variety of implementation options as shown in Figure 4 ranging from multiple smaller independent, autonomous systems (A-1) to smaller systems that are integrated and coordinated (A-2) to highly-integrated systems with large centralized generation (B). The preferred option was A-2 using a combination of multiple small reactors combined to achieve the power requirements for commercial-scale propellant production. The full range of cases considered for the number of reactor units and the reactor unit size are presented in Figure 5. As for the final implementation for LFRs, a combination case of 4 x 100 kWe is selected to meet the power requirements for Moon Phase 2 (2A on GER). Based on the conclusion, the primary study is focused on 100 kWe electrical output for a single reactor.

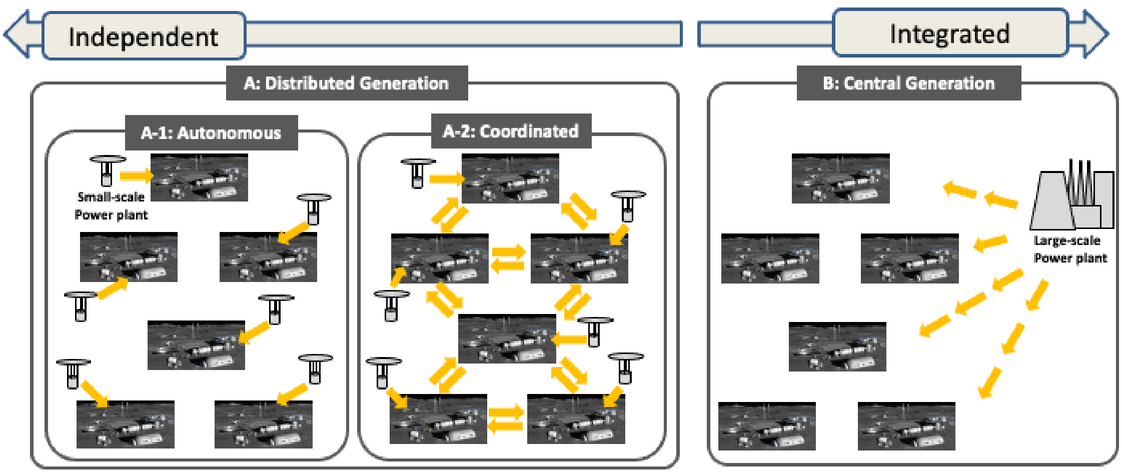

Figure 4. Expected configuration for the Large Fission Reactors

	Cases	
	1 x 400 kW	
	2 x 200 kW	Expected combination
Large Fission Reactors scope	4 x 100 kW	
Small Fission Reactors scope	8 x 50 kW	
	10 x 40 kW	
	20 x 20 kW	
	40 x 10 kW	
	80 x 5kW	
	100 x 4kW	

Figure 5. Expected combination for the Large Fission Reactors

iii) Past development and design target

To identify the reactor concept which is defined as a baseline for the gap assessment, past developments for the same or close to 100 kWe and the design target are studied. For the past development study, three projects; SP-100 in US, RAPID-L in Japan, and Prometheus project in US; are found for the output range as shown in Table 8. For the design target study, the following four points are identified from the viewpoint of space use. Main consideration points for the typical design target definition are:

a) **Safety**: Informed by prior studies and policy documents previously discussed in this report, e.g., [RD03][RD04][RD05][RD06].
b) **Electrical output**: Based on the scope of this sub-group, 100 to 1000 kWe should be defined. In addition, power per unit weight also should be taken into account for this point.
c) **Design life, maintainability**: Long-term use viewpoint and assumption whether manned or unmanned mission should be considered.
d) **Weight, size**: It is one of restriction on launch. Minimization will be needed.

Notes:

- Reliability which will be ensured by defining quality assurance program for each component is not included in the above points.
- It should be considered in the design phase that a terrestrial cooling system such as a passive core cooling system may not be feasible for a lunar system due to the low gravity on the Moon and the heat conduction and radiation of cooling system may not be applicable due to gravitational effects.

Based on the consideration points, the design target is broken down and quantitative target values are studied with the reference to the past development specification as shown in

Table 9. The target values and its basis for LFRs are defined in column "Planned design target and its basis" in the table. These values are used for the following conceptual study.

Table 8. Past development of same or closely matching units to 100 kWe

Category	SP-100	RAPID-L	Prometheus Project
Output power	100 kWe	200 kWe	100 kWe
Country	U.S.	Japan	U.S.
Period	1980's to 1990's	2000's	2000's
Summary	Following utilization has been studied: • Brayton power generation for Moon surface; two different turbine inlet temperatures. • Thermoelectric power generation for a satellite.	• The 200 kWe uranium nitride fueled lithium cooled fast reactor combined with thermoelectric power conversion system that can be operated unmanned without refueling for up to ten years.	• Fission Surface Power System derived from Prometheus Jupiter Icy Moons Orbiter power plant • Gas-cooled reactor with Brayton power conversion • Man-rated shielding through reactor burial on lunar surface
Weight	8,600 – 9,500 kg for the Brayton system with earth-delivered man-rated shield (4,600 kg for thermoelectric with instrument shield)	7,600 kg	5,500 kg Power Plant 1,000 kg for lunar installation 6,500 kg total

Table 9. Design target for Large Fission Reactors

Item	SP-100 Brayton for lunar surface	RAPID-L	Prometheus Project	Planned design target and its basis
Reactor thermal power, kWt	400	5,000	500	Not to be specified. Focused on the electrical power.
Electrical power, kWe	100	200	100	**100** Based on preferred GAT reactor size.
Design life, year	7 – 10	Over 20 (Mission duration: over 20, fuel design life 10)	10	**Minimum 20 (TBD)** Maximum value from RAPID-L.
Size, m	Lander integrated system approx. 4 x 4 x 11 Tall 4 Radiators: 4 x 11	Reactor vessel: 2 (Diameter) x 6.5 (Height)	Reactor & Brayton: 1 (Diameter) x 4.2 (Height) Radiator approx. 29 x 5	**Within 4.6 (Diameter) x 14.3 (Length), available volume of 151.7 m³ (TBD)** Based on 5.1m payload fairing for SLS Block 1 CARGO.
Mass, kg	8,600 with 1300K Brayton and on-board shield	7,600 with Thermoelectric	6,500 with 1144K Brayton and buried reactor	**Less than 7,600 (TBD)** Based on RAPID-L system. This value is within payload delivery capability of SLS Block 1B (34-40 tons).
Specific power, We/kg	11.6	26.3	15.4	**Over 25 (TBD)** Referred the maximum value from RAPID-L.
Maintainability	Unknown	Not needed	Unknown	**Not needed** Assuming operation without maintenance.

iv) Reactor concept

The reactor concept including basic elements is defined based on the following sub-studies of reactor type, fuel enrichment and trade-off of concept. Detail of the studies are described in the following:

a) **Reactor type:** There are two main types of reactors: fast and thermal reactor. The fast reactor type can have a high-power density reactor core using high density fuel and no moderator. This reactor type will have potential for electrical output, weight, and size from the design target viewpoint. SP-100 and RAPID-L are the fast type and the element test results from the development shown in Table 10 may be utilised. Based on the design target viewpoint and the past development, it is concluded that the fast reactor would be an applicable type for the conceptual study.

