

Future-Proofing Investments in US Development and Deployment of Advanced Nuclear Propulsion Technologies

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ABSTRACT

Space nuclear propulsion (SNP) technology was demonstrated over 55 years ago, with early designs performing at just under 900 seconds of specific impulse (I_{sp}). However, SNP technology is still in its infancy. Novel thermal propulsion and pulsed fission/fusion system design concepts have the potential to provide a large range of specific impulses up to 100,000 seconds. Turning advanced system concepts from ideas to hardware requires a dedicated research, development and testing program that not only develops fuels and materials but also provides test facilities that can prove the function, operation, lifetime and limitations of these components and subsystems under prototypic conditions. The Subscale Maturation of Advanced Reactor Technologies Testing (SMART) facility is a concept being considered that will test advanced fuels, materials, and components under prototypical conditions in order to measure performance and provide critical data for follow-on testing of full nuclear cores at the Engine Test Stand (ETS). Licensing for these nuclear tests in the modern era will have an impact on both the development schedule and deployment costs of advanced nuclear propulsion systems. Performance of the Exhaust Management System (EMS) will be critical in satisfying federal regulations to protect workers, the public, and the environment. As such, EMS technology is the backbone that will enable future testing in the biosphere. Like advanced fuels and materials, it will require a dedicated and strategic development path supporting aggressive and accelerated development and deployment of advanced nuclear propulsion systems to enable the United States' ambitious scientific exploration and national security goals.

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1. INTRODUCTION

Chemical rocket engine testing has been ongoing for decades. With each new generation of engine, analytical capabilities—driven by an expanding knowledge base—have advanced so that today's chemical engines achieve qualification in fewer tests than their predecessors. While numerous reactor and engine prototypes were ground-tested during Rover/NERVA, only one integrated engine system (XE Prime) approached flight-representative operations. Although this accomplishment was significant, it was more than 50 years ago and testing ceased before full qualification¹.

NASA's Space Nuclear Propulsion (SNP) Office aims to revolutionize space travel by developing and demonstrating higher performance propulsion systems to achieve the agency's ambitious science and exploration goals. Developing advanced nuclear propulsion systems is key to NASA's Moon to Mars vision

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and exploration of the outer solar system. Higher performance propulsion systems also support national security strategic advantage by providing rapid response capabilities and more efficient movement of assets in space.

The potential nuclear propulsion technology landscape in the region of high engine thrust to weight ratios, shown in Figure 1, is vastly unexplored experimentally and includes a variety of potential technologies, most of which are envisioned to be based on fission reactions, including thermal rockets with solid, liquid, and gas cores, as well as pulsed fission/fusion and bi-modal systems. Within each of these categories are a variety of technology options and implementations, some of which are yet to be discovered let alone developed. Most of these potential systems are categorically unproven technologies, except for a few solid core designs that were developed and tested during the Rover/NERVA program, which demonstrated specific impulse (I_{sp}) of nearly 900 seconds¹. Other solid fuel options have been under some level of development and testing to the present day and will provide incrementally higher thrust to weight ratios and better economics. Advanced thermal propulsion and pulsed fission/fusion system design concepts have the potential to provide a large range of specific impulses, potentially up to 100,000 seconds.

