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INTEGRATED DEVELOPMENT STRATEGY FOR SPACE NUCLEAR PROPULSION

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An integrated development strategy to realize operational nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP) systems is presented. A generational development approach is employed, where each generation of a propulsion system is more capable and reliable than the previous. These systems will either enable missions that were not possible or, for missions that could be performed using other systems (including earlier generations of space nuclear systems) will improve the mission metrics, most notably greater delivered mass, reduced trip time, or longer mission endurance. Present and ongoing investments in materials development, component design and testing, and modeling and simulation lead the way in developing demonstration flight systems and expose gaps in the nation's capabilities. Developing future generations of systems with greater utility will require additional capabilities, including those for large-scale nuclear test and evaluation.

INTRODUCTION

Space Nuclear Propulsion (SNP) systems are an enabling capability to meet the vision of providing robust and enduring access to destinations throughout the solar system. Nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP) represent complementary technical solutions, with the former providing high thrust at specific impulses that are at least double that of the best chemical systems and the latter delivering low thrust at specific impulses that are several times greater than chemical or NTP systems. Spacecraft equipped with nuclear propulsion systems can deliver more payload, support increased launch and Earth departure windows, potentially reduce transit times, and provide unprecedented amounts of electrical power for missions.

Fission-based nuclear power is useful in space in two general mission scenarios. The first scenario encompasses missions where solar power is limited, either because a spacecraft is far from the Sun or because it operates in the shadows of other bodies or extraplanetary terrains where solar-battery systems cannot meet the power demand during eclipse or night periods. While this portion of the trade space has traditionally been occupied by radioisotope thermal generators, the mass of these systems can be prohibitive if the mission requires much more than a kilowatt of electrical power. The second scenario for nuclear power in space represents a mission set requiring a very high level of on-demand power (on the order of tens to hundreds of megawatts-thermal or greater)

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delivered by a compact system having a high power output per unit mass. In either case, the use of a nuclear fission system represents the only reasonable near-term means to generate the levels of power required at a reasonable system mass, enabling new and novel missions that cannot presently be executed with current state-of-the-art systems.

NASA's SNP program has been maturing technologies that support both NTP and NEP through various activities and investments. In this paper, a generational approach to developing ever more capable SNP systems is presented, starting with initial flight demonstration systems and culminating in a series of ever more capable operational systems. This is accomplished by continually reevaluating progress to identify development and capabilities gaps, making investments to close those gaps, and infusing newly-matured technologies into each generation. The developmental challenges facing NTP and NEP systems and some of the near-term investments being pursued to address those challenges are discussed. Finally, this paper describes high-value nuclear test capabilities, some of which existed in the past in the U.S., that will be needed to reduce development risk and eventually to qualify and certify space nuclear systems for operation.

STEPWISE, GENERATIONAL NUCLEAR PROPULSION DEVELOPMENT

Given the significant challenges in bringing these revolutionary propulsion technologies into regular use, NASA's SNP program is taking on a "crawl-walk-run" approach to incrementally mature the critical technology elements of these propulsion systems. In this approach, different generations of systems are developed and demonstrated, with each building upon the performance capabilities of the previous generations to yield increasingly capable systems. Figure 1 illustrates this approach for both NTP and NEP systems.

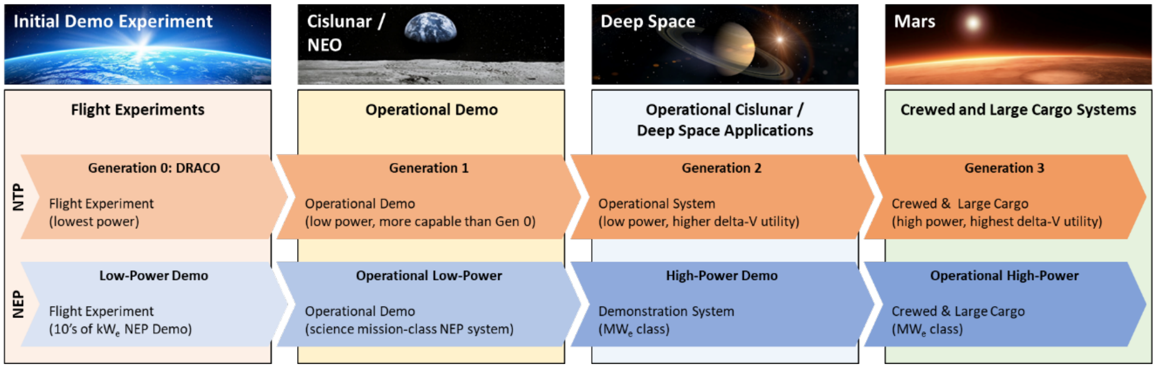

Figure 1: Generational developmental approach for NTP and NEP

The path towards an operational NTP engine starts with an initial Gen 0 flight demonstration system, such as the ongoing DARPA/NASA Demonstration Rocket for Agile Cislunar Operation (DRACO) program. Such missions can serve as regulatory pathfinders to navigate the approval process for launching and operating a nuclear system in space, while also providing valuable technical experience, uncovering development and capabilities gaps, and returning data for use in future systems. The first flight demonstration lowers the advancement degree of difficulty[*] (AD^2) for future nuclear systems, with additional technology maturation efforts pursued in parallel to advance system TRL across a range of power levels and support future flight demonstrations and operational systems.