b) **Fuel enrichment:** For the sake of more efficient operation, increasing uranium enrichment is one of the rational options but it is pointed out that there is an issue in defining the fuel enrichment due to the non-proliferation stance of each country for use of highly enriched uranium (HEU) and impacts of uranium enrichment on reactor design complexity and system mass. For the first item, it is assessed that use of HEU would go against current common policy for minimization of the HEU in countries that have HEU. For the second item, it is initially studied that HEU can be used for both thermal and fast reactor because HEU—which is uranium enriched to at least 20 percent uranium-235—has been applied on thermal reactor for military use and experimental fast reactor such as Fast Critical Assembly (FCA) in Japan. Based on the study, it is assessed that the thermal reactor with HEU needs moderator and shielding, and a mass penalty of 1,000 kg at 100 kWe power is calculated relatively to the shielding of a fast reactor. Based on the above assessment results and following viewpoints, it is concluded that low enriched uranium (LEU) application would be reasonable and maximization of enrichment within the definition of LEU such as application close to 20 percent uranium-235 would be preferred from the more efficient operation viewpoint. Options relevant for fuel enrichment selection:

- In the case of thermal reactor, over 1,000 kg for the moderator/shielding will be added but the total mass would be within the capability of SLS Block 1B (see
  - Table 9. Design target for Large Fission Reactors
  - Increasing uranium enrichment may have a potential of more efficient operation but there is difficulty to use HEU in current countries' situation.
  - UN Resolution 47/68. "Principles Relevant to the Use of Nuclear Power Sources In Outer Space" (Principles) discusses the use of HEU, but does not address the use of LEU. As discussed in the 2023 Final Report of the UN COPUOS STSC NPS WG, "[…] future efforts could be directed towards compiling best practices and, if applicable, providing enhanced guidance on support of the fundamental safety concepts embodied in the Principles and the Safety Framework."

Trade-off concept: From the configuration of terrestrial nuclear power plant, major elements for the power generating are identified as shown in Figure 6. As for reactor type and fuel, a fast reactor is assumed from the discussion in section iv-a above. Fast spectrum reactors can minimize the need for additional shielding or moderator even if using a fast reactor with LEU, potentially offering mass advantages compared to a thermal reactor. Trade-off of concepts are performed based on component comparison of remaining elements; reactor coolant, power convertor, and power generator shown in Figure 6. According to previous studies, Stirling, Brayton and Rankine are valid options for 100 kWe output although the mass and life/reliability may not meet the target values in

c) Table 9. However, Thermoelectric could generally meet the target values based on the development of SP-100 and RAPID-L.

Table 10. Potential technology for utilisation from past developments

Category	SP-100	RAPID-L	Prometheus Project
Development status	• For thermoelectric, following items have been performed until the project discontinuation in 1995: ➢ Conceptual study of reactor, shield, power conversion, heat rejection, instrumentation & controls ➢ Thermoelectric converter design and performance testing. ➢ Development of fuel and heat resistant materials. • For Brayton, technology is based on Brayton Rotating Unit (BRU) and mini-BRU development from 1960s and 1970s.	• Conceptual study of overall plant system. • Critical experiment using Fast Critical Assembly. • Neutron radiography measurement for Lithium Injection Module (LIM) and Lithium Expansion Module (LEM). • Element tests of: ➢ High Temperature LIM Specimen ➢ Bond Free Compliant Pad for Thermoelectric Energy Conversion System. ➢ Crack Propagation Resistant Intelligent Material with Anisotropic Thermal Conductance. Note that the element development has not been completed.	• Reactor physics, thermal and mechanical design evaluations, reactor core and plant arrangements, etc. have been performed for the following concepts until the project discontinuation in 2005: ➢ Brayton energy conversion system with gas-cooled reactor ➢ Thermoelectric energy conversion system with high temperature liquid lithium cooled reactor ➢ Stirling energy conversion system with lower temperature liquid sodium reactor
Potential technology for utilization	(General) • Fast reactor with UN fuel, lithium coolant and thermoelectric or Brayton power conversion. (Element) • Fuel and Heat resistant material.	(General) • Fast reactor design using thermoelectric power conversion. (Element) • Reactor control method without conventional control rods; High Temperature LIM • Improvement of specific energy for thermoelectric conversion; Compliant Pad • Heat diffusion function can be utilized for a radiator and mitigating impacts; Crack Propagation Resistant Intelligent Material.	(General) • Fast reactor design using thermoelectric, Brayton and Stirling power conversion.

Based on the result, Thermoelectric conversion appears to have a technical potential to meet the design target values. All conversion systems have deficiencies on mass, but Stirling, Brayton and Rankine would moreover have challenges on design life and maintainability. Thermoelectric may have a relative advantage with regard to the life and maintainability targets. In addition, Thermoelectric can leverage various development heritage, not only SP-100 and/or RAPIL-L as identified in the previous study. From the above assessment, Thermoelectric can be utilised for the conversion system from the technical performance and maturity viewpoints. Among the other choices, Stirling has higher thermal efficiency, relatively less system complexity than Brayton/Rankine and potential for the terrestrial application of 100kWe class power plants (e.g., the Microreactor Applications Research Validation and Evaluation or MARVEL project). This system might be an option but technical issues such as the design life and maintainability need to be addressed. Note that the conclusion for the power conversion technology is based on the study for LFRs in this report and it is different from the previous studies such as the Mars Design Reference Architecture (DRA 5.0) and current studies by space agencies. Based on the comparison result, a drafted conceptual view showing a rough system configuration and its elements based on the trade-off is illustrated in Figure 7.