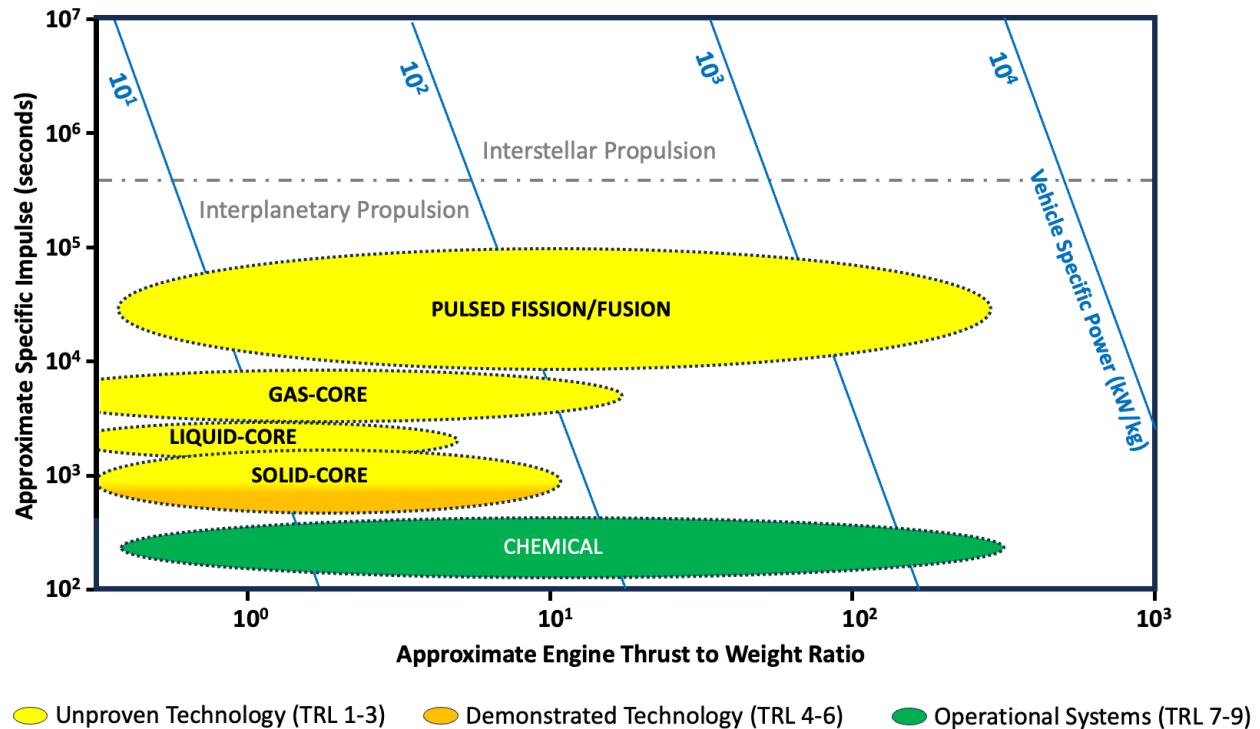


Figure 1. Potential nuclear propulsion technology landscape.

2. NUCLEAR PROPULSION TECHNOLOGY DEVELOPMENT AND INFRASTRUCTURE STRATEGY

The SNP Program Office plans to continue advancing nuclear propulsion technology through an optimized “building block” strategy. This structured and strategic approach aims to maximize efficiency, innovation, and technical readiness while leveraging modular development principles. Such an approach enables flexibility, scalability, and reusability across multiple applications and technologies—an approach proven effective during the Rover/NERVA program¹.

Future infrastructure development efforts can be viewed as a continuation and modernization of the Rover/NERVA program. Although the program was canceled in 1972 prior to a prototype flight test, several NTP (Nuclear Thermal Propulsion) designs based on highly enriched uranium fuels achieved a technical readiness level (TRL) of 6 relative to solid-core performance goals established in the 1960s and 1970s. Rover/NERVA generated a robust data foundation still relevant for modern system designs, which will utilize lower enrichment fuels, but also provides a valuable model for infrastructure development strategies for developing advanced fuels and technologies. A key realization near the conclusion of the Rover/NERVA effort was that cost and risk of full-scale reactor construction and ground testing can be reduced through earlier testing of full-length fuel elements under representative conditions. This experience strongly informs today's strategic emphasis on subscale and component-level validation before committing to full-scale engine development.

The continued maturation of nuclear propulsion concepts from laboratory-scale technologies to full demonstration requires substantial investment in novel nuclear testing infrastructure capable of advancing TRLs from 4 through 6. Among candidate systems, nuclear thermal solid-core propulsion remains the most mature option for potential early opposition-class human Mars missions. However, no existing facilities can currently provide prototypic conditions for representative mission durations or testing cadences—whether for individual NTP fuel, reflector, insulator, or moderator elements, or for integrated reactor systems. To address this critical capability gap, the Subscale Maturation of Advanced Reactor Technology (SMART) and Engine Test Stand (ETS) facilities are being considered as cornerstone infrastructure investments for developing and deploying the next generations of nuclear propulsion technologies. The role of SMART is to advance fuel and materials development from TRL 4 through TRL 5 (prototypic power densities, and hydrogen flow) and provide critical data for construction and testing of full-size cores at ETS, similar to the mission space that the nuclear furnace was designed to fulfill at the end of the Rover/NERVA program.

