BNL-223718-2022-JAAM

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To be published in "Progress in Nuclear Energy"

November 2022

Nuclear Science and Technology Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC), Nuclear Physics (NP) (SC-26)

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Subscale Maturation of Advanced Reactor Technologies (SMART): a path forward for nuclear thermal propulsion fuel and reactor development

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Abstract

Nuclear Thermal Propulsion (NTP) systems are actively being developed for future crewed missions to Mars. NTP systems excel in missions where both high thrust and high specific impulse are required, but modern NTP systems currently do not have a Technology Readiness Level (TRL) high enough for use in crewed space exploration. TRLs are used to demonstrate the level of rigor with which a component/system has been tested/demonstrated for its intended use. While space systems technology in general must be qualified as a unit, nuclear technology must be first demonstrated to meet qualification level requirements both at the fuel (component) level and the reactor (subsystem) level. In this paper, historic NTP development programs are surveyed to identify a testing and development strategy that can be effectively implemented to allow for NTP reactor development. Based on this strategy, required facilities to enable such activities are identified. Current domestic experimental capabilities to support NTP qualification are limited to separate effects testing of individual components. Separate effects testing is found extensively in historic NTP development efforts but is not sufficient for full fuel and reactor qualification. Combined effects testing allows for an accurate assessment of fuel performance but is not achievable for NTP conditions in existing facilities. Assessment of historic development programs suggests that an intermediate, subscale test facility is necessary to advance NTP TRLs. A solution to meet this need is proposed, namely the Subscale Maturation of Advanced Reactor Technologies (SMART) facility. SMART will mitigate risk to NTP development by enabling performance and reactor physics demonstrations of NTP subsystems. A SMART facility could be built by modifying existing nuclear test facilities, which may potentially enable schedule and cost savings. To pursue reactor qualification beyond the subscale, a new ground test facility will be necessary. This ground test facility should be developed concurrently with SMART to allow for the facility to be operational in time for expedited NTP engine demonstration.

Keywords

Nuclear Propulsion, Nuclear Fuels, Nuclear Reactors, Technology Readiness Level, Qualification, Experimental Testing

List of Figures

List of Tables

Nomenclature/Abbreviations

NASA – National Aeronautics and Space Administration

SNP – Space Nuclear Propulsion program

DOE – United States Department of Energy

NTP – Nuclear Thermal Propulsion

NERVA – Nuclear Engine for Rocket Vehicle Application program

MW_{th} – Megawatts of thermal power

HEU – Highly Enriched Uranium

HALEU – High Assay Low Enriched Uranium

TRL – Technology Readiness Level

SMART – Subscale Maturation of Advanced Reactor Technologies

US – United States

USSR – Union of Soviet Socialist Republics

NNSS – Nevada National Security Site

ANL NR – Argonne National Laboratory Nuclear Rocket program

GE 710 – General Electric 710 program

SNPO – Space Nuclear Propulsion Office

Cermet – Ceramic-Metallic composite

Cercer – Ceramic-Ceramic composite

SNTP – Space Nuclear Thermal Propulsion program

SEI – Space Exploration Initiative

AEC – United States Atomic Energy Commission

NF – Nuclear Furnace

NRX – Nuclear Reactor Experimental

XE – Experimental Engine

RIFT – Reactor In-Flight Test

WEMU – Weight and Envelope Mockup

ICBM – Intercontinental Ballistic Missile

NRTS – National Reactor Test Station

TREAT – Transient Reactor Test facility

PBR – Particle Bed Reactor

SDI – Strategic Defense Initiative

USAF – United States Air Force

SNL – Sandia National Laboratories

ACRR – Annular Core Research Reactor

PNT – Particle Nuclear Test

PHT – Particle Heating Test

LEO – Low Earth Orbit

GSO – Geosynchronous Orbit

NET – Nuclear Element Test

PIE – Post-Irradiation Examination

NEPA – National Environmental Policy Act

ATR – Advanced Test Reactor

NRTS – National Reactor Test Station

1. Introduction

The National Aeronautics and Space Administration's (NASA's) Space Nuclear Propulsion (SNP) project, in partnership with the United States Department of Energy (DOE), is actively developing Nuclear Thermal Propulsion (NTP) technologies for future crewed missions to Mars. In an NTP system, thrust is provided to the spacecraft by pumping a propellant through a reactor core, where the heat from fission in the fuel is transferred to the propellant. Once the propellant is heated to a sufficiently high temperature (> 2500 K) the propellant is expanded and accelerated out a rocket nozzle. NTP systems have a long history of testing and development, with the most extensive efforts undertaken in Project Rover and the Nuclear Engine for Rocket Vehicle Application (NERVA) program (Rover/NERVA) (Borowski et al., 2012). Rover/NERVA demonstrated reactor operations and component level performance under the operating conditions with a flowing high temperature (T > 2500 K) hydrogen propellant under various reactor power levels (5 – 4,000 MW_{th}), thereby demonstrating NTP feasibility and validating modelling approaches (Robbins and Finger, 1991). The NTP engines produced by the end of this program performed well, with thrust-to-weight ratios (0.01-30) (Sutton and Biblarz, 2001) comparable to that of chemical rockets and specific impulses (efficiency of generating thrust) at least twice as high (841 – 1000 s). While NTP systems' specific impulse is much lower than electric propulsion systems, electric propulsion systems produce very low thrust comparatively and are designed for different applications (Black and Gunn, 2003).

NTP systems are attractive candidates for missions where both high thrust and high specific impulse are required, such as deep space transit missions to Mars and beyond (Houts and Mitchell, 2016). Although these systems have received considerable development historically, historic reactor concepts were designed using Highly Enriched Uranium (HEU) fuels, which is a weapons-grade enrichment (93 weight percent Uranium-235) and thus are considered by some to be a nuclear non-proliferation concern. Current U.S. policy limits NTP reactor fuel designs to High Assay Low Enriched Uranium (HALEU) whenever technically feasible, which limits Uranium-235 enrichment to less than 20 weight percent (wt%) (Office of the Secretary, Department of Energy, 2020). HALEU fuels have the potential for much less risk from a non-proliferation standpoint (Lal and Locke, 2021) (Office of the Secretary, Department of Energy, 2020). Because of this shift, recent studies have shown historical fuel and material systems would need modification to enable criticality of the reactor system under the desired performance attributes for modern missions (Eades et al., 2015) (Patel et al., 2016) (Venneri and Kim, 2017) (Poston, 2018). Additionally, new manufacture technologies and modern materials development activities may enable the manufacture of new fuels or materials technologies which may have more attractive material or high temperature properties for NTP applications (O'Brien and Jerred, 2013) (Webb and Charit, 2014) (Ang et al., 2019) (Raftery et al., 2021) (Mireles et al., 2021). Due to required changes to the material systems, experimental results from historical programs are not necessarily directly transferable to modern designs. By significantly modifying historic designs or introducing wholly new designs which have not yet been demonstrated, the overall Technology Readiness Level (TRL) may be lower than that demonstrated in historic programs, when assessing the maturity of NTP systems for use in modern missions. Therefore, it is anticipated that modern NTP reactor designs will require additional technology development and demonstration prior to a reactor-engine demonstration.