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[*] The advancement degree of difficulty (AD^2) is a qualitative, dynamic descriptor meant to characterize the difficulty in maturing or advancing the technology readiness level (TRL) of a component or system from its present value.

Beyond a Gen 0 flight demonstration, three major generations of development are envisioned with each successive generation improving upon engine specific mass, specific impulse (I_{sp}), thrust, reusability, and lifetime capability. These improvements give each generation additional utility, permitting them to perform more difficult and complex missions. Table 1 below provides highlights of the objectives for each NTP development generation, with conceptual design images shown in Figure 2. In Gen 1, the system would have improved thrust, I_{sp}, and reliability relative to the Gen 0 demonstration engine. Such a system will demonstrate the ability to operate and recover when conditions deviate from nominal. Gaps in national nuclear test and evaluation capabilities, identified during Gen 0, will be partially addressed. The resulting capabilities should be sized for use in the development of Gen 1 and beyond. For Gen 2, the NTP engine will have a longer lifetime and higher overall Δv capability compared to Gen 1. This development will be supported by completed and fully-capable national nuclear test and evaluation capabilities. Gen 3 engines will be higher thrust and power per engine, capable of supporting the most difficult missions, such as fast-transit human to Mars.

Beyond specific space nuclear technologies, other technologies will be incorporated into NTP systems as they become ready, further improving the utility and capability of NTP systems. These include cryogenic fluid management for liquid H_2 propellant storage and autonomous rendezvous & docking.

Table 1: NTP Generational Technology Development Objectives

NTP Generation	**Development Objectives**
Gen 0	First-of-a-kind NTP system demonstrated in space. Pathfinder for clearing the regulatory and nuclear launch approval process. Nominal startup, steady-state operation, and shutdown in space.
Gen 1	Operational NTP system. Able to demonstrate fully controlled operations and maneuvers. Capabilities beyond those of Gen 0. Demonstrate closed-loop engine control, materials compatibility, and lifetime at high-temperature for longer-duration missions and multiple restarts. Gaps in national nuclear test and evaluation capabilities partially closed to support system development.
Gen 2	Operational system with longer life and higher overall Δv capability compared to Gen 1 system. Potential for reusability or to boost payloads from Earth orbit with a high escape velocity. Additional potential use for orbit capture at the destination. Gaps in national nuclear test and evaluation capabilities fully closed to support system development.
Gen 3	Higher thrust/power compared to Gen 1 and 2 systems. Support long-duration applications requiring high thrust to minimize trip time, such as Mars human and cargo missions. Capability to boost very large deep space science missions out of Earth orbit with a high escape velocity.

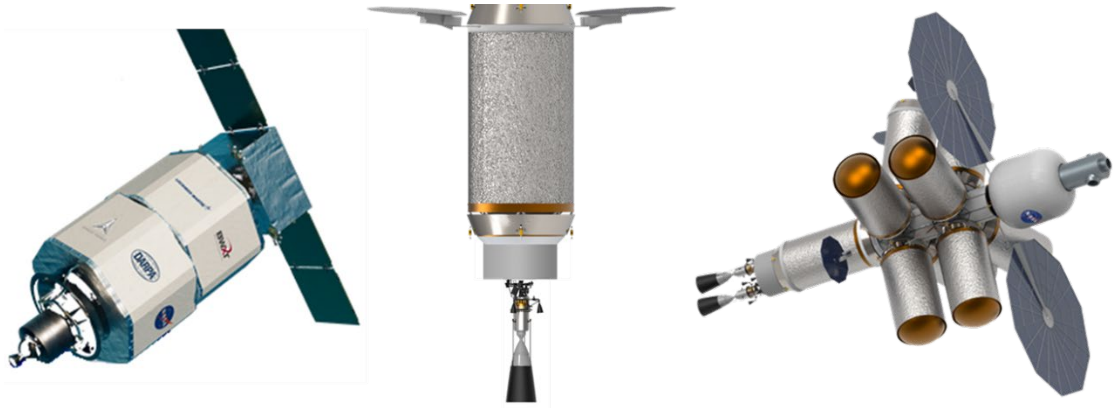

Figure 2: Generational NTP spacecraft – (left) DRACO technology demonstration spacecraft, (center) notional Gen 1/Gen 2 NTP stage, (right) notional multi-NTP engine crewed Mars vehicle with multiple propellant tanks. (images not to scale)

A similar generational development approach is envisioned for NEP. An initial low-power (10s of kilowatts-electric, or kW$_e$) demo would use aspects of the first fission surface power (FSP) system and infuse additional technology maturation advancements to yield an NEP system with a reduced specific mass (mass per unit of power generated). While much of the technology maturation for the Gen 0 system is aimed at producing a lower specific mass low-power NEP system, the effort will also intentionally mature the technologies that will be needed for much higher power systems.[1] This approach will develop and mature those technologies in a manner such that the resulting advancements can also improve the capabilities (specifically the power generation capabilities) of lower-power systems, with the latter providing a testbed for high-power technologies that is not as stressing. In Gen 1, an operational NEP system is developed with lower specific mass and very high reliability and lifetime to support the transportation and power needs of deep space science and planetary defense missions. Developments in Gen 2 and Gen 3 are aimed at realizing the high-power (100s of kW$_e$ to multi-MW$_e$) systems required to propel large spacecraft to Mars. Technology maturation to support Gens 2 and 3 aim to further reduce the NEP system specific mass and realize reliability levels commensurate with the requirements for the transportation of humans or those payloads supporting human Mars missions. Highlights of the NEP generational development approach are summarized in Table 2, with low- and high-power NEP system conceptual design images shown in Figure 3.