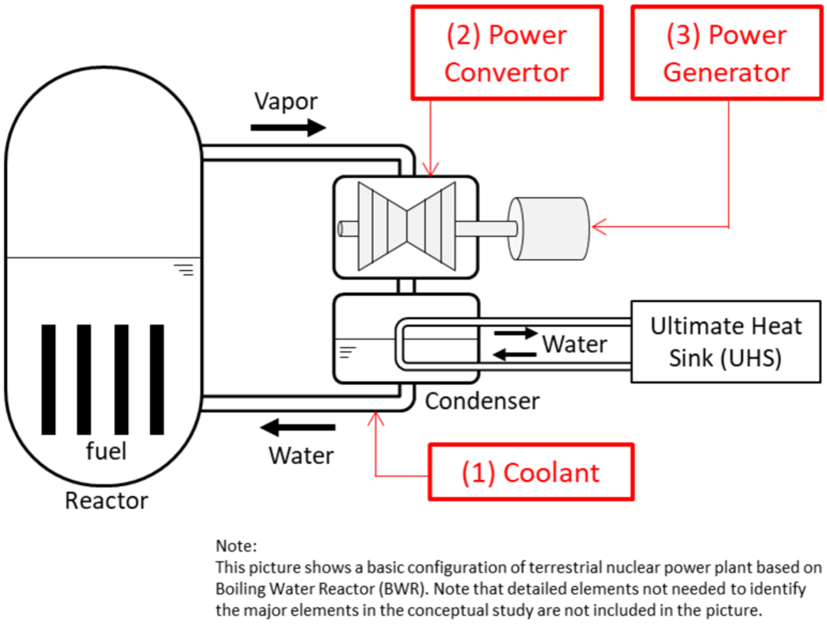

Figure 6. Basic configuration of terrestrial nuclear power plant

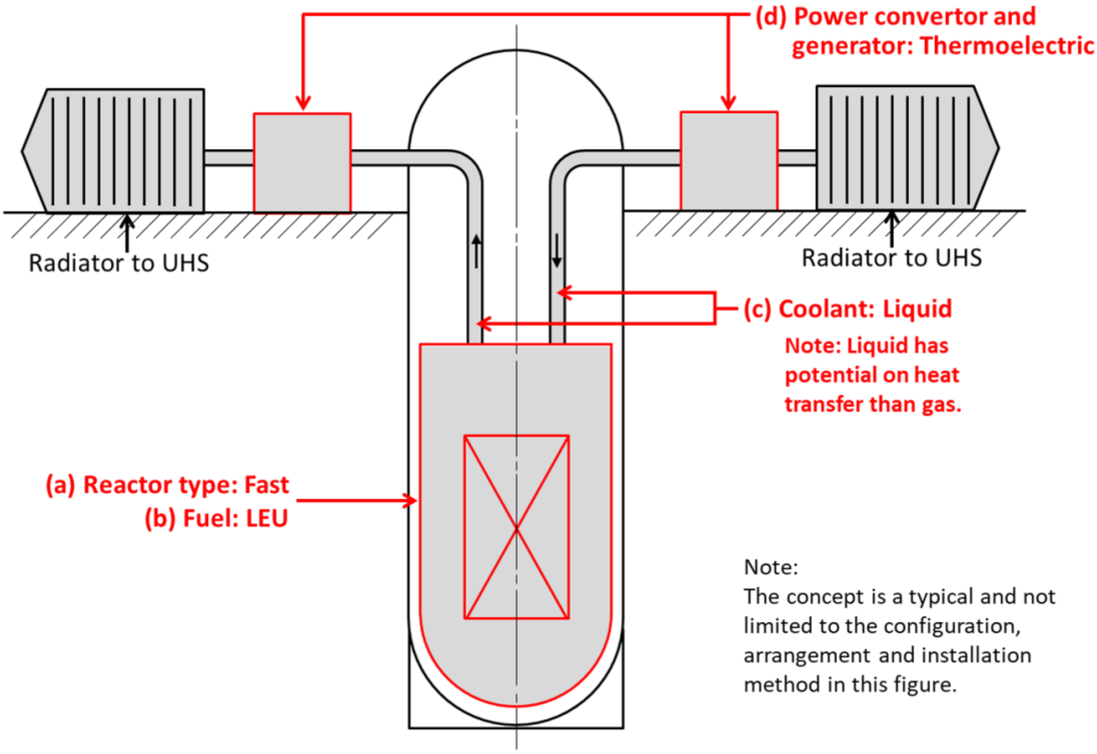

Figure 7. Typical reactor concept for Large Fission Reactors

10.2 Summary of Gap Analysis

As described in Table 8, past development of same or close to 100 kWe exists but there are limited space applications for the output power class so far. In addition, there are relatively few on-going technology efforts among the ISECG agencies related to (a), (b), (c) and/or (d) applicable to the target reactor concept and no significant technology investment plans have been disclosed through the discussions among participating agencies. From this background, technology development for each element on the reactor concept to meet the design target in

Category	SP-100	RAPID-L	Prometheus Project
Output power	100 kWe	200 kWe	100 kWe
Country	U.S.	Japan	U.S.
Period	1980's to 1990's	2000's	2000's
Summary	Following utilization has been studied: • Brayton power generation for Moon surface; two different turbine inlet temperatures. • Thermoelectric power generation for a satellite.	• The 200 kWe uranium nitride fueled lithium cooled fast reactor combined with thermoelectric power conversion system that can be operated unmanned without refueling for up to ten years.	• Fission Surface Power System derived from Prometheus Jupiter Icy Moons Orbiter power plant • Gas-cooled reactor with Brayton power conversion • Man-rated shielding through reactor burial on lunar surface
Weight	8,600 – 9,500 kg for the Brayton system with earth-delivered man-rated shield (4,600 kg for thermoelectric with instrument shield)	7,600 kg	5,500 kg Power Plant 1,000 kg for lunar installation 6,500 kg total

Table 9 would be needed.

10.3 Options for Gap Closure

d) Based on the past development of reactors which have the same or close to 100kWe output, technology heritage from SP-100 and RAPID-L listed in

could be utilised to close the technology gap for the main elements shown in the reactor concept of Figure 7. In addition, development of the smaller scale reactors is planned for the near-term exploration mission such as NASA's fission surface power project, which expands on prior work done by NASA and DOE during the Kilopower project, focusing on a 40-kilowatt class lunar demonstration in the late 2020s. It is expected to reflect lessons learned and experiences obtained through the lead development process to LFRs.

10.4 Technology Development Milestones

The technology development milestones for large nuclear fission reactors are in line with the Lunar exploration roadmap supplement to the GER [RD02]. As shown in the previous power requirement table, approximately 100 kWe and 400 kWe output will be needed for Phase 2A and 2B respectively. It is necessary to develop technology for the main components shown in the reactor concept of Figure 6 considering the major milestones for the human exploration mission, ISRU pilot plant and ISRU plant in the figure, and back calculating design, fabrication, and construction phase from those milestones. In addition, it is necessary to consider of basic concept that LFRs applies a 100 kWe reactor and its enhancement for further power requirements as described in the previous chapter regarding the expected combination of the LFRs.

10.5 Direct Partnership Opportunities

As described in section on Gap analysis, there are no significant on-going or planned technology investments to address the need for large fission reactors in the 100 to 1000 kWe range. It is expected to find new partners to realise the reactor concept, not only component manufacturers but also a system designer such as Engineering, Procurement and Construction (EPC) company for terrestrial nuclear power plants. In addition, it is pointed out for the thermoelectric application as follows. For the direct partnership establishment to resolve the issues, it is an option to consider in the development not only space application but also the possibility of dual utilisation which focuses on the feasibility of commercialization/innovation, or a secondary effect such as contribution to spin-off technologies and the development of human resources that helps promote the skills to be maintained, improved and handed down on the ground.

Issues for the thermoelectric application:

- The low efficiency of thermoelectric generators increases the size of the reactor, and also impacts thermal transport and shielding.
- There is a limit to current manufacturing capabilities for thermocouples, which may impact the feasibility of using thermoelectric generators in the kilowatt-scale.

Table 11 lists potential items that may be relevant for terrestrial application.