As shown in Figure 1, NASA's TRLs are meant to demonstrate the level of rigor with which a component or system has been tested for its intended use (Mankins, 1995). Qualification of a system/subsystem/element for use by NASA is the process of evaluating this system/subsystem/element of its ability to perform its intended function for a mission within its intended operating environment (Frerking and Beauchamp, 2016) (Mankins, 2009). In this way, the TRL scale is a useful way to break down this process into incremental development tasks. Despite its utility however, the TRL system has been inconsistently applied throughout its decades of use, necessitating carefully defined definitions to qualification for each TRL step in order to use the system effectively for specific technologies (JANNAF Spacecraft Propulsion Subcommittee, 2019). Since TRL definitions are not explicitly defined in the context of NTP reactor development, required testing conditions or technology development tasks to improve NTP reactor subsystem maturity beyond the conceptual stage are not well defined.

At this point, an important distinction must be made between typical space systems qualification and NTP reactor qualification: while space systems technology must be qualified as an entire integrated system to satisfy TRL 8 or greater, nuclear technology is typically qualified in several steps with increasing complexity (Kimmel et al., 2020) (Department of Energy, 2011). These steps include fuel qualification, i.e. the "demonstration that a fuel product fabricated in accordance with a specification behaves as assumed or described in the applicable licensing safety case, and with the reliability necessary for economic operation of the reactor plant", followed by reactor operations and system level qualification (Crawford et al., 2007).

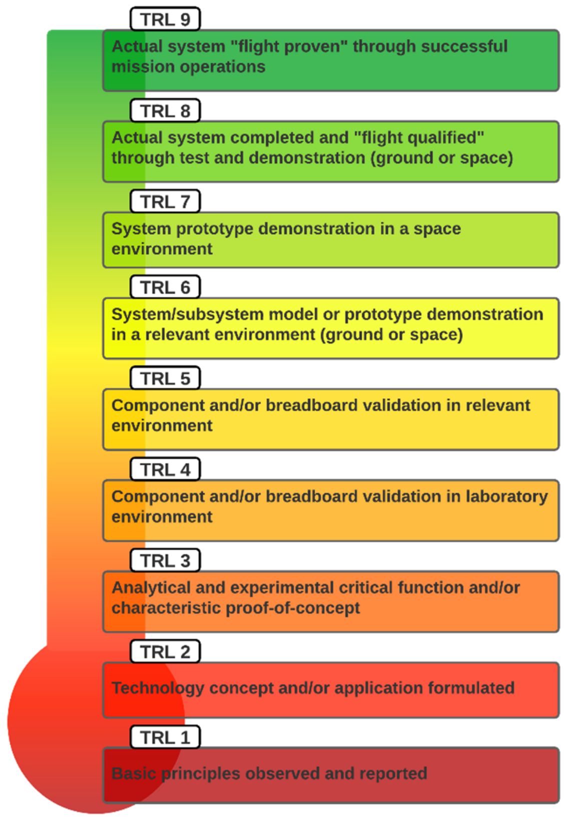

Figure 1: NASA's TRL meter with descriptions of each level, as recreated from the original (Mankins, 2009)

In this survey, historic nuclear propulsion development programs are reviewed to identify the primary technical risks related to reactor development, as well as the key testing activities and test conditions recommended for improving reactor readiness ahead of an integrated system (reactor-engine) prototype demonstration (TRL 6). Presented in this paper is a summary of historic NTP reactor testing programs, assessment of task interdependencies and a recommended set of baseline reactor testing tasks for modern NTP development programs, as well as a preliminary assessment of related facilities requirements to enable such testing. Since TRLs 1 and 2 are for basic technology research, this study focused on identifying the activities for advancing NTP reactor subsystem and component TRLs in the 3 – 6 range. Previous surveys of NTP literature have primarily focused on NTP fuel maturation approaches and qualification needs prior to reactor testing (Werner et al., 2019) (Howard et al., 2017) (Palomares et al., 2020). While fuel maturation approaches are included in this survey, this assessment focuses on reactor subsystem maturation, including non-fuel component development activities and reactor testing program objectives that reduce the most risk prior to an integrated reactor-engine demonstration test.

2. Background

Through past historic NTP development programs, there has been considerable effort devoted to developing a testing program which can effectively mature nuclear fuels and reactors for an NTP system. Since the 1950s, there have been five major historic nuclear thermal propulsion programs for in-space and terrestrial aerospace propulsion: Rover/NERVA (1955 – 1973), Pluto (1957 – 1964), the General Electric 710 Gas Reactor (1962 – 1968), the Argonne National Laboratory Nuclear Rocket (1963 – 1966), and Space Nuclear Thermal Propulsion (1987 – 1994). Table 1 summarizes the major findings of the historic nuclear propulsion literature review, with programs presented in chronological order by program start date. None of these programs yet demonstrated a NTP reactor matured to the readiness desired for mission implementation, however significant progress in understanding underlying physics and reactor sub-system level performance was achieved. A summary of each program is included in the following paragraphs and the following sections include a review of each program's testing program for NTP reactor development.