Beyond the generations described in this section, one can consider development paths that could yield additional utility by combining the strengths of both NTP and NEP technologies. For example, a "hybrid" nuclear transportation system – consisting of separate NTP and NEP modules, each with their own reactor – would provide for high-thrust departure and capture maneuvers using the NTP system, while the NEP module would provide high specific impulse propulsion yielding efficient momentum transfer during the long transfer trajectory. In such a system, the NEP module would also be available to provide significant electrical power at the destination. Furthermore, the NTP stage could be used for Earth departure and then be potentially staged to separate and return to Earth for refueling and reuse. Beyond this envisioned state and further into the future after NTP and NEP systems have been separately matured, a "bimodal" nuclear transportation system might also be realized, where a single reactor could be designed to provide the power for both NTP and NEP functionality.

Table 2: NEP Generational Technology Development Objectives

NEP Generation	Development Objectives
Gen 0 (low-power NEP demo)	Low power (10s of kW$_e$) NEP demo. Using aspects of the first fission surface power (FSP) system and infusing additional technology maturation for a lower system specific mass.
Gen 1 (low-power operational NEP)	Low power (10-50 of kW$_e$) operational NEP system. Improved system lifetime and lower specific mass relative to the Gen 0 system. Able to support the interplanetary needs of long-duration deep space science missions, including the continued production of power at the destination.
Gen 2 / 3 (high-power demo and operational NEP)	High power (100s-1,000s of kW$_e$) NEP operational systems. Able to support missions delivering heavy payloads (e.g. Mars human and cargo missions, very large deep space science missions). Potential to produce very high on-demand power in-space at any location.

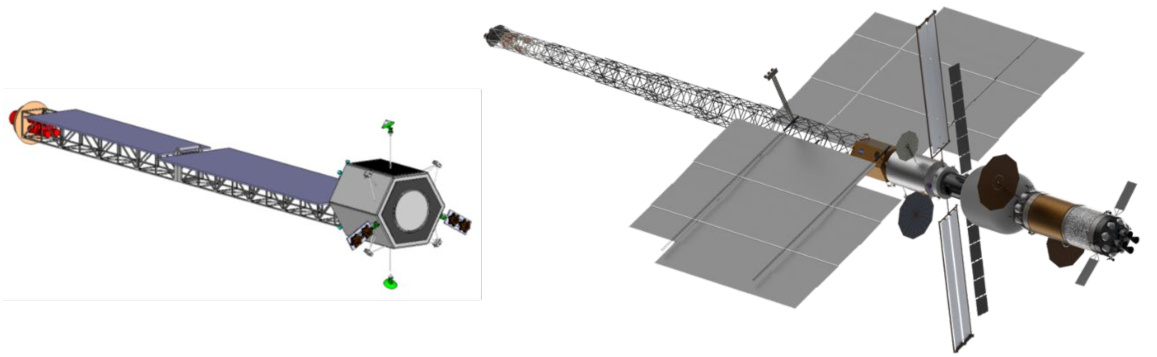

Figure 3: Conceptual NEP spacecraft – (left, image courtesy of the Glenn Research Center's Compass Concurrent Engineering Team) a low-power 40 kW$_e$ NEP planetary defense vehicle precursor, (right, image courtesy of the Marshall Space Flight Center's Advanced Concepts Office) a high-power multi-megawatt NEP human Mars transportation vehicle with a chemical propulsion stage. (images not to scale)

CHALLENGES FOR OPERATIONAL NUCLEAR PROPULSION SYSTEMS

There are many challenges to overcome to support the regular use of NTP and NEP systems. Flight demonstrations of Gen 0 systems (such as DRACO) can help in this respect and will certainly reduce the AD^2 for follow-on designs. However, the very nature of a flight demonstration mission limits the ability to close gaps through flight alone, since such a system cannot be recovered and returned to Earth for inspection after operation to quantify performance and wear mechanisms. Even if the system could be recovered post-test, this may provide little information about system lifetime because of limited operating time (constrained by the propellant load). Nonetheless, these early flight demonstrations, and the process undertaken to design and fabricate the nuclear systems, serve to highlight gaps that require additional focused effort. What follows is a short description of some challenges that will be addressed during the successful development of the post-Gen 0 systems described in the previous section.

To achieve the performance levels that make space nuclear systems competitive, the reactors must operate at significantly higher temperatures than those found in standard terrestrial nuclear power plants (at least 600 deg K hotter and operating for thousands of hours in space nuclear power reactors, and over 2000 deg K operating multiple times for up to an hour each time in NTP systems*). Developing materials that can survive those temperatures in the radiation environment while potentially exposed to reactive fluids (such as hydrogen propellant at high temperature) has been an ongoing effort since the first space nuclear projects in the 1950s and 60s.