Modern nuclear propulsion testing infrastructure must be designed to safely and effectively to 1) assemble, fuel, and operate nuclear propulsion test articles, 2) measure thrust, temperatures, pressures, radiation, and effluent compositions accurately, 3) contain or mitigate radiological and chemical releases, 4) handle, cool, and store nuclear materials and activated components, 5) provide safe operating environment for personnel safety, and 6) support post-test disassembly, inspection, and waste management. As nuclear propulsion evolves towards reactor systems operating at higher temperatures, including advanced designs such as a centrifugal nuclear thermal reactor, liquid core reactor, or gas core reactor (capable of obtaining 2000-5000 s I_{sp}), test facilities will potentially require increased Exhaust Management System (EMS) capabilities as more fuel, fission products and other materials are more likely to be in the hydrogen exhaust and must be captured and maintained in a deeply subcritical state. As core power densities in advanced systems increase, the danger of melting core components is more likely. Operation of reactor cores at higher power densities will also result in higher production rates of radioisotopes. The EMS and supporting nuclear facility infrastructure must also be designed to mitigate these unique extreme maximum hypothetical accidents and provide data to support advanced systems development and testing.

The timeline for deploying advanced nuclear propulsion systems remains speculative. Continued progress in solid-core technology is essential to ensure that emerging infrastructure can fully support ongoing development within that domain. At the same time, advanced propulsion concepts such as high-temperature or alternative reactor architectures must be considered in the design of SMART and ETS facilities. Although the availability of these next-generation systems is uncertain, their maturation is likely to occur within the anticipated operational lifetimes of these facilities. The development path for the EMS is critical for enabling tests of increasingly advanced nuclear propulsion systems. Achieving regulatory approval for these tests will require state-of-the-art modeling and simulation capabilities as well as high-quality experimental data to validate those models. The SMART facility provides a sub-scale testing environment that matures reactor components while also maturing the EMS, offering the ability to generate the targeted data needed to support licensure and accelerate the development of EMS technology. Designing

infrastructure to be inclusive and adaptable from the outset and/or with modularity and extensibility will accelerate the transition to advanced technologies while minimizing the need for future, technology-specific capital investments.

3. LICENSING

The advanced nuclear propulsion testing infrastructure will be combining reactor-grade nuclear safety with advanced rocket-engine-grade performance testing – two disciplines that have never coexisted in the modern licensing era. Any facility or test that uses special nuclear material or produces a fission chain will trigger oversight by national nuclear authorities, such as Department of Energy or the Nuclear Regulatory Commission. Obtaining a license to operate or to test a reactor is complex, multi-year, and requires detailed safety analyses. Key aspects of meeting these requirements are ensuring control of reactivity and containment of radioisotopes. In addition to nuclear safety reviews, federal-level environmental assessments are required under the National Environmental Policy Act for any major federal action that may significantly affect the environment. The preparation of an Environmental Impact Statement (EIS), including public comment periods and alternatives analyses, can extend program timelines by several years and often impose substantial mitigation or design constraints, particularly when evaluating iterative or evolutionary designs.

Regulators will require bounding analyses of worst-case, or “maximum hypothetical” accidents scenarios. Demonstrating that potential accident consequences are acceptably low is both challenging and costly, particularly for novel systems that operate under unique conditions not addressed by existing nuclear test facility precedents. Among all safety systems, the EMS will receive tremendous scrutiny during licensing given their unique and onerous operational requirements – up to gigawatt-scale cooling, full fission product species capture, up to full core relocation capture, hydrogen containment and compatibility, no pressure buildup, radiation resilience, thermal shock resistance, withstand high erosion, have a compact format, and be serviceable. Any design shortcomings and uncertainties will likely result in administrative or operational restrictions imposed through the facility’s licensing basis. Such constraints would directly affect testing scope, cadence, and throughput, thereby influencing overall program timelines and deployment readiness.

The conceptual “holy grail” EMS would be a perfect, regenerative, zero-leak, gigawatt-class exhaust capture system capable of converting nuclear rocket exhaust into harmless gas while maintaining subcriticality even following a molten-core relocation event. The successful realization of such a system would be transformative - it would enable full-power ground testing of any advanced propulsion concept, streamline the regulatory process, dramatically reduce development timelines from decades to years, and render nuclear propulsion both politically and environmentally acceptable for sustained long-term advancement.