Table 1: Summary of historic NTP programs and their accomplishments, with TRLs determined based on accomplishments

Program Name	Program Duration	System Description and Target Key Performance Parameters	Program Cost (2021 US Dollars)	Major Achievements	Readiness at Cancellation
NERVA/Rover	1955–1973	HEU (U, Zr)C, Graphite Moderator (cercer) Target: 200,000/75,000 lbf, 2361 K chamber temperature, 3.103 MPa chamber pressure, 825 s Specific Impulse	$8.82B (assumes total budget spent during 1973, $11B if median year, 1967, used instead)	200,000 lbf (4100 MW_{th}, Pewee), 55,000 lbf (XE-Prime), 6540 s at full power (NF-1), 2750 K chamber temperature (Pewee), 3.8 MPa chamber pressure (XE-Prime), 31.8 kg/s flow rate (Kiwi-B4E), 848 s Specific Impulse (Pewee)	Reactor Readiness: TRL 6 (multiple reactor ground tests, near prototypic) Fuel Readiness: TRL 6 (extensive fuel ground tests, near prototypic) Key Remaining Challenges: Demonstrating operation and corrosion resistance with multiple restarts at full power, pressure and flow rate
Pluto Program	1957–1964	HEU UO_2 homogenously mixed with BeO Target: 485 MW_{th}, 35,890 lbf, 11,542 s mission operation, 1642 pulses/s airflow rate (Mach 2.8, 3.05 km above sea level conditions), 1550 K chamber temperature	$2.28B	485 MW_{th}, 37,900 lbf, 303 s at full power, 1660 pulses/s, 1566 K chamber temperature (Mission operation length assumes 11,000 km trip to missile target at constant Mach 2.8)	Reactor Readiness: TRL 6 (reactor ground test, near prototypic) Fuel Readiness: TRL 6 (fuel tested at prototypic conditions) Key Remaining Challenges: Demonstrating rapid start-up, automatic control rod operation at operating conditions, demonstrating operation for entire mission duration
GE 710 program	1962–1968	HEU W-UO_2 cermet elements, Ta-W-Hf cladding Propulsion system Target: 3073 K fluid temperature, 33,000 W/cm^3 fuel power density, 10-hour operating lifetime Brayton power system Target: 1473 K fluid temperature, 17,000 W/cm^3 fuel power density, 10,000-hour operating lifetime	$117M	0.872 MW_{th}, 121.67 hours at full power, 1811 K chamber temperature Static out of pile: 12,072 hours, 1922 K Flowing (dynamic) out of pile: 8,005 hours, 1922 K In pile: 8,500 hours, 1811 K	Reactor Readiness: TRL 4 (full reactor never tested, but constituent elements tested) Fuel Readiness: TRL 5 (fuel elements extensively tested in near prototypic environment) Key Remaining Challenges: Demonstration of fuel bundles at prototypic conditions in-pile
ANL's Nuclear Rocket program	1963–1966	HEU W-UO_2 cermet, Be reflector, Inconel pressure vessel Target: 200 MW_{th} reactor, 10,530 lbf engine, fission product loss (in clad) <1%, 821 s Specific Impulse, 2507 K chamber temperature	Unknown	Out of pile: 49 hours at full power, 2973 K chamber temperature Flowing (dynamic) out of pile: 12 hours, 40.3 kW, 2723 K; 6 min, 613 kW, 2543 K (heater failed in both small and large loop) In pile: 180 MW_{th}, 3 s at full power, 3023 K chamber temperature	Reactor Readiness: TRL 3 (reactor designed but not tested) Fuel Readiness: TRL 5 (fuel elements tested in a relevant, near prototypic environment) Key Remaining Challenges: Testing of full fuel elements at prototypic conditions, testing fuel bundles at prototypic conditions
Space Nuclear Thermal Propulsion program	1987–1994	HEU UC_2 particles coated with pyrolytic C and ZrC (particle bed reactor) Target: 40,000 lbf, 1000 MW_{th}, 40 MW/L, 3000 K chamber temperature, 600 s at full power, 3 starts	$373M	In pile: 3000 K, 600 s at full power (particles failed) 1.5 MW/L, 2300 K outlet temperature, 2 cycles (hot frit cracked)	Reactor Readiness: TRL 3 (design finished but no full scale experiments finished) Fuel Readiness: TRL 5 (fuel concept evaluated, prototypic conditions elusive) Key Remaining Challenges: Successful prototypic testing of partial and full fuel elements, fuel assemblies and engine subsystems

The Rover/NERVA program first began at Los Alamos National Laboratory under the name Project Rover. Rover/NERVA was the most significant NTP system development program yet conducted, running mostly concurrently with the Space Race efforts of the United States (US) and Union of Soviet Socialist Republics (USSR) (Finseth, 1991). Through the ground testing of multiple reactor series (Kiwi, Phoebus, Pewee, Nuclear Furnace) and reactor-engine series (NRX, XE) (Arnold Jr., 1965; Holman and Pierce, 1986; Rice and Esselman, 1967; Schroeder, 1968), Rover/NERVA produced many full scale engine tests demonstrating NTP reactor feasibility and confidence in operation of the designs.

Beginning around the same time, the Pluto program was a demonstration program for reactor-propelled cruise missiles (Carniglia, 1958). Although a different application than space exploration, Pluto can be considered a precursor effort to many of the NTP programs that followed. The Pluto program was led by the Lawrence Livermore National Laboratory, and culminated in the demonstration of a full scale reactor at full power at the Nevada Test Site (now the Nevada National Security Site, NNSS) (Nuclear Propulsion Division Staff, 1964).

Subsequently, the Argonne National Laboratory Nuclear Rocket (ANL NR) program and the General Electric 710 Gas Reactor (GE 710) program began within similar timeframes with the goal to develop a reactor for space (Nuclear Energy Division, 1968a) (Argonne National Laboratory, 1968). Both programs were funded through the same office as Rover/NERVA, a joint NASA/Atomic Energy Commission (AEC) endeavor called the Space Nuclear Propulsion Office (SPNO). Because of this, they can be thought of as sister, or feeder, programs to the Rover/NERVA program. Both programs focused primarily on materials development, specifically the development of ceramic-metallic (cermet) composite fuel forms, as an alternative to the graphite-based Rover/NERVA fuel. GE 710 succeeded in developing a manufacturing process for full-size cermet fuel elements, and tested fuel elements in a radiation environment and both flowing and static gas environments (Nuclear Energy Division, 1968b). ANL NR achieved several transient irradiation tests in addition to long, high temperature exposures to flowing hydrogen (Argonne National Laboratory, 1968). Due to the nature of these programs being focused on individual fuel elements, both programs produced articles with lower TRLs than Rover/NERVA at program culmination. However, each managed to produce significant results towards fuel qualification despite lower operating budgets, through effective use of separate effects testing through thermal cycling/irradiation.

The US Department of Defense began to take interest in NTP again in the late 1980s, eventually leading to the Space Nuclear Thermal Propulsion (SNTP) program (Haslett, 1995). The program, codenamed Project Timber Wind, was initially envisioned for a missile intercept rocket's highest stage (Lieberman, 1992). Timber Wind was later renamed the SNTP program after expanded interest in space applications under NASA's Space Exploration Initiative (SEI) (McCurdy, 1992). Preliminary irradiation testing was performed on both fuel particles and the cylindrical frits that would hold them, but both experienced material failures unresolved before program closure. Additionally, a ground testing facility for full sized fuel elements and subsystems was planned (Beck et al., 1993), but changing priorities led to program cancellation before construction on such a facility had begun.