Since the dawn of the space age, countless research labs have contributed to the materials database for conventional chemical rockets, from mechanical, fracture, and heat transfer properties of various structural materials, to fluid and combustion properties of the combustible fuels and oxidizers. This knowledge forms the cornerstone for vehicles like SpaceX's Falcon 9 and Starship-Super Heavy, Blue Origin's New Glenn, and ULA's Vulcan-Centaur rockets. The equivalent database of properties for materials that could comprise a space nuclear reactor is very limited, especially for the temperatures and induced nuclear environments expected. Furthermore, the behavior of many materials used in aerospace applications have not been studied and catalogued for their performance and survivability when exposed to the reactor-induced radiation environment.

A significant challenge is the ability to perform testing, specifically nuclear testing, on materials, components, and fully-integrated space nuclear systems. The SNP program is leveraging a combination of non-nuclear testing capabilities (thermal-hydraulic testing without the use of nuclear reactions) and employing various research reactors to partially close the gap in test capabilities. There are limits to the conditions at which these facilities can support test and evaluation activities, and in some cases availability of the test facilities (especially the nuclear test facilities) is such that demand far exceeds supply. Beyond the patchwork of existing nuclear and non-nuclear capabilities, there are additional nuclear test capabilities that will be required to fully quantify and qualify space nuclear systems. These test capabilities, if they ever existed in the U.S., have atrophied over the past several decades. These capabilities and their utility merits a separate, focused discussion, which are presented later in this paper.

The rapid, systematic development of space nuclear systems for flight requires significant improvements to modeling and simulation capabilities. Testing efforts will need to provide significant data to support the development and validation of those tools, but it is not reasonable to expect that every operating condition and off-nominal case can be evaluated by test. Consequently, the goal in developing modeling and simulation tools – be they physics-based models of processes at various sizes and scales (micro, meso, macro), multiphysics analyses, coupled systems analyses, or representative and realistic digital twins – is to realize a predictive capability that will shorten design cycles and permit the design of higher performance, ready-to-fabricate systems.

There are many other gaps and challenges to address in realizing the regular use of space nuclear systems. There must be a means to satisfy nuclear and other regulatory requirements, from transportation to payload integration to launch approval and in-space operations. A successful Gen 0 demo will start to address these issues, providing an existence proof that these requirements can be fulfilled and nuclear launch approval can be obtained. However, it is recognized that the path may deviate depending upon the organization performing a launch and mission. There are different authorities granted to different government agencies, and a successful path for one mission and organization may need revisited for others. NSPM-20 regularized the approach in gaining approval for the launch and in-space use of space nuclear systems, and developing approaches to gain

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* Compared to terrestrial pressurized water reactor (PWR) systems operating at just below 600 K.

regulatory approval for the period of time leading up to a launch will be just as crucial in reducing process uncertainty and encouraging the routine use of these systems.

Finally, there are national strategic challenges that must be addressed when fielding space nuclear systems. A prime challenge is the supply of nuclear fuel at the high-assay low-enriched uranium (HALEU) levels (5-20% ^{235}U enriched), but only slightly behind that is the supply chain for nuclear grade non-fuel materials and components that comprise the balance of a reactor. There are few outlets to provide such materials and the production of these materials can be challenging, requiring specialized manufacturing and handling techniques. An additional national challenge is the cultivation of a dedicated workforce that can design nuclear systems for aerospace applications, which is a significantly different proposition from the design of nuclear systems for terrestrial power generation or naval applications. Part of this challenge is transitioning the space nuclear field from designing 'paper reactors' to fielding 'practical reactors', much like the U.S. Navy had to do in the 1950s for ship-borne reactors.[2]

NEAR-TERM SPACE NUCLEAR PROPULSION DEVELOPMENTS

What follows next is a discussion of the near-term developments and investments that have been made or are presently being pursued to advance and mature NTP and NEP systems to support the generational development path previously discussed in this paper. This discussion focuses on work aimed to address some of the gaps and challenges identified in the previous section.

NTP Near-Term Development

To achieve the highest specific impulses possible, an NTP reactor must operate at temperatures and power densities well above those of terrestrial nuclear reactors, where uranium and many uranium-bearing mixtures and compounds melt. In addition, the components of various candidate nuclear fuels are reactive with hydrogen, especially at elevated temperatures, leading to potentially-rapid corrosion of the nuclear fuel during operation. These were leading issues at the end of Project Rover[3] and the Nuclear Engine for Rocket Vehicle Application (NERVA) program.[4] There were limited efforts to address these materials issues in the intervening years (the most notable and expansive being the USAF Space Nuclear Thermal Propulsion (SNTP) program[5-7] in the 1990s). In the mid-2010s, NASA – through what would become the SNP program – established a focused fuel development program (FDP) leveraging advanced manufacturing and coating techniques, non-nuclear high-temperature testing, and limited testing in the cores of research reactors to develop a nuclear fuel form (or forms) that would survive the harsh thermal, chemical, and neutronic environment within an NTP engine. As this work proceeded, the need for high-temperature moderator materials was the next most difficult issue identified, which resulted in the multi-year fuel and moderator development program (FMDP). Over time, work to address additional NTP technology gaps was initiated and continues to this day. This included the development of other in-core materials such as thermal insulators, and the study of flow channels and other coating techniques to keep reactive hydrogen away from the nuclear fuel while still permitting sufficient heat transfer to the working propellant. In addition, the engine requires turbomachinery, regeneratively-cooled nozzles, valves, and other components, configured around the reactor in the manner shown in Figure 4. While these components are standard and well-developed for pump-fed liquid engines, materials research has been required in some cases to identify replacements for materials that do not react well to the neutron and gamma radiation environment induced by the reactor. Operationally, an NTP engine is significantly different from, for example, launch vehicles, with NTP often requiring extended thrusting (30-60 mins at a time) and multiple thrusting maneuvers per mission, many after extended (months-long) cold soaking in space.