Table 11. Potential items relevant for terrestrial application

Item	Potential for the terrestrial application
Heat pipe	Heat pipe technology could be an option to transfer thermal energy from reactor to power convertor. According to the public information, there are multiple examples of terrestrial microreactors utilizing primary heat pipes. Westinghouse is currently developing the megawatt-scale eVinci™ mobile microreactor that is reported to use sodium heat pipes. Atomic Energy of Canada Limited (AECL) has designed a 600 kWe reactor with heat pipes called the “Nuclear Battery” in the 1980’s and the past development heritage might be applied.
Remote control system	Research and development activities that support the ability to remotely operate a space fission power system could be applied to terrestrial plant operation to reduce staff or permit remote operations. According to the public information, small modular reactors (SMRs) are currently being explored for terrestrial applications in remote and

	off-grid mines and communities. In addition, several SMR technology vendors have proposed remote operations as an opportunity to reduce the costs associated with deploying a SMR in remote areas, as it enables operating costs to be spread over multiple sites and units.

There may be an opportunity to leverage Canada's expertise in space, nuclear innovation, and mining to support higher power ISRU activities on the lunar surface. Through Canada's SMR Action Plan, nuclear and mining sector stakeholders are engaged on SMR development for deployment in remote mining environments.

Certain technology vendors with designs suitable for applications in off-grid mining environments are participating in an 'Invitation to Site' a SMR as a demonstration unit at a site owned by Atomic Energy of Canada Limited (AECL) and operated by Canadian Nuclear Laboratories (CNL). A SMR technology that could potentially be suitable for space applications may be pursued as a demonstration unit through this CNL process. The first micro-SMR demonstration unit is currently going through CNL's siting process.

11 Nuclear Propulsion for Interplanetary Transportation

Exploration of the solar system requires propulsion to produce a change in spacecraft velocity to move between orbits, and to transfer between planets. The greater the change in orbits, and the farther the transfer between planets, the greater the change in velocity required, stated as ΔV. Travelling faster between planets also increases ΔV.

All current propulsion technology is based on the physics principle of producing a force upon a free body, such as a mass of propellant, resulting in an equal force upon the acting body, in this case a spacecraft in space, thereby producing an acceleration, and hence the desired change in spacecraft velocity. Because the propellant mass is accelerated in the opposite direction from the spacecraft, it is expended, and the rate at which propellant mass is expended times the velocity the propellant is accelerated to, determines the force on the spacecraft, called thrust. The higher the propellant velocity, the greater the thrust produced per unit of propellant mass – hence greater efficiency. This propellant efficiency is termed "specific impulse" and measured in force per mass flow rate of propellant, which reduces to units of seconds. Because propellant is expended, and there are no "refuelling stations" yet available in space, especially in regions of exploration, the amount of propellant that a spacecraft can carry, and the specific impulse of its propulsion system, determines the ΔV capability.

Because more demanding, more distant, and faster missions to explore the solar system require increasing ΔV, we need higher specific impulse (I_{sp}) propulsion systems. The world has relied on the energy released from chemical combustion of propellants, accelerated through a super-sonic nozzle, as a "conventional" form of propulsion since the rocket age began. Chemical Combustion Propulsion (CCP) is limited by the energy of chemical reactions to about 460 sec of I_{sp} and below, determined by the chemical reactants. This propellant efficiency has been sufficient to get rockets to orbit, propel spacecraft flyby all the planets, orbit the closer ones, and land small payloads on the Moon and Mars. To orbit the more distant planets, move faster throughout the solar system, and move more masses to land humans on the Moon and Mars to stay long periods, we need much higher propellant efficiency.

Nuclear fission produces seven orders of magnitude greater energy per unit of reactant mass than the best chemical reactants (hydrogen and oxygen). Thus, the heat from uranium-235 fission in a nuclear reactor can theoretically accelerate a propellant to much higher velocities. This process is Nuclear Thermal Propulsion (NTP) and the device is a Nuclear Thermal Rocket (NTR). In practicality, thermally accelerating a propellant in a nuclear reactor is constrained by material limits (before melting) and heat transfer methods. A high performance, solid core NTR is generally projected to achieve about 900 sec I_{sp}. The combination of high specific impulse and high thrust provides capabilities to go farther, faster, and deliver more mass. Such a propulsion system may be an enabler for human exploration beyond the Earth-Moon system (See Figure 8).

More advanced NTP would require operation beyond the material limits by operating with liquid or even gaseous nuclear reactor fuel, but heat transfer becomes even more problematic, and there is a risk that the nuclear fuel itself could be lost in the propellant stream over time. If such issues can be solved, liquid core NTRs could reach 1,500 sec I_{sp}, and gaseous cores perhaps 3,000 sec I_{sp}, enabling even higher ΔV missions, or delivering much more payload mass.

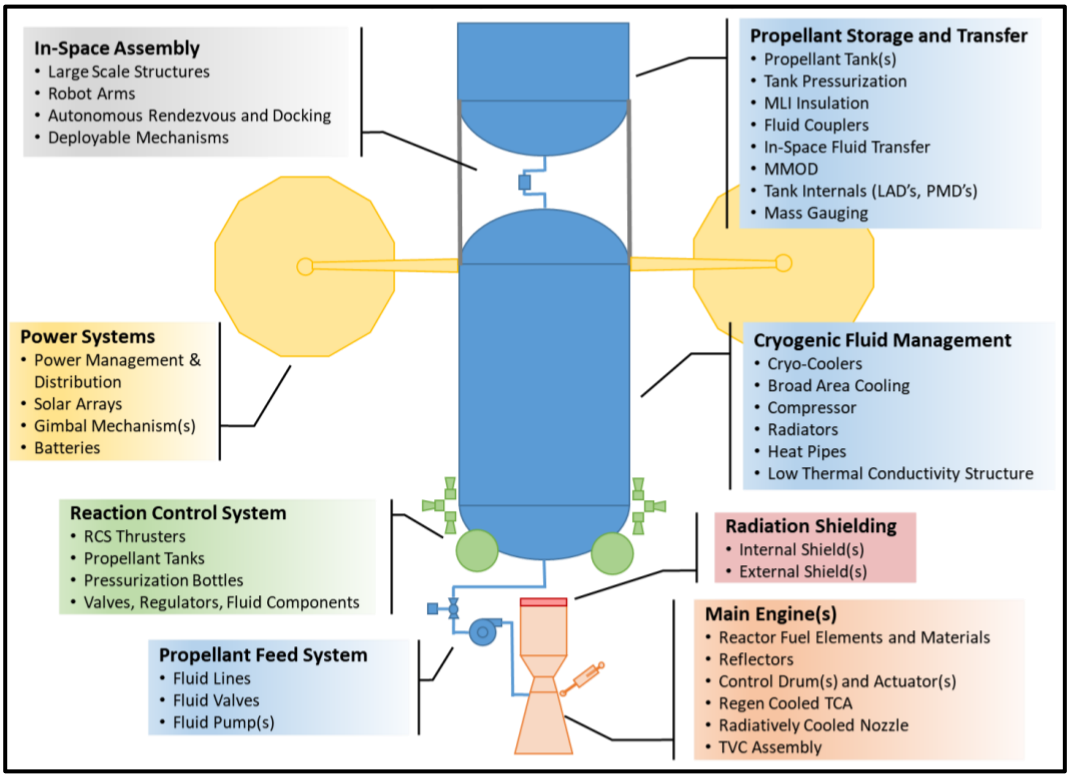

Figure 8. Example NTP system schematic from NASA

There are other means to achieve specific impulse much greater than 1,000 seconds, using electricity to accelerate an ionised propellant, termed "electric propulsion". Various electric propulsion devices, or "thrusters" can achieve a specific impulse (I_{sp}) of 1,000 to 10,000 sec. Solar photovoltaics, harvesting energy from the Sun, has been the conventional means to provide long-duration power to spacecraft since the beginning of the space age. When solar power is used to provide electricity for propulsion it is termed "Solar Electric Propulsion", and SEP has been propelling spacecraft successfully since the 1990s. But the energy available from the Sun decreases with the square of the distance from the Sun, so SEP is not a practical propulsion approach to reach more distant planetary orbits, nor are large SEP spacecraft practical due to the size of the solar arrays required above about 1 MW_e.