Several modern NTP development efforts have been led by NASA, including those under SEI and the more recent SNP project (Ballard, 2019, 2007; Houts et al., 2012a, 2012b). Most of these modern efforts have focused on knowledge recapture or modification of historic NTP fuel and reactor designs. However, more recent programs have begun assessing the use of new and novel materials technologies to enable improved performance and reactors which require lower fuel enrichments. No modern NTP development program has yet reached the readiness to be able to assemble and ground test an NTP reactor (subscale or full scale).

2.1. Rover/NERVA Program

The Rover/NERVA program (1955-1973) was the most extensive effort thus far to develop an NTP rocket engine. The reactor's development began at Los Alamos Scientific Laboratory (now Los Alamos National Laboratory) under the name Project Rover, and was rolled into NERVA in 1961 with the expansion of resources and interest from NASA (Finseth, 1991). NASA split management of the program with the US AEC, the precursor to the US Department of Energy, under the SNPO. The primary contractors for the NERVA project were Westinghouse (for the reactor) (Westinghouse Astronuclear Laboratory, 1972) and Aerojet-General (for the engine and turbomachinery) (Aerojet-General Corporation, 1970a). While the SPNO also pursued fuel and reactor development for NTP under the ANL NR and GE 710 programs, the Rover/NERVA program was the mainline program for Apollo-era development of in-space NTP systems.

The Rover/NERVA program consisted primarily of three ground reactor test campaigns under the Rover project and engine-reactor development under the NERVA project (Figure 2). The Rover ground test reactors included the Kiwi (A1 & A3, B1 A & B, B4 A – E and TNT), Phoebus (1 A & B and 2), and Pewee-1, tests which demonstrated the feasibility of NTP reactor operations with a hydrogen working fluid at extremely high temperatures (up to 2750 K peak fuel temperature) (Finseth, 1991). The goal of the Kiwi series was to demonstrate proof-of-concept operation of the reactor design based on a high temperature graphite matrix fuel form with dispersed fuel particles. Later Rover ground testing (Phoebus and Pewee) focused on demonstrating reactor operations over a large range of power levels (40 – 4100 MW_{th}) and thrusts (15 – 250 klbf) which allowed for the development and refinement of relevant reactor components (including fuel), model and simulation development and validation, as well as identification of failure modes and safety related data (including fission product release rates). Rover development primarily focused on reactor ground testing to prove the overall feasibility of an NTP reactor and understand how reactor operations scaled over a range of power levels. However, during testing, fuel failure was observed in nearly every reactor test due to either structural failure of the fuel, which at times led to fuel segment ejection from the core, or corrosive interaction of the fuel with the hydrogen propellant.

As the project evolved, significant effort was devoted to fuel development including fuel reliability testing, production scale manufacture, and quality assurance techniques. Cold flow testing of mockup reactor cores under prototypic hydrogen flow rates without fission heating was undertaken to identify root causes of fuel structural failure (Finseth, 1991). It was found that interactions with the propellant and fuel could lead to fuel cracking and changes in the mechanical design of the reactor structures were implemented to limit fuel failure. In addition, considerable effort was invested in modeling and simulation of fuel elements to optimize the design and minimize stresses within the fuel. Changes to the fuel design, including minimizing the coefficient of thermal expansion mismatch between the fuel matrix and coatings as well as mechanically loading the fuel in compression to alleviate high tensile thermal stresses, led to improved fuel performance (less corrosion and cracking). New fuel element designs were subjected to hot hydrogen testing, thermal stress testing, and non-destructive examination techniques to provide feedback to optimize fabrication processes as well as develop a level of quality control/assurance of as-fabricated fuel elements (Taub, 1975). Towards the end of the project, the development of higher performance fuel forms was pursued, and the testing program shifted from prototypic testing of fuels in fully assembled ground test reactors to Nuclear Furnace (NF-1) testing of fuels in a modular reconfigurable test reactor with a flowing hydrogen loop (Kirk, 1972).

The NERVA project allowed for a more nuanced understanding of reactor operations representative of the NTP system, which cumulated in the testing of integrated reactor-engine systems in near prototypic configurations, including the Nuclear Reactor Experimental (NRX) series and the Experimental Engine (XE). These engine series demonstrated effective use of propellant feed and control subsystems with the Rover reactors, and experimentally validated reactor-engine operation for different operational modes, such as startup, steady state operations, and multiple restarts (Walton, 1991) (Figure 3).

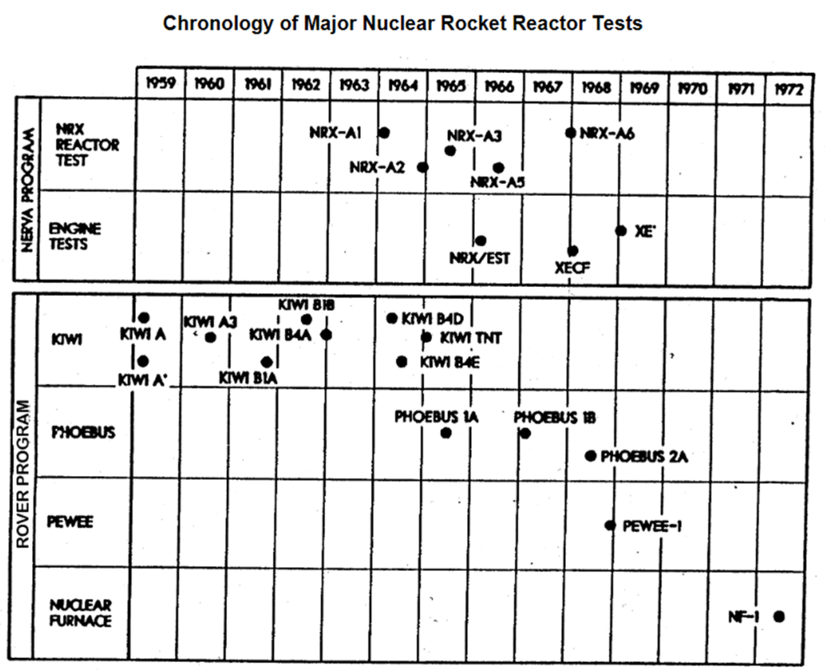

Figure 2: Summary of Rover/NERVA's reactor and engine test series (Bhattacharyya, 2001)

Figure 3: NERVA's XE-PRIME engine on its test stand (Robbins and Finger, 1991)

The Rover/NERVA testing program was originally intended to transition from reactor-engine development to a ground qualification program and Reactor In-Flight Test (RIFT). The qualification program was proposed to consist of 3 reactors (1 pre-qualification, 2 full qualification) to qualify the reactor design and transition to reactor-engine qualification testing with 6 qualification units (3 pre-qualification, 3 full qualification) (Aerojet-General Corporation, 1970b; Gerrish Jr., 2014). The pre-qualification reactor unit was meant to demonstrate design performance, controllability and cycling capability for 600 minutes, and the full qualification units were meant to meet these requirements on top of testing to the full endurance condition and demonstrating full assembly and disassembly. The pre-qualification reactor-engine units were meant to demonstrate performance over the entire map of engine operating conditions, restart capability and engine control dynamics, with the full qualification reactor-engine units demonstrating operation of the full mission profile. Finally, the RIFT series was intended to develop a flight demonstrator rocket engine based on the Kiwi reactor design for the third stage of the Apollo program.