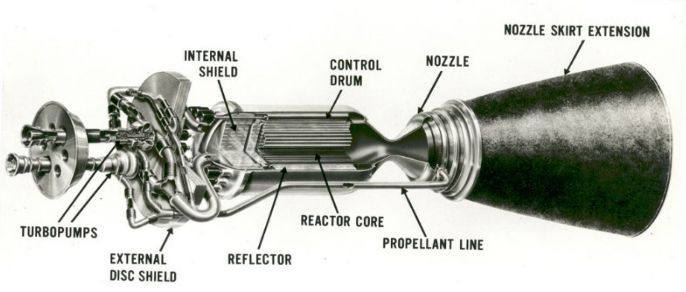

Figure 4: NERVA program image of an NTP engine, showing the relative layout and locations for all major subsystems.

NASA has invested significant resources in materials and subcomponent testing to produce data demonstrating that candidate NTP engine components, especially the reactor fuel elements, will retain sufficient integrity under all expected normal and selected off-normal operational conditions. Furthermore, the testing is yielding data aimed at showing these designs will prevent the release of fission products into the exhaust flow during ground testing, or that any products that manage to enter the flow are at levels where they can be captured and removed prior to exhaust to the environment, allowing for very safe ground testing conducted well below any nuclear regulatory and safety limits. The SNP program is investing in studies to design the facilities described in a later section that would support both in-core testing of full-scale nuclear fuel elements under conditions approaching those found in NTP engines and ground testing of full-scale NTP engines.

In addition to nuclear testing, several other developments and tests must occur to ensure the engine will operate as expected. Early NTP engines suffered issues with very damaging in-core flow induced vibrations,[8] which must be avoided in any operational system. The control and operation of the nuclear reactor and of the pumped flow system are tightly-coupled, and demonstrating through test that these systems can be monitored and controlled to yield target performance is a critical step. The engine will require shock, vibrational, and thermal-vacuum testing to demonstrate that all components will survive the transportation and launch environments and operate as expected upon reaching space.

Not mentioned previously but critical for operation are robustness and reliability of the instrumentation systems and control actuators on the engine. Nuclear reactor actuators and instrumentation are typically designed for terrestrial operation on reactors operating at much lower power densities and with plentiful cooling available. Instrumentation and control components are being examined and tested to determine if they will survive not only in space on an NTP engine, but through the same transportation and launch environments to which the rest of the engine is exposed.

Finally, to make lasting progress NASA is investing to improve modeling and simulation (M&S) capabilities, developing predictive capabilities that will support the rapid advancement of NTP systems through the generational approach previously described. It is recognized that not every operational contingency can be quantified by test and that M&S will be required to fill knowledge gaps in the operational parameter space. The existing nuclear, materials, and systems-level M&S capabilities have also proven useful in explaining experimental results that were previously not understood, and they are valuable in conducting design trade studies and in configuring experiments to gain meaningful and useful data.

NEP Near-Term Development

NEP employs a fission reactor-based power generation system to produce electricity, which is directed to electric thrusters. In-space nuclear power generation has been the subject of multiple research projects since the 1950s, starting with the Systems for Nuclear Auxiliary Power (SNAP) program.[9] This program resulted in the only spaceflight of a nuclear reactor by the United States, the SNAP-10, which was launched in 1965.

NASA is presently pursuing a path aimed at maturing critical technology elements (CTEs) to support an integrated flight demonstration of a low-power (i.e., tens of kW_e) nuclear electric propulsion system. An NEP system is comprised of five CTEs, as illustrated schematically in Figure 5.

CTE-1: The nuclear reactor and coolant subsystem is the thermal power source, generating the heat required for conversion to mechanical power by the power conversion subsystem (CTE-2).

CTE-2: The power conversion subsystem converts the heat from CTE-1 into mechanical power[*] that is used to turn an electric power generator that is a part of CTE-3.

CTE-3: The power management and distribution subsystem incorporates all the components necessary to generate power from the input of CTE-2 and then transmit that power to the electric propulsion subsystem (CTE-4).

CTE-4: The electric propulsion subsystem is composed of the thruster and power processing unit (PPU), the latter being required to converting the power received from CTE-3 to the current and voltage required by the thrusters.

CTE-5: The primary heat rejection subsystem is composed of the radiators, heat exchangers, and thermal transport means necessary to reject the waste heat from the power conversion cycle to space.