4. EFFLUENT MANAGEMENT SYSTEM DEVELOPMENT

The EMS represents the core enabling technology for conducting safe, licensable ground testing of nuclear propulsion systems. Its performance will determine the ability to operate full-power nuclear propulsion reactors within the biosphere while meeting regulatory, safety, and environmental protection standards. Developing a gigawatt-class, regenerative, zero-leak EMS capable of maintaining a deeply subcritical configuration is a complex, multidisciplinary challenge that requires a structured, risk-informed approach, which includes an incremental development strategy that significantly benefits from subscale prototypic testing at SMART.

Any system designed to treat the exhaust from a solid core SMART or NTP ground test reactor must perform five basic functions.

- Initial cooling of the hot reactor exhaust to temperatures compatible with normal engineering materials.
- Filtering and retainment of any debris and large particulate ejected from the core.
- Intermediate cooling to temperatures at or below atmospheric.
- Fission-product retention of small particulates, halogens, and noble gases to prevent uncontrolled release of contaminants to the environment. Current designs use a multi-stage process to filter and decontaminate radioactive core coolants. Key components can include centrifuges for separating solids, specialized filters, and ion exchange resins, cryogenic distillation and holdup tanks and to remove radioactive particles and allow for short lived radioactive decay.
- Waste stream processing to properly handle retained fission products, cleaned or processed hydrogen effluent and any other potentially contaminated fluids generated by the system.

The long-term vision for the EMS should be a modular, regenerative design capable of supporting repeated testing campaigns across multiple propulsion technologies. Modularization will permit parallel development of thermal rejection, filtration, condensation, and isotope capture subsystems, while regenerative operation—enabled by replaceable or clean-in-place components—would ensure rapid turnaround between tests. A system that can maintain a deeply subcritical configuration following any credible failure scenario will be key to meeting licensing expectations and enabling long-duration, high-power nuclear propulsion testing.

The most effective path forward in developing effluent management systems follows a phased “building block” development strategy, consistent with the broader SNP program approach. The EMS design process begins with conceptual design and analytical modeling to establish bounding thermal, radiological, and chemical requirements for the system. During this initial phase, advanced computational fluid dynamics, neutronic, and chemical transport models are developed and used to explore design options and down-select viable system configurations and materials. These analyses define the foundational parameters for follow-on experimental testing and licensing evaluations.

Integration of the EMS development into a robust systems engineering and regulatory framework is an essential first step. The use of physics-based and model-based systems engineering tools will ensure continuous traceability between functional requirements, performance verification, and regulatory compliance. The development of a formal Functional Requirements Document aligned with regulatory safety standards provides a clear baseline for design verification and validation. In parallel, detailed design-basis accident and beyond-design-basis accident simulations should be performed early and throughout the design cycle to identify bounding conditions and to guide system architecture development, advanced simulations development, and facility safety planning.

The second phase focuses on subscale subcomponent non-nuclear experimental testing to validate thermal-hydraulic and particulate capture models. In this phase, researchers can construct bench-scale components to study hydrogen compatibility, heat transfer, gas–solid interactions, candidate materials, filtration media, chemical processes, and flow-handling components can be evaluated safely and cost-effectively. Data generated during this phase are used to calibrate and refine the computational models, reduce design uncertainties, and identify any failure modes or operational limits. This iterative coupling of analysis and experiment enables progressive and cost-effective maturation of EMS subsystems and provides a foundation in the formulation of credible safety bases and licensure documentation for subsequent scale-up testing.

The third phase involves assembling laboratory-scale EMS prototypes comprising representative condensers, filters, heat exchangers, and containment hardware. These systems must demonstrate stable heat rejection and high-efficiency capture performance under variable and controlled flow and temperature conditions. The data collected in this phase will further validate advanced codes at the integrated system scale and provide insights into further technology, hardware, and simulation development.

Once the design's basic functionality and reliability have been established, limited radiological testing becomes appropriate. In this fourth phase, small-scale radioisotope or fission-product surrogate testing may be conducted. These experiments will be used to further verify EMS performance and validate simulations for development and licensing considerations.