In addition to the main reactor and engine series, several reactor and engine mockups for design basis accidents and manufacturing demonstration were constructed. Kiwi TNT was constructed as a worse-than-worst-case scenario of an extreme temperature excursion; in order to achieve such an excursion, the neutron poison control shims (spacers) were all removed from the core, and the control drums were modified to spin 100 times faster than usual (Finseth, 1991). For reactor/engine qualification, several engine mockups were constructed for Rover/NERVA, including the WEMU, E-X and E-C (Gerrish Jr., 2014; Westinghouse Astronuclear Laboratory, 1972). The Weight and Envelope Mockup (WEMU) was a pair of nuclear rocket engines built without any nuclear components, to develop and demonstrate safe handling of engine subsystems during engine installation, removal and transport at the Nevada Test Site (NNSS). The E-X engine was a spare mockup engine to be used in case a primary mockup engine was unavailable for formal engine qualification. Finally, the E-C engine was an unfueled rocket engine with actual flight components intended for use with NERVA and served to provide qualification for vibration and space storage tests.

The Rover/NERVA program resulted in a significant testing database which demonstrated the performance of NTP reactor components under prototypic conditions, and also highlighted the technology challenges of working with a high temperature reactor made from novel material systems (Houts et al., 2012a, 2012b). The following technical milestones were achieved along the way: the Kiwi B4E (~1000 MW_{th}) demonstrated the highest flowrate of the program (31.8 kg/s) in 1964. The NRX-A6 was the final tested engine model of the NRX series, reaching the highest power (1120 MW_{th}) and operating time (62 minutes) after incremental improvements in operation and control on the models before it. The Phoebus 2A reactor achieved the highest reactor thermal power (4100 MW_{th}) of any series during its 1967 tests, also achieving the 200,000 lbf thrust goal. The Pewee reactor (500 MW_{th}) achieved the highest peak chamber temperature (2750 K) and specific impulse (901 seconds in vacuum). The XE-Prime tests achieved a thrust of 55,000 lbf, with 28 engine restarts. In summary, the program demonstrated reactors and fuels for NTP engines at a TRL above that attempted in other NTP development programs (Farbman, 1991). The NRX and XE series proved that the NERVA engine was capable of the functionality required for a Mars mission, and the significant fiscal support allowed them to forge ahead through materials development at the very cutting edge and fine-tune their designs to meet requirements. While the program was broadly successful, a program of its budget size is unlikely to materialize again, which means a qualification schedule of smaller, evolutionary tests from subscale assemblies to a full integrated engine would allow a modern NTP design to proceed with experimental validation at a significantly lower cost compared to the NERVA series.

2.2. Pluto Program

The Pluto Program (1957-1964) was led by the Lawrence Radiation Laboratory, now the Lawrence Livermore National Laboratory. The Pluto program's goal was to produce a reactor that could power a ramjet cruise missile capable of flying at Mach 2.8 at 3.05 kilometers above sea level (Reynolds, 1961). A ramjet is a jet engine capable of supersonic air intake, with a compressor that slows air to subsonic speeds, before receiving heat and being accelerated back to supersonic speeds through the nozzle. The ramjet's advantage for supersonic travel is in improved heat transfer to the air (Merkle, 1959). Prior to the Pluto program, there were ongoing efforts to develop aircraft nuclear propulsion technologies but there was limited information available about high temperature air interactions with reactor fuel and moderator materials (McKisson, 1956). Therefore, it was decided that Pluto would need full scale reactors (the Tory series) to gather test data to better understand these interactions. The main reactors built and tested during the program were the Tory II-A (Hadley, 1959) and the Tory II-C (Nuclear Propulsion Division Staff, 1961a). Both reactors completed successful tests in 1961 and 1964 respectively, at the NNSS (Nuclear Propulsion Division Staff, 1961b). The late Tory II-C completed its full power test (#89) just after the program was officially cancelled (Nuclear Propulsion Division Staff, 1964). Testing proved difficult throughout the program, as air needed to be injected into the core at 2.41 MPa and 811 K, resulting in a complex test bed with heavy flow injection systems. Flow rates of up to 318 kg/s (Tory II-A) and 817 kg/s (Tory II-C) were achieved during testing (corresponding thrust range 14,750 – 37,900 lbf). Due to the difference in application between Pluto and Rover, Tory reactor testing was performed horizontally with a specially designed test bed on a railroad car (shown in Figure 4, as opposed to NERVA's vertical configuration).

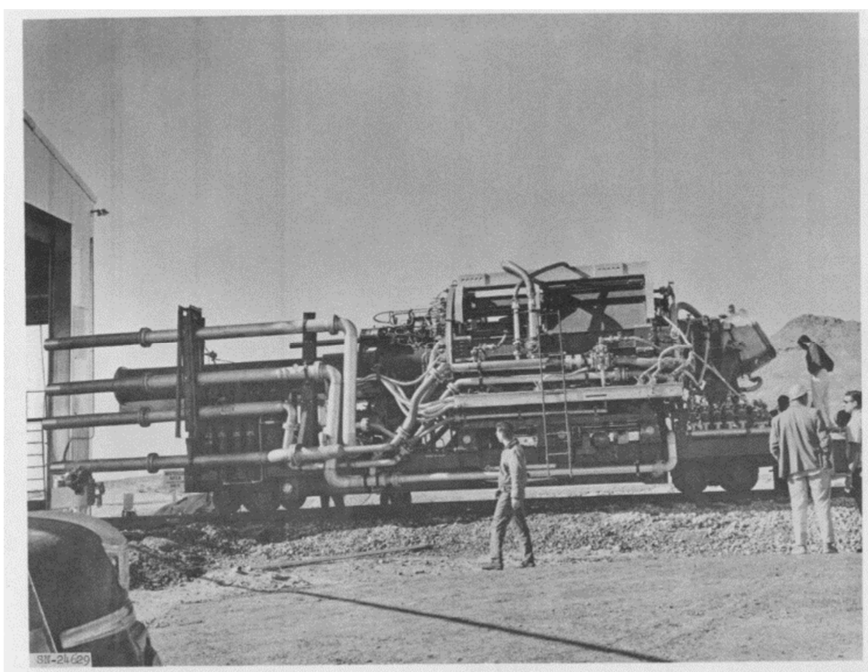

Figure 4: Pluto program Tory II-A Test Cart being withdrawn from its bunker at the Nevada Test Site (Nuclear Propulsion Division Staff, 1961a)