Apart from the electric propulsion subsystem, there is a natural synergy between NEP systems and the fission surface power (FSP) systems designed for use on other planetary bodies, with both having the same basic systems. While mass is not a primary driver for stationary terrestrial nuclear power plants, it has historically been a driver for space nuclear systems. In addition to reducing the specific mass of NEP and FSP power generation systems, these systems must possess a reliability and lifetime to support unattended operation for a mission lasting many years. It is reasonable to expect that, as the nation alternatively fields iterations of FSP and NEP systems infused with technologies that have been continually matured to reduce specific mass and increase reliability, these power systems will converge and exhibit significant commonality.

Recent investments have been aimed at demonstrating the capability to manufacture specific, long-lived, and low mass pieces of hardware and then to demonstrate that hardware under conditions expected for an NEP system. One of the levers to reduce specific mass is to operate at a higher temperature, leading to smaller radiators rejecting heat to space at a correspondingly higher radiative heat rejection temperature. While the advantage realized by operating at higher temperature is not as great at lower power (where the size of the system limits the realizable benefit), the low power case represents an opportunity to develop and infuse various materials and manufacturing techniques that will support higher power systems, gaining operational experience and producing data in a less-challenging environment.

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[*] For the case where a dynamic power conversion cycle is employed. CTE-2 and CTE-3 will be slightly different if a solid-state (thermoelectric, thermionic, or thermal photovoltaic) power conversion system is employed.

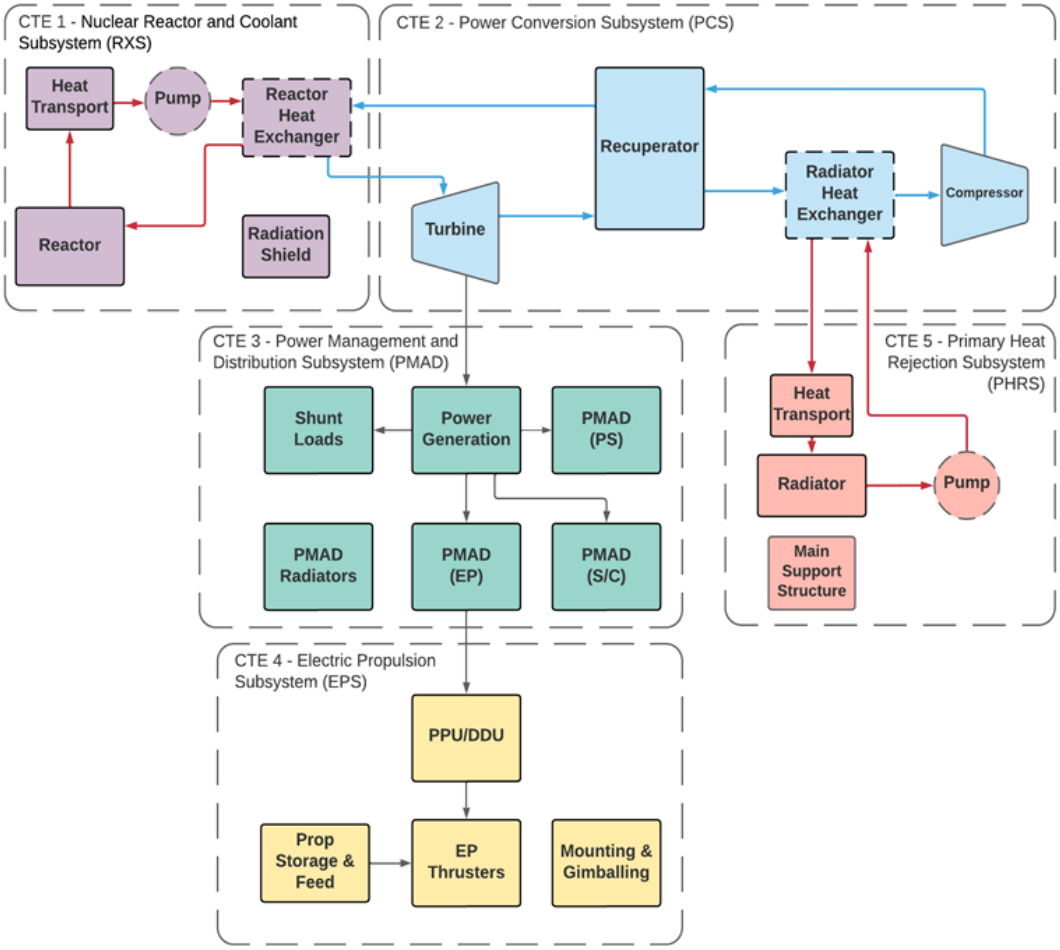

Figure 5: Schematic diagram of the interconnections between the CTEs comprising an NEP system (assuming CTE-2 is a closed Brayton cycle system).