A nuclear reactor can generate heat to be converted to electricity for space applications, as they do to produce electricity on Earth, and as discussed earlier in this report. When a space nuclear power system produces electricity for electric propulsion it is termed Nuclear Electric Propulsion (NEP). The first and only NEP system to fly was the US SNAP-10A in 1965, which used a 500 W nuclear reactor to power a cesium gridded ion thruster for 43 days before an electronics malfunction caused the reactor to permanently shut down. Using NEP of various reactor sizes, we can move large payloads throughout the solar system and even into interstellar space – truly opening up exploration. If high power density can be achieved, measured in watts per kilogram of propulsion system, then fast missions to Mars and other destinations can be enabled. (Specific mass is an alternative measure of performance, it is the reciprocal of power density in kg/kW_e). NEP represents the ultimate in currently practical nuclear propulsion efficiency without achieving advanced technology, such as liquid or gas-core NTR or fusion energy for propulsion (See Figure 9).

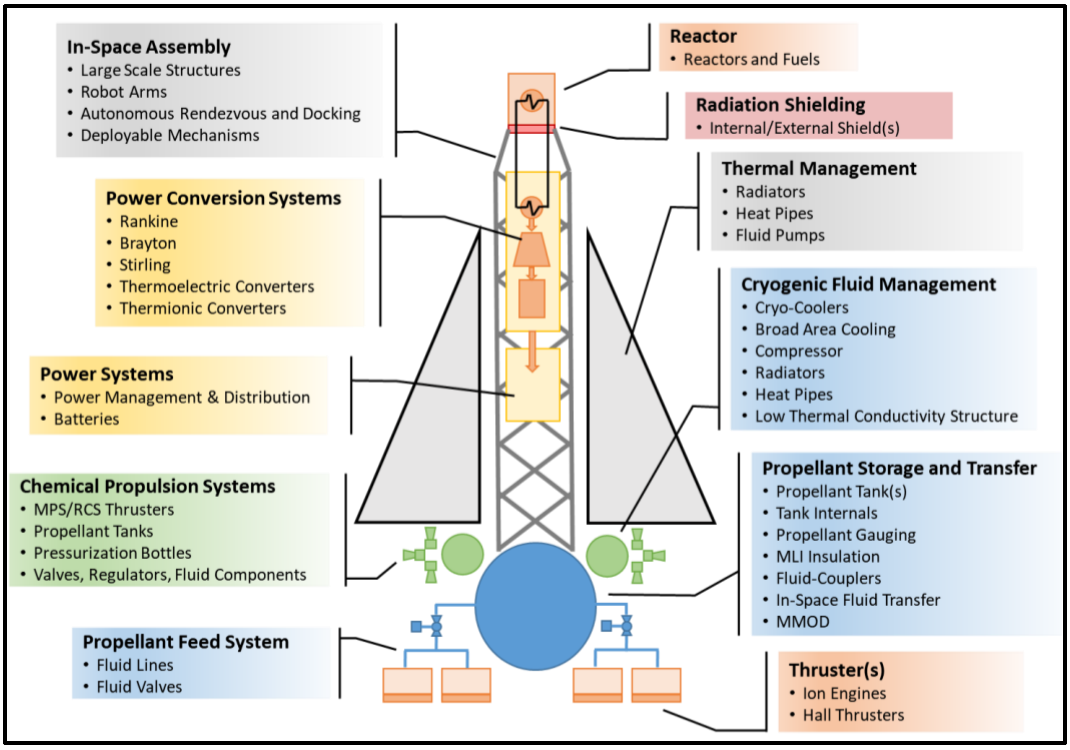

Figure 9. Example NEP system schematic from NASA

A major difference between the operation of NTP and NEP is the achievable thrust acceleration, which is a result of orders-of-magnitude difference in power density. NTP is the direct conversion of thermal energy to thrust and does not require the system mass for power conversion, power transmission, and electric thrust generation; thus, NTP systems effectively have a power density of 100,000+ W_{th}/kg. Comparatively, NEP systems are projected to achieve power density of 50 W_e/kg in the near term and must be better than 8 W_e/kg to be practical. This means that NEP systems provide thrust acceleration much lower than local gravitational acceleration around planetary bodies and require a long time to provide enough energy to escape or capture into their gravity. Pairing an NEP system with a chemical system in a hybrid vehicle allows high thrust acceleration for rapid capture and departure into and out of planetary gravity, while the low thrust NEP systems provide high I_{sp} acceleration in interplanetary space. This hybrid NEP/CCP approach can improve the sizing considerations for NEP somewhat by reducing the required electric propulsion thruster power by a half or more for missions requiring high energy trajectories, such as fast human Mars missions.

Radioisotope Electric Propulsion (REP) is a subclass of NEP where a radioisotope power system provides the electricity for electric thrusters. REP systems are applicable to missions of much smaller scale of power and thrust than NEP or NTP systems, where the fission core mass would make such propulsion systems impractically oversized. Studies over the last decade have shown that radioisotope-based NEP will enhance and enable smaller robotic missions beyond the main asteroid belt in the far reaches of the solar system. A major advantage for REP is gained by the fact that smaller, lower mass REP spacecraft can be delivered to high Earth escape velocity by current launch vehicles, thereby obtaining a boosted energy trajectory to deep space where the high I_{sp} electric propulsion can continue accelerating the spacecraft, then slow it down to rendezvous as approaches its destination. REP will require high power density RPS greater than 8 W_e/kg in order to achieve practical acceleration. Blending the two systems of electric propulsion for deep space transit and on-board chemical propulsion for orbital manoeuvres provides flexibility in operation of the REP system.

11.1 Gap Analysis

Several nations are currently considering the development of various classes of nuclear propulsion. The US is developing an NTR engine for a technology demonstration in the 2026 timeframe, with the goal of advancing technologies that could be adapted for human missions to Mars. The US is also studying NEP as an alternative for human missions to Mars, as well as smaller NEP and REP for robotic science missions. Various public internet reports suggest that Russia is developing a high power NEP tug for missions to the moon, Venus and Jupiter. The goals for these developments are detailed in Table 12.