In preparation for building the Tory II-A engine, two critical assemblies, Spade and Snoopy, were evaluated to assess the neutron spectrum of the Tory reactor (Nuclear Propulsion Division Staff, 1959). Critical assemblies are experiments where nuclear fuel and moderator materials are added together such that the properties of neutron multiplication from fission can be closely examined, an effective way to validate the reactor physics of a design (Loaiza and Gehman, 2006). The Snoopy assembly was a homogenous graphite and uranium-235 mixture with a ratio of 9550:1. The Spade assembly was a homogenous beryllium oxide (BeO) and uranium-235 mixture with a ratio of 120:1 (equivalent to that of Tory II-A). These mixtures were successfully fabricated to be homogenous, without significant (>1%) fuel loss and without significant (>5%) volume change during reheating after sintering. Slabs of Hastelloy with gold foil were inserted into the assembly center, and the assembly was surrounded by a graphite reflector. The Spade experiments led engineers to substitute Hastelloy R235 tie (structural support) rods for molybdenum (Mo) rods due to the Mo rods suppressing the neutron population. An additional critical experiment involved using a "hot box" critical assembly similar to Spade but with graphite slabs and demonstrated safety against sudden over-moderation of neutrons. These critical experiments were essential to validating the neutronic performance of the Tory reactors, minimizing the risk of power excursions in later cold and hot flow power testing.

Flow testing is an effective experimental technique for understanding fluid interactions with reactor materials, as well as evaluating the distributions of fluid temperature, pressure and other state variables (Bojanowski et al., 2021). Several flow tests were conducted with Tory II-A: a design core temperature and thermal stress test with reduced inlet air temperature, a full design point test and a 90 second excessive thermal stress test (twice that of Tory II-C levels) (Nuclear Propulsion Division Staff, 1961c). A thermal power of 185 MW and a core temperature of 1560 K were achieved, with an air inlet temperature of 775 K and flowrate of 288 kg/s. These tests provided assurance that the homogenous core concept could be operated successfully, with effluent releases of fission products found to be below 0.1% of the core mass. These tests led to tests conducted with Tory II-C, a larger reactor core closer to a demonstration engine.

The Tory II-C's final set of tests were at low, intermediate, and full power. Run 87, the Low Power Test, served as a final check of nuclear control systems under high air flow and provide data on the temperature coefficient of reactivity. The reactor power was increased up to 1 kW, where the reactor temperature was then modified solely by inlet air temperature. As airflow ramped up to 817 kg/s, position signals from actuators became noisy due to electrical shorting. Run 88, the Intermediate Power Test, sought to simulate steady-state reactor operation at Mach 2.8 and 3.05 kilometers above sea level. The reactor power was raised to 80 kW, held for 40 minutes to adjust exhaust chambers for coverage during high power operation, and airflow was brought up to 572 kg/s. After reaching 572 kg/s, reactor power was increased to provide a measured 1405 K in the core, and this flow rate was maintained for several minutes before air reserves were depleted. Run 89, the Design Power Test, was intended to simulate realistic reactor operating conditions, or prototypic conditions, at a steady-state Mach 2.8 at sea level. Similar to the medium power test, reactor power was raised to 700 kW and held to adjust power control, then airflow was raised from 186 kg/s and the reactor power with it to achieve predicted values of 753 kg/s and a core temperature of 1566 K. Although the airflow rate was inconsistent due to heating system limitations, this high-power state was maintained for 5 minutes as planned, and then shut down like Run 88 with low pressure blowers used to cool the air and reactor. The high power test concluded with no loss of reactivity detected, and no difficulties in reactor operation. The core of the Tory II-C during the High Power Test can be seen at different points in Figure 5.

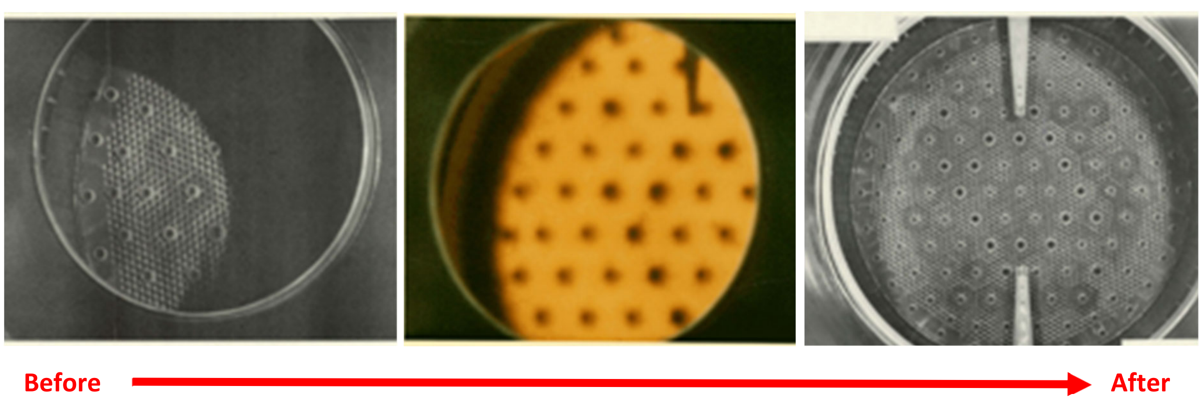

Figure 5: Pluto program Tory II-C High Power Test (Run 89) core views (compiled from (Nuclear Propulsion Division Staff, 1964)*)*

While the Tory II-C tests provided validation of the nuclear-powered ramjet concept, political concerns arose over the use of these missiles and their dispersion of radioactive fission products during flight. Also, the success in development of Intercontinental Ballistic Missiles (ICBMs) diminished the strategic importance of cruise missiles with nuclear warheads, and thus the Pluto program was cancelled to reflect these factors. Planned tests before program cancellation included a fast, 1 minute engine startup from 1 kW to high power, and a fast start up with a constant shim rod removal, demonstrating control of the reactor using aerodynamic measured parameters like airspeed instead of reactor parameters like temperature.