Specific national investments for NEP include the manufacture and testing high-temperature lithium (Li) heat pipes to extract power from the nuclear core, the design and analysis of components to support high temperature closed Brayton cycle systems, the design and fabrication of a high temperature-capable power generator, and the development and testing of high-power field-effect transistors (FETs) that may survive in the radiation environment. Additionally, there are two separate efforts to develop lightweight, high-temperature radiator panels and a project that aims to show how radiators could be assembled after launch using in-space servicing, assembly, and manufacturing (ISAM) techniques. Finally, while there exist multiple electric thrusters that are likely capable of fulfilling the immediate propulsive needs for low power NEP (including the 12.5 kW_e Advanced Electric Propulsion System (AEPS) [Hall], the 6 kW_e BHT-6000 [Hall], and the 7 kW_e NASA’s Evolutionary Xenon [ion] Thruster (NEXT)), a suitably-mature high-power thruster does not presently exist. To this end, NASA has been investing in maturing Li-fed magnetoplasmadynamic (MPD) thruster technology, building upon an earlier demonstration[10] of 500 hours of continuous operation at a power level of 500 kW_e. The goal of the present effort is operation at a megawatt-electric for several thousand hours, with data acquired to demonstrate sufficient capability and lifetime for a Mars mission.

Terrestrial Nuclear Developments

In addition to the investments in space nuclear technologies, it would be an error of omission to not briefly mention recent activities focused on the development of terrestrial nuclear power systems. Many of the terrestrial nuclear activities and investments have been spurred by the development of HALEU-fueled small modular reactors (SMRs, also known as microreactors). The higher fuel enrichment for HALEU relative to large-scale terrestrial nuclear power plants enables reactor designs that can produce 10s of MW_e at a size that can fit on a large flatbed truck or in a rail car. While space nuclear reactors operate at temperatures that are higher than their terrestrial counterparts (whether they are large power plants or SMRs), the types of fuel, enrichment levels, and many of the processes and manufacturing techniques developed for the terrestrial application can be leveraged for in-space reactors. Terrestrial nuclear investments are growing the nuclear engineering and manufacturing workforce and expanding HALEU fuel production capacity, which can be leveraged in the development of HALEU-fueled space nuclear systems. Mass is always a key driver for space applications, and there are challenges to developing low specific mass space nuclear systems using HALEU fuel. Successful development of lower mass, higher temperature reactors will lead not only to success for in-space nuclear systems, but also result in improved terrestrial nuclear systems.

NUCLEAR TEST CAPABILITIES

Significant progress has been achieved over the past several years in maturing space nuclear systems. However, there still exists the need to perform component and system testing in the combined thermal, hydraulic, and nuclear irradiation environment for extended testing durations. Ground testing is required to quantify performance, demonstrate integrated system operations, and identify life-limiting mechanisms through post-test disassembly, detailed physical measurements, and post irradiation examination (PIE) of the test articles and all their constituent components. This strategy of ground testing and post-operation measurement and quantification will assure that the various generations of space nuclear propulsion systems will meet their performance and lifetime goals.

There were several nuclear ground test and evaluation capabilities employed in the past (1950s-1970s) during the NTP-focused Project Rover and NERVA programs and the NEP-focused SNAP program. However, most of those test capabilities and methods have since been either decommissioned or would likely not be permitted under current nuclear regulatory and licensing rules. What follows are descriptions of four specific types of nuclear test and evaluation capabilities that, if realized, would serve to permit the types of testing described above. These capabilities are aimed at accelerating technology maturation and allowing for regular and sustained testing cycles to develop and qualify new systems.

As a point of interest, while these capabilities represent significant capital investments, if designed and sized properly from the outset they will support the nations space nuclear development needs for the foreseeable future through multiple generations of system development. They could additionally support the growing test and evaluation needs of terrestrial SMRs.

Test Reactor for In-Pile Experiments

In-core (in-pile) nuclear testing of various reactor components can be employed to gain significant performance data and quantify long-duration effects before committing to the large investment of building complete nuclear propulsion system reactors. This method was employed in the early 1970s with the Nuclear Furnace 1 (NF-1) reactor,[11] permitting testing of full-sized nuclear fuel elements and other components that would be in-core in a space nuclear system.

The SNP program has employed numerous existing nuclear test facilities to perform in-pile testing of nuclear fuels, moderator materials, insulators, and assemblies that would comprise space nuclear systems. These include the Transient REActor Test (TREAT) facility at the Idaho National Laboratory, the MIT Research (MITR) reactor, and the reactor at The Ohio State University. While these have all produced valuable test data, none can match the thermal and nuclear conditions experienced in a nuclear propulsion system (most specifically an NTP system) for the full mission operating durations (up to an hour at a time for NTP systems, and multiple years for NEP systems). Therefore, a new test reactor (similar to NF-1) that has been termed Subscale Maturation of Advanced Reactor Technologies (SMART)[12] has been proposed as a means of subjecting reactor components and test articles to the combined thermal and nuclear effects they would experience in space nuclear applications, including long-duration testing and extremely fast startup and shutdown transients. A conceptual image of the SMART reactor is shown in Figure 6.

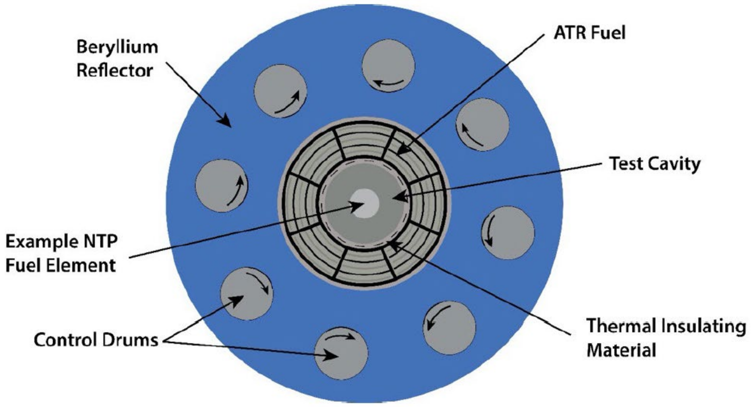

Figure 6: Conceptual cross-section of a driver core SMART facility (from Ref. [12]).