Table 12. U.S. nuclear propulsion technology goals

Nuclear Propulsion System	Nuclear Thermal Propulsion	Large Nuclear Electric Propulsion	Small Nuclear Electric Propulsion	Radioisotope Electric Propulsion

Funding Authority	NASA	NASA	NASA	NASA
Thermal or electrical?	Thermal	Electric	Electric	Electric
Date of availability	2026	TBD - No current funding	TBD - No current funding	TBD - No current funding
Thrust or Power	110 kN	1 to 2 MW_e	5 to 10 kW_e	1 to 5 kW_e
Thrust/Weight or Power Density	2 to 3	50 W_e/kg 20 kg/kW_e	8 to 10 W_e/kg 100-125 kg/kW_e	8 to 10 W_e/kg 100-125 kg/kW_e
Lifetime	4 burn hours	4 years	15 years +	15-30 years
Specific Impulse	700-900 sec	2,600 sec	3,000-5,000 sec	4,000 sec +
Propellant	LH_2	Supercritical Xenon	Supercritical Xenon	Supercritical Xenon
Power Conversion	Not bimodal	1200K Brayton	1000K Stirling	1000K Stirling
Fuel isotope	Uranium-235, 20% enriched	Uranium-235, 20% enriched	Uranium-235, high enriched	Plutonium-238
Constraints coming from technology e.g., fuel quantity	Use of 20% enriched LEU required moderated core, limits fuel temperature	Use of 20% enriched LEU required moderated core, limits lifetime	Long life system to reach the outer planets likely requires HEU, also for performance at <10 kW_e	Pu238 required for performance.
Remarks	US Rover/NERVA developed NTP to near-flight readiness in 1960s. Current efforts to develop LEU version.	Studied in US and Europe. No current funding	Power conversion technology under development.	Power conversion technology under development.

The European Community, in partnership with Russia and Brazil, has performed various studies and is considering the development of an International Nuclear Propulsion and Power System (INPPS), as defined under the MegaHiT (**Mega**watt **Hi**ghly efficient **T**echnologies for space power and propulsion systems) project in 2013-2014, and its predecessor the DiPoP (**Di**sruptive technologies for space **Po**wer and **P**ropulsion) project in 2011-2013. The European, Russian and Brazilian DEMOCRITOS project has conducted some component technology testing with the goal of developing a potential flight demonstrator for a megawatt-class NEP system. The goals for these developments are detailed in Table 13 below.

Table 13. European nuclear propulsion technology goals

Nuclear Propulsion System	DiPoP, Low Power	DiPoP, Medium Power	MEGAHIT, High Power
Funding Authority	Europe	Europe, Russia	Europe, Russia, Brazil
Thermal or electrical?	Electric	Electric	Electric
Date of availability	2030+	2030+	2030+
Thrust or Power	30 kW_e	200 kW_e	1 MW_e
Thrust/Weight or Power Density	10 W_e/kg 100 kg/kW_e	40 W_e/kg 25 kg/kW_e	50 W_e/kg 20 kg/kW_e
Lifetime	10 years at full power, 15 years total	10 years at full power, 15 years total	5 years at full power, 10 years total
Specific Impulse			3000 to 8000 sec
Propellant			
Power Conversion		1200K Brayton	1000K Stirling
Fuel isotope	Uranium-235	Uranium-235,	Uranium-235, high enriched
Constraints coming from technology e.g., fuel quantity			1000 m^2 radiator
Remarks	Planetary surface power and high-power space science	Earth threatening NEO deflection, survey & mining. Outer planet robotic	INPPS flagship for Human Mars Mission. DEMOCRITOS

	instruments	exploration. Large infrastructure transportation.	efforts are first steps towards MEGAHIT

The GER scenario does not require nuclear propulsion for lunar exploration; however, in an evolving human exploration campaign that reaches to Mars, nuclear propulsion becomes enabling. Once nuclear propulsion capabilities are available, nuclear propulsion can be enhancing to ongoing exploration of the Moon, providing more efficient transportation of large material masses for development and resupply. Another mission-enabling application of nuclear propulsion for the Moon is the use of single-stage fully reusable vehicles shuttling between the lunar surface and Earth or high lunar orbit.

Nuclear propulsion opens the distant destinations of the solar system to robotic exploration but requires systems of a smaller scale than required for human missions. Table 14 summarises the potential missions where nuclear propulsion is enabling, and which will drive the development of these capabilities. The European efforts towards developing several classes of INPPS are to support a number of missions requiring high ΔV and large payload capability.   These are detailed in Table 15 below.

Table 14. Nuclear propulsion expected mission need in the GER

Nuclear Propulsion Mission	Human Mars Mission NTP	Human Mars Mission NEP	Robotic Science Mission NTP	Robotic Science Mission NEP/REP
Thermal or electrical?	Thermal	Electric	Thermal	Electric
Date of mission need	2035+	2035+	2030+	2030+
Payload Mass (kg)	50,000 kg TBD	50,000 kg TBD	1,000 kg TBD	100 – 1,000 kg TBD
Thrust or Power	300-500 kN	2+ MW_e	20 kN	1-10 kW_e
Specific Impulse	900+ sec	2,600-3,500 sec	700+ sec	3,000-5,000 sec
T/W or Specific power	>3	> 50 W/kg	>3	>10 W/kg
Power degradation rate %/yr	3.2%/yr	~1%/yr	1.9%/yr Target	1.3%/yr Target
Mission Lifetime	4 thrust hours	2-4 years	1-2 thrust hour	15-30 years

Constraints coming from mission	Long-term LH2 storage & refrigeration with minimal loss is critical for performance.	Requires high specific power to be practical for fast transits. Low specific power would still be practical for slower cargo transfer.	Requires high T/W to be practical when compared to conventional propulsion. Requires bimodal (power) operation and long-term LH2 storage & refrigeration for multiple burns	Requires long life to reach the outer planets. Requires high specific power to be practical. Stirling or Brayton power conversion. No fuel availability issue.
Remarks				

Table 15. Nuclear propulsion expected mission needs

Nuclear Propulsion Mission	Human Mars Mission NEP	Jupiter Sample Return	Neptune Orbital Survey and Lander	NEO Management and Deflection
Funding Authority	TBD	TBD	TBD	TBD
Thermal or electrical?	Thermal	Electric	Thermal	Electric
Date of mission need	2035+	2035+	2030+	2030+
Payload Mass (kg)	50,000 kg TBD	50,000 kg TBD	1,000 kg TBD	100 – 1,000 kg TBD
Thrust or Power	300-500 kN	2+ MW_e	20 kN	1-10 kW_e
Specific Impulse	900+ sec	2,600-3,500 sec	700+ sec	3,000-5,000 sec
T/W or Specific power	>3	> 50 W/kg	>3	>10 W/kg
Power degradation rate %/yr	3.2%/yr	~1%/yr	1.9%/yr Target	1.3%/yr Target

Mission Lifetime	4 thrust hours	2-4 years	1-2 thrust hour	15-30 years
Constraints coming from mission	Long-term LH2 storage & refrigeration with minimal loss is critical for performance.	Requires high specific power to be practical for fast transits. Low specific power would still be practical for slower cargo transfer.	Requires high T/W to be practical when compared to conventional propulsion. Requires bimodal (power) operation and long-term LH2 storage & refrigeration for multiple burns	Requires long life to reach the outer planets. Requires high specific power to be practical. Stirling or Brayton power conversion. No fuel availability issue.
Remarks				