The Pluto program successfully operated the Tory reactors in cold and hot flow conditions up to full power, indicating the feasibility of a reactor powering a ramjet missile. Both the critical experiment series and the rigorous flow testing of the reactor in conjunction with air blower subsystems were crucial to the success of these tests, which were a validation of all the design work that came before. The Pluto program developed cutting-edge materials and demonstrated reactor operations under conditions not previously demonstrated.

2.3. General Electric 710 Reactor Program

The GE 710 reactor program (1962-1968) focused on developing a fast neutron spectrum, high temperature reactor with hexagonal cermet fuel elements for submarine, aircraft and rocket propulsion applications (Nuclear Energy Division, 1968a). These applications are listed in order as the program shifted objectives multiple times throughout its duration. The reactor was designed with a closed loop of neon coolant and an open loop of hydrogen coolant, with the open loop discontinued in 1963 to focus on the closed loop performance. The 710 program was shifted to focus on fuel element development in 1966, with detailed studies performed on cermet fuel form fabrication, testing and qualification. The SNPO discontinued the 710 program in 1968 due to budgetary constraints and to focus on its main Rover/NERVA program. The major accomplishment of the GE 710 program was in fabricating quality reactor-size cermet fuel elements and cladding in a reproducible fashion. All fuel elements fabricated and tested passed qualification tests, demonstrating strong stability and fission product retention under extended cyclic exposure to high temperatures. The critical experiments and analytical correlation methods developed for the 710's design provided complementary information about the neutron energy spectrum, critical mass and control system reactivity worth. The program's final focus before cancellation was on the design of a 200 kW_e Brayton cycle space power unit (for crewed space stations).

The GE 710 program was broad in scope with many objectives throughout program lifetime (Figure 6). For its first objective (May 1962 – October 1963), demonstrating a small, high-performance fast-spectrum reactor, static closed loop hydrogen tests at 2873 K were performed on a tantalum (Ta)-clad W - 60 volume % uranium dioxide (UO_2) sample for 10 hours, and a W - 25 atom % rhenium (Re) sample for 50 hours. The program's second objective (October 1963 – July 1965) aimed to develop technologies to enable a full power demonstration of fuel elements within a closed loop, but for a subscale, partial core length (~ 1/3 of a meter). Under this phase, fuel elements developed with 91 and 37 coolant channels, Ta-clad (and a single W-Re-Mo-clad) fuel elements were fabricated and tested at 2423 K for 100 hours and 30 cycles. Post-test characterization activities revealed insignificant dimensional changes of the fuel form, which was satisfactory for a passing of initial qualification. Following this testing, a series of mockup critical experiments of the 710 reactor were fabricated and went critical in January 1965 (Nuclear Energy Division, 1968d).

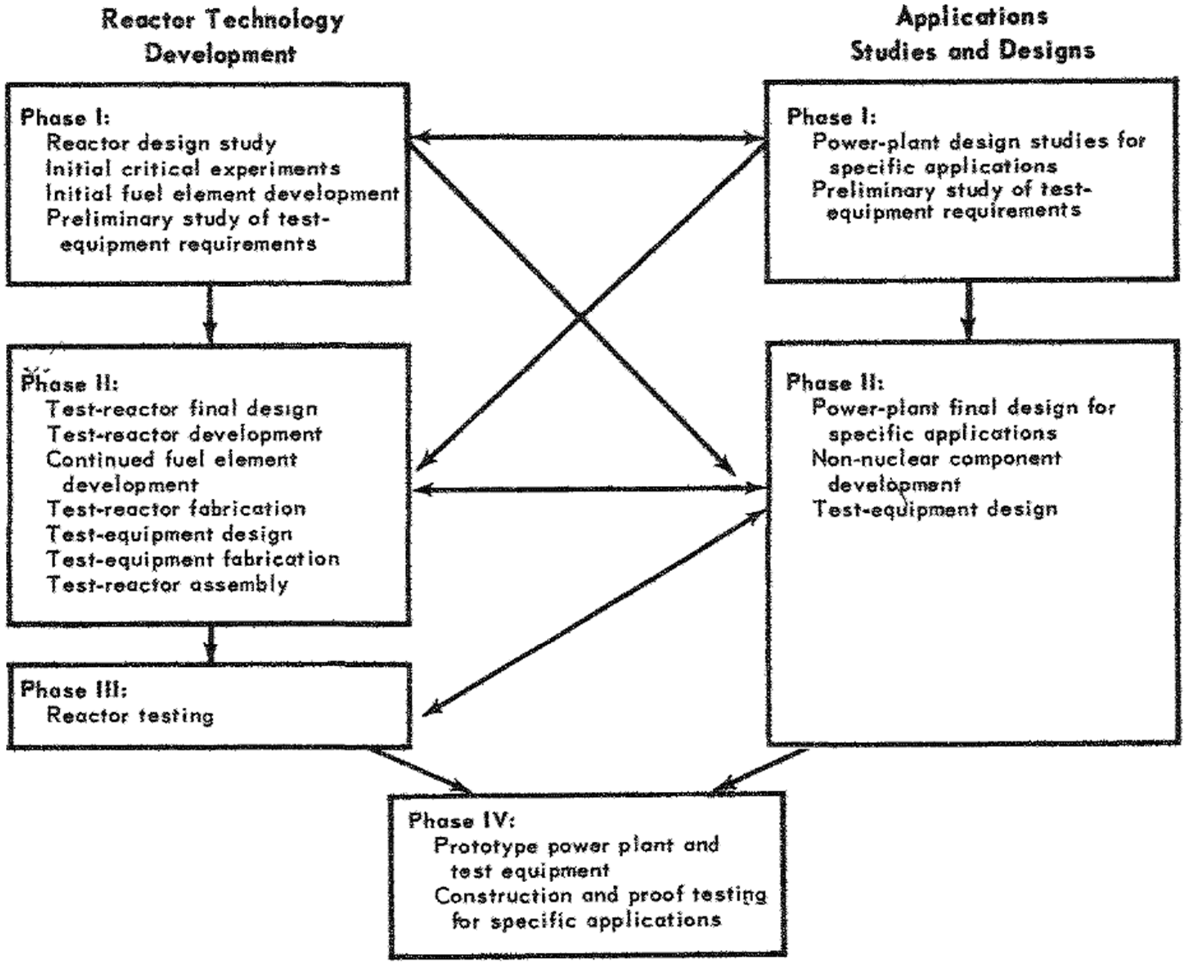

Figure 6: Program phases for the GE 710 program (Nuclear Energy Division, 1968a)