Nuclear Thermal Propulsion Engine Test Facility

Multiple nuclear reactors and engines were hot-fire tested in the Nevada desert during Project Rover and the NERVA program. The propellent in these tests flowed through the reactor and was exhausted into the open air. The present regulatory environment would likely preclude such ‘open-air’ testing of nuclear rocket engines, necessitating an NTP engine test facility requirement for the capability to capture the exhaust and scrub the gas stream to ensure the removal and safe sequestration of any radioactive materials.

There are multiple reasons why the full NTP engine should be tested on the ground. While the test reactor capability described in the previous subsection will permit significant and (relatively) low-cost throughput in evaluating multiple candidate materials and designs, the power densities in an NTP reactor are so high that the test reactor may not be able to match all the expected operational conditions. In addition, there are multiple issues that can only be tested through complete engine system testing, such as the integrated control and the response of an NTP reactor and the non-nuclear components that control the supply of propellant to the engine (turbopumps, valves, regeneratively-cooled nozzles). These systems must be tested to demonstrate controllability and reliability, to expose all the components and subsystems to the full combined environments that will be experienced during operation, and to qualify and certify engines for operation, much like any other pumped liquid-fed rocket engines.

Nuclear Power Reactor Testing Capability

Nuclear reactors for generating electrical power (for NEP, fission surface power on another planet or moon, or terrestrial microreactors on Earth) operate at very different conditions compared to the reactors for NTP systems. While the former operate at lower temperatures, they must do so for much longer durations (many years to decades compared to 30-60 min per NTP thrusting maneuver). The issues driven by this long-duration operation include much higher overall nuclear fuel burnup and exposure of all the components and subsystems to a high radiation fluence over the lifetime of a mission. Fully quantifying these effects requires new test cells to support long-duration and off-nominal testing of power reactors. Since each reactor test will likely last a significant length of time, it will be advantageous to have several test cells to support parallel reactor testing at power levels up to multimegawatts-electric.

Irradiated Nuclear Test Article Disassembly Facility

The final capability needed to support the other three listed in this section is a disassembly facility. After testing, whether as an in-pile experiment, an NTP engine test, or long duration nuclear power reactor experiments, the test article will be radioactive ("hot"). To perform a full engineering assessment and quantify the results of the test, the test article must be disassembled and evaluated. The irradiated components that require evaluation pose an obstacle to this proposition and must be disassembled in special "hot" cells with the disassembly performed using remotely-actuated tools and manipulators so as not to expose humans to harmful radiation. Once disassembled, the various constituent components of a test article can be distributed to labs across the country for detailed physical measurements and PIE.

While there are existing capabilities to disassemble "hot" components and systems, most of those cells either have test article size limits or they already contain and store other nuclear materials. The existing cells already storing materials from other tests typically have an upper bound on the amount of moderator material that can enter the cell and the HALEU-fueled space nuclear reactors presently under consideration contain levels of moderator material well above those limits.

One disassembly facility from the Project Rover/NERVA era still exists: the Engine Maintenance And Disassembly (EMAD) facility at the Nevada National Security Site. This long-neglected facility would require significant investment to make it operational, and it may be more pragmatic to use or modify a different facility (or construct a new facility) to perform "hot" disassembly operations. It should be noted for the record that the large concrete-walled hot cells in EMAD (the most important part of a disassembly facility) were inspected in the summer of 2024 and appear to still be in good condition.

CONCLUSION

The use of fission-based SNP systems enables missions that cannot presently be performed using conventional chemical propulsion systems. High-thrust NTP with double the specific impulse of the best chemical propulsion systems and low-thrust NEP with specific impulse values an order of magnitude greater than conventional systems offer complementary propulsion solutions for missions that cannot presently be accomplished. While there are advantages to both options, there may be additional advantages to employing NTP and NEP systems the same mission.

A generational approach to developing SNP systems yields a pathway to advance system maturity and address risk in a manageable fashion, with each generation representing a reasonable step-change in system capability that enlarges the overall set of missions that can be performed by space nuclear systems. There are many challenges to fielding operational systems, stemming from the fact that the operating envelopes for NTP and NEP systems are extreme in very different ways.

There are significant gaps currently being addressed regarding the development of candidate materials and components that can survive under these conditions. While some non-nuclear and nuclear test capabilities have been applied towards screening candidate materials and expanding the materials property database for a range of options, gaps still exist with respect to testing in the combined thermal-hydraulic, chemical, and nuclear environments present in SNP systems. The closing of these identified national nuclear test capability gaps and the production of data at all phases of development to support and validate predictive modeling capabilities will reduce development risk and lead to the qualification and certification of multiple generations of operational space nuclear propulsion systems.

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