There have been several uncompleted efforts in both the US and Russia to develop nuclear propulsion for various space applications since SNAP-10A flew in 1965. A recent US effort, Project Prometheus, sought to develop a ~100-200 kW_e NEP system to support the Jupiter Icy Moons Orbiter (JIMO) mission to orbit Ganymede, Callisto, and Europa. Project Prometheus was cancelled due to shifting NASA priorities before NEP hardware was developed. Currently there are no nuclear propulsion capabilities to support the missions identified Table 14 and Table 15 though the US, Russian, and European nuclear propulsion development and demonstration efforts are aimed at closing those gaps. NASA has continued efforts to develop nuclear thermal propulsion technology through various recent efforts such as the Nuclear Cryogenic Propulsion Stage project, Game Changing Development (GCD) NTP project, and current Technology Demonstration Mission (TDM) Space Nuclear Propulsion project. NASA and the Defense Advanced Research Projects Agency (DARPA) recently announced plans to collaborate on the Demonstration Rocket for Agile Cislunar Operations (DRACO) which seeks to flight test an NTP system in the mid to late 2020s.

NASA recently completed an initial phase of study of propulsion options to support a human Mars mission. Without an efficient propulsion system, the propellant mass for a Mars mission can become prohibitive, especially for fast Mars transits. Higher propellant efficiency also enables more robust missions, as the propulsion system can afford propellant margin to respond to contingencies. Due to limited resources, the Mars Transportation Assessment Study (MTAS) focused on the two most promising propulsion technologies: NTP and NEP. Because of propellant efficiency, each of these propulsion technologies has significant advantages over Chemical Propulsion (CCP) and could potentially enable more robust and faster transits to Mars. The study innovated a hybrid NEP/CCP approach, similar to the hybrid SEP/CCP approach identified as a non-nuclear alternative for Mars conjunction class missions in the 1990s, whereby a balance of high thrust chemical propulsion and low thrust electric propulsion can perform fast missions with less propellant using less advanced technology.

11.2 Options for Gap Closure

No nuclear propulsion capabilities are currently flying in space, and thus the entire table, above, of enabled missions represents the top-level requirements for development.

Both the recent US MTAS study and European-Russian-Brazilian DEMOCRITOS efforts recognise an evolutionary approach as advantageous to developing the propulsion system required for human transportation to Mars. Conceptually, small NEP/REP (5-10 kW_e) could be developed for robotic science, leading to medium NEP (100-250 kW_e) for NEO threat mitigation, leading to large NEP (1-5 MW_e) for human Mars missions. NEP of medium-to-large class can also support lunar infrastructure build-up in preparation for human Mars missions.

Similarly, the US project to develop the DRACO NTP demonstrator could be adapted to serve as an earth departure stage for deep space missions, leading to clusters of the same-size or larger NTRs for human Mars missions. NTP of even a small class (20 to 60 kN) can deliver Mars lander precursors as demonstrators to retire risk for both systems.

11.3 Technology Development Milestones

Nuclear technology for propulsion shares the technology development needs of those of fission reactors (see section 10.4). It has however specific challenges when it comes to fuel and test facilities, which are discussed here.

Fuels: Nuclear fuel development is unique for NTP due to challenging operating conditions, including temperature, power density, and hydrogen corrosion, operating at the extremes of material capabilities and engineering design. This is necessary to achieve the highest reactor temperature to maximally add energy to, and accelerate propellant to high exhaust velocity, which translates to high specific impulse. Past NTR reactors designed for high I_{sp} operate close to the melting point of the fuel (within ~100-200 K). Since hydrogen is not only the propellant, but the reactor coolant, any significant imbalance in H_2 flow could lead to hot spots and melted fuel. Furthermore, NTR reactors have been the highest power density nuclear reactor cores ever designed to provide thrust at minimal mass, which translates to high thrust-to-weight ratio. However, high power density translates to quicker reactor response to transients, and higher risk of melting the core. Thus, nuclear thermal rockets require precise control to balance hydrogen flow and criticality control during reactor start-up, when the core is cold and dense hydrogen flow is introduced; and during transition to full thrust, as hot hydrogen becomes less dense, while the hot core requires more hydrogen cooling to keep from melting.

Test facilities: Because of the tightly coupled operation of an NTR engine with hydrogen propellant, NTP development requires a full scale, integrated ground test to prove the system and qualify it for spaceflight. While the fission product inventory for an NTR test is very small due to the short run times of the engines, such testing cannot be performed without capturing and/or filtering all the rocket exhaust to eliminate any risk of releasing radioactive fission products into the environment. This requires a new test facility which does not exist in the world today. Such a facility will be costly and require significant time for construction. The design and development of this facility has been, and remains, a major schedule and cost hurdle for the development of NTP. Alternative methods of design verification and testing, such as simulation and modelling and zero-power criticality testing, are being considered as more affordable approaches.

Launch safety: (Consistent with other sections of the report)

Space qualification: (Consistent with other sections of the report)

11.4 Direct Partnership Opportunities

Nuclear Thermal Propulsion requires a tightly coupled development and operation of the nuclear reactor, nuclear reactivity control system, hydrogen propellant feed system, and rocket engine thermal management system. NASA is already partnering with DARPA to demonstrate NTP reactor operations in a space environment. A potential follow-on partnership opportunity for NTP could be between the nuclear thermal rocket engine developer and the cryogenic hydrogen propellant system developer.

Nuclear Electric Propulsion systems may have the potential for development partnerships due to the large number of distinct subsystems with relatively well-defined interfaces. Reactor and power conversion are the most co-dependent subsystems, and thus should be developed in closest coordination. Heat rejection, power management and distribution, electric propulsion, and propellant storage, management, and distribution are all subsystems that could be developed by separate partners in effective coordination.

Several areas of cooperation in the development of NEP can be explored:

- Fuels development and fuels testing
- Power conversion
- Space rated, rad-hard electronics
- Electric Propulsion
- Propellant – xenon
- Launch and resupply missions

REP systems could be developed with separate partners developing the radioisotope power system and the electric propulsion system.

12 Overarching Coordination Opportunities

When considering the coordination opportunities of the different categories of space nuclear technology described above, it is apparent that there are significant opportunities to improve coordination despite the existing export and knowledge control limitations in place today. The establishment of this GAT and the progress made by the Team in evaluating technology options provides evidence that collaboration among international space agencies on space nuclear systems is both possible and beneficial. This report does not factor in any information or participation from the Russian or Chinese space agencies. Since both countries appear to be pursuing space nuclear systems in significant ways that could influence the broad space community, it would be useful to revisit the gaps identified in this report and consider opportunities for further coordination if the Russian and Chinese space agencies were to provide information on their space nuclear endeavours.

The NPP GAT identified three specific opportunities for partnership and coordination: 1) Terrestrial energy systems, 2) Common for space nuclear systems, and 3) Promoting agency investment in space nuclear technologies.