SMART operates at roughly an order of magnitude smaller scale than the ETS and represents a tremendous opportunity for generating experimental data to support ETS licensing. By validating computational models, scaling relationships, and subsystem interactions under prototypic conditions, SMART enables extrapolation of system behavior to full-power ETS operations. The SMART facility enables testing of key components such as fuel elements, exhaust management systems, containment structures, and remote handling procedures, providing evidence of safe and reliable operation. Additionally, materials performance, hydrogen compatibility, and fission-product capture can be assessed in a controlled, subscale ETS environment, informing safety analyses and bounding assumptions for ETS licensing. While SMART cannot replicate the full core power density or total fission-product inventory of ETS, the experimental results, combined with conservative scaling and advanced modeling and simulations, provide a robust foundation for demonstrating compliance with regulatory licensing requirements. In this way, SMART serves as another opportunity, possibly essential, in supporting the maturation of advanced nuclear propulsion technology while mitigating cost, schedule, and regulatory risk prior to full-scale ETS operations.

Throughout this process, parallel (nuclear materials and components) qualification efforts must be maintained. The EMS architecture will be exposed to extreme environments involving high-temperature hydrogen flow, fission product chemistry, radiation damage, and transient loading. Candidate materials such as refractory metals (molybdenum, niobium, tantalum) and ceramic composites (silicon carbide, zirconium carbide) should be investigated for corrosion resistance, hydrogen embrittlement tolerance, and long-term durability. In parallel, getter materials and adsorbents capable of capturing cesium, iodine, and noble-metal species must be developed and tested. Components such as heat exchangers and filters will require rigorous evaluation for erosion, corrosion, and thermal shock resistance to ensure operational longevity and serviceability.

The final phase of development is the licensing-grade qualification effort, in which the accumulated design and test data are integrated into a safety case suitable for regulatory review. This phase includes preparation of probabilistic risk assessments and bounding analyses of design-basis and beyond-design-basis accidents using validated advanced simulations. The resulting safety documentation will support the licensing and operational authorization of the EMS and nuclear propulsion test facilities.

The EMS development effort will almost certainly require strong interagency and commercial collaborations, including appropriate investment strategies. A joint partnership between US agencies and industry would allow the program to leverage the existing expertise and test infrastructure across the complex. Early deployment of subscale modules can accelerate operational data collection before sub-scale commissioning at SMART. Performance data collected at SMART can then be used to license the full-scale system at ETS. Lessons learned and technologies from adjacent sectors—such as hydrogen management, fusion exhaust handling, tritium containment, and rocket-engine effluent management—will further inform design refinements and future risk reduction strategies.

In summary, the development and evolution of the EMS must proceed expeditiously through disciplined, sequential, and collaborative engineering supported by targeted materials research and early regulatory engagement. By combining rigorous systems engineering and advanced simulations, advanced materials development, and an integrated testing and licensing strategy, the United States will have an opportunity to establish the exhaust management capability required to safely and responsibly demonstrate advanced nuclear propulsion within the biosphere for decades to come. The EMS will therefore serve not only as a cornerstone technology for the SNP Program but also as a critical enabler of the nation's long-term scientific exploration and national security objectives.

5. CONCLUSIONS

Designing, testing, and launching SNP systems requires tight coordination and communication within and across many government agencies, laboratories, and industrial partners. Well defined responsibility and authority will need to be centralized in order to effectively lead and manage all aspects of the space reactor propulsion development, including test and research facilities, and planning for the extensibility of technologies and systems to more advanced concepts will be essential for a successful long-term program.

Construction and operation of new nuclear propulsion testing infrastructure requires uniting the disciplines of reactor testing, rocket engine testing, and radiological safety within a single facility—something no existing site has achieved under modern licensing requirements. Both SMART and the ETS will depend on a robust EMS development program that can support current, near-term, and next-generation fission-based propulsion concepts. Early engineering decisions regarding SMART and ETS designs, facility interfaces, and site layout will have significant implications for EMS performance, cost, and regulatory approval, and thus must be addressed with urgency.

Licensing nuclear propulsion tests under contemporary regulatory frameworks will strongly influence development timelines and the overall deployment cost of advanced propulsion systems. The EMS will be central to meeting federal requirements that protect workers, the public, and the environment. As such, EMS technology development forms the backbone of safe nuclear propulsion testing within the biosphere for decades to come. Like advanced fuels and materials, it requires a coordinated, strategic, and well-resourced development pathway to support the aggressive schedules associated with the United States' scientific exploration priorities and national security objectives for the foreseeable future.

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