On the topic of terrestrial energy, the NPP GAT sees great potential for space nuclear systems to leverage advances being made in terrestrial nuclear technologies. It is recognised that there are serious differences among traditional terrestrial nuclear power plants that produce 100s of megawatts and space systems that produce 10s or 100s of kilowatts. Small modular reactors and microreactors in the megawatt-class are gaining attention for terrestrial power applications. The intersection between terrestrial and space power is expanding. Included among the potential areas for collaboration are advanced high-temperature materials, reactor fuel design and testing, reactor instrumentation and controls, thermal-hydraulic fluid systems, and turbine-based energy conversion systems. In the past, there have been limited interchanges between the space community and terrestrial power companies. There was consensus agreement among the GAT members that benefits could be realised through greater collaboration. The US has already begun to explore partnership opportunities with terrestrial energy providers like X-energy, Westinghouse, and BWXT. CSA is also pursuing partnership with NRCan to leverage their experience with the CANDU reactors. The infusion opportunities are bi-directional. The advancement of space nuclear systems can provide benefits to terrestrial nuclear technologies that could address world-wide goals for climate change and energy resiliency. Space nuclear systems could influence terrestrial power through advances made in small, lightweight systems, autonomy, and reliability. The Nuclear GAT recommends that the synergies between space and terrestrial nuclear systems continue to be exploited.

Regarding standards, the NPP GAT envisions a system of space nuclear standards that enables cooperation and coordination with a stable and fully agreed framework. These standards would enable cross-agency partnerships in exploration missions utilizing nuclear technology. A potential example of such a partnership is a multi-agency mission to the Moon or Mars using nuclear technology from one partner that is integrated and launched by a different partner. Other aspects of include non-proliferation measures, safety standards for launch and mission operations, certification, transportation, and ground testing, interface standards, and technical environment standards. It is the definition, agreement, and implementation of this standards framework that represents an early opportunity for international partnership. As one of the major outcomes of the work of the NPP GAT we recommend the continuation of this pursuit under the auspices of an international space nuclear standardisation group within a suitable engineering standardisation organisation (e.g. ISO).

In order to close the nuclear technology gaps identified in this report, coordination and steady investment among the ISECG-member agencies will be required. The NPP GAT urges agency leaders to prioritise and sustain the growing number of space nuclear programs across the international space community. The US is leading efforts to develop new ^{238}Pu-based RPS, lunar FSP systems, and NTP systems for human cislunar and Mars missions. The UKSA is maturing radioisotope systems that leverage abundant supplies of ^{241}Am, and ESA is establishing the ENDURE program as a mechanism to supply future missions with nuclear power. Other agencies such as KAERI and ISRO are also pursuing advanced RPS to meet upcoming mission needs. The CSA is partnering with NRCan to leverage long-standing terrestrial capabilities to supply isotope fuel and develop novel space reactors based on earth-based microreactors, under their Lunar Surface Exploration Initiative (LSEI) and Federal Nuclear Science and Technology (FNST) program. Emphasizing these programs will help to close the nuclear technology gaps and facilitate the use of nuclear systems in future space missions.

It is recognised that the above opportunities might require that the ISECG designates a specialised team to implement these recommendations. To that end, the NPP GAT proposes the establishment of a small ISECG Nuclear Focus Group with volunteers from member agencies to execute these actions on their behalf.

13 Key Findings

All member agencies of the NPP GAT have unique capabilities which can be leveraged to advance the technology readiness of space nuclear systems. There is significant mission pull for nuclear systems that span the range from small science platforms to lunar habitats to industrial-scale ISRU to crewed Mars transportation vehicles; ISRU was determined to be a major driver. We find that each category of nuclear technology has slightly different yet overlapping mission drivers, as shown in Table 16.

Table 16: Mission drivers for the categories of space nuclear technology

Category	Mission driver
Radioisotope heating and electricity	Small robotic science platforms on Moon, Mars, and the outer solar system, robust thermal survival of human exploration systems on Moon (night) and Mars (dust storm season)
Small nuclear fission reactors	Habitation and science modules on Moon and Mars, ISRU pilot and research plants and small-scale industrial activity
Large nuclear fission reactors / modular grid of fission reactors	ISRU, operations-scale industrial capability on the Moon and Mars
High-power nuclear fission reactors for propulsion	Crew transportation to and from Mars, fully reusable shuttles to and from the lunar surface

The development of new space nuclear systems presents both technical and geopolitical challenges, which can be facilitated through international coordination and collaboration. Nuclear launch safety is a key area for cross-agency collaboration; further efforts are needed to establish common policies and standards that assure safe launch and operating practices for future space nuclear systems. Benefits include shared/consensus methods to address safety, cross-agency missions, and opportunities for involvement by smaller agencies.

The implementation of nuclear systems in the GER would benefit from a strategy that starts with smaller simpler systems and evolves to larger more complex ones. The categories of large and small reactors for planetary surface applications share many technological characteristics; large-scale production of electricity on the Moon and Mars can be achieved by a modular network of small reactors. Concurrently, there is great potential for space nuclear systems to leverage advances being made in terrestrial nuclear technologies while addressing climate change and providing socio-economic benefits.

Specifically, in regards to the use of highly enriched uranium (HEU), low enriched uranium (LEU) also provides a potential solution that would address international non-proliferation goals. Regarding the Principles related to the use of HEU, future discussions on "[…] best practices and, if applicable, on providing enhanced guidance on support of the fundamental safety concepts embodied in the Principles and the Safety Framework," could be considered.

Ten detailed findings achieved in the frame of this assessment are listed in the executive summary in section 1.

14 Recommendations and Way Forward

There is much work to do to address the gaps for nuclear technologies and realise their benefits in future space exploration missions. Nuclear technology development can be difficult and requires patience to achieve the desired outcomes. There have been multiple prior attempts to field space nuclear systems that have ended prematurely due to high cost and excessive complexity. There are numerous examples where the development took too long and the mission application changed, or the customer chose a different approach due to slow progress. It is incumbent upon current nuclear projects to make steady progress and show meaningful advancements that address mission needs. History supports an approach of starting simple and making incremental technology improvements as experience is gained. The first SNAP-3 RTG flown in 1961 produced only 3 watts. It took nearly 30 years and four design iterations to develop the GPHS-RTG that produced nearly 300 watts and enabled cutting-edge missions like Galileo, Ulysses, and Cassini.

A key to achieving success on the nuclear technology gaps is continued attention from the ISECG and its member agencies. The NPP GAT is seeking ISECG concurrence and support for the formation of a Nuclear Focus Group, under the auspices of the Technology Working Group, to monitor progress on space nuclear developments and pursue the recommendations outlined in this report. The Nuclear Focus Group would be staffed with subject matter experts from ISECG member agencies (resources permitting) and convene on a periodic basis to coordinate actions and review cross-agency progress on nuclear technologies. Specifically, it is recommended that the Nuclear Focus Group execute the following forward actions:

1. Identify methods / opportunities for space-terrestrial technology transfer and the standardization of operational practices,

2. Monitor progress of nuclear technology / program developments across participating agencies, for annual or bi-annual reporting to ISECG.

The members of the NPP GAT collectively call on the ISECG agencies for action to engage and invest in new emergent developmental programs with the objective of closing the gaps identified in this report.

15 Reference Documents

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