For the 710 program's third objective (July 1965 – October 1966), development activities efforts shifted towards developing a 200 kW_e Brayton cycle space power reactor. Additional W-Re-Mo-clad elements were fabricated for a parametric study comparison with Ta-clad elements. Engineering of a pilot loop for in-pile dynamic tests at the Idaho National Reactor Test Station (NRTS, now Idaho National Laboratory) were halted as the 710 reactor facility was removed from the SPNO's Fiscal Year 1967 budget. As the basis of a 10,000-hour fuel qualification test program, failure mode analysis was conducted using static (no flow) & dynamic (flowing fluid) tests of single and multiple partial-length fuel elements, and finally static in-pile tests of single partial-length elements. Fuel element designs were altered to better suit a Brayton cycle power system; namely, the number of channels were reduced from 37 to 19, the channel hydraulic diameter was doubled, and fuel operating temperatures were reduced from 2423 K to 1923 K. A sketch of a representative fuel element is shown in Figure 7.

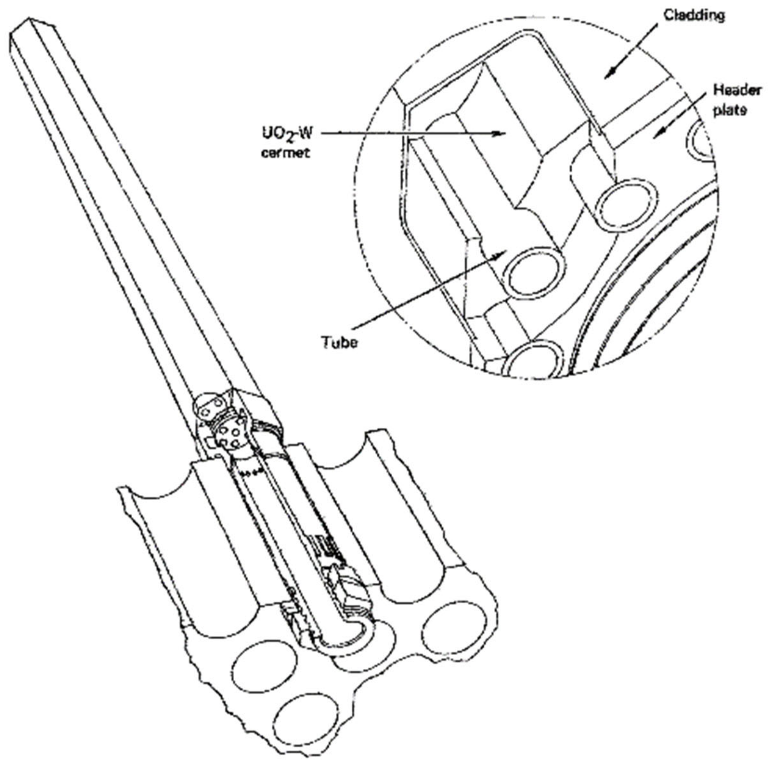

Figure 7: Sketch of GE 710 fuel element integrated into an assembly (Nuclear Energy Division, 1968a)

A long-term demonstrator plan was drawn up for the AEC, with a reference design test by 1971, reactor demonstration in 1975, and service possible starting in 1980. This plan indicated that both in-pile and out-of-pile testing needed to be complete by 1969, and all major program decisions were tied to these test results. To this end, partial length fuel elements clad with T-111 (a Ta-based alloy) were fabricated and tested for 1000 hours in August 1966, and a dynamic hydrogen loop for full-size elements was made operational and tested a full-size T-111-clad element in the same timeframe. Two in-pile tests at Oak Ridge National Laboratory's Low Intensity Test Reactor were designed and conducted in June and August of 1966 (Nuclear Energy Division, 1968c).

At this stage, the 710 program was reduced in scope to a fuel element development program, with all critical experiments cancelled in December 1966. The program conducted an optimization study of the Brayton cycle space power system and found that a helium-xenon (He-Xe) mixture (with an average molecular weight of 40) could maintain the lowest average surface temperatures in the core, to allow for maximum fuel burnup. Fuel performance was demonstrated in-pile at 1813 K in April 1967. The need to test 710 fuel elements in a fast-flux environment was identified, with a fast-flux filter determined feasible for static in-pile tests using either the Engineering Test Reactor at the Idaho NTRS or the Oak Ridge Research Reactor (Nuclear Energy Division, 1968e). The first full-length W-30Re-30Mo-clad fuel element (19 channel) was fabricated in August 1967, with a second produced in November indicating reproducibility, but the GE 710 program was terminated starting in November 1967, bringing all testing to an end. Experimental results indicated that fuel qualification was on schedule for June 1969 completion.

The GE 710 program succeeded in developing prototypic-scale cermet fuel elements and cladding in a reproducible manner that would satisfy program requirements. Early 710 fuel element testing focused on qualification for 100 hours at 2423 K and 30 thermal cycles, and fuel elements were qualified for these standards by the time the program's scope had changed to fuel development only. The 710 program's dynamic non-nuclear tests indicated that gas stream impurities and radial temperature differentials are not the limiting cause of fuel element failure at operating conditions, information that static tests couldn't provide. The in-pile tests concluded that the cermet fuel elements tested could retain fission products and maintain necessary performance for the 10,000-hour space power reactor and higher. Both the W-Re-Mo and T-111 claddings performed without failing in all tests, but the W-Re-Mo was judged superior in terms of oxygen permeability, diffusion voiding at the boundary and hydrogen/lithium reactivity. Overall, the 710 program's safety testing (defined as testing beyond design points (Werner et al., 2019)) demonstrated fuel element performance that met its program objectives.

2.4. Argonne National Laboratory's Nuclear Rocket Program

Argonne National Laboratory began its Nuclear Rocket program (1963-1968) with a preliminary design study of a rocket powered by a refractory metal-based fast neutron spectrum reactor. The design study focused on a 2000 MW_{th} (100,000 lbf) and a 200 MW_{th} (10,000 lbf) reference system, with a core of W-based cladding and cermet fuel, a BeO reflector and an Inconel 718 shell. The program successfully produced W-clad cermet fuel that could withstand high temperatures (2773 K) for tens of hours and dozens of thermal cycles, and test specimens exposed to high pressure and high speed hydrogen performed as expected. Development of fuel element fabrication was cancelled in July 1966 prior to completion due to budgetary constraints, but the preliminary results suggested confidence in the feasibility of a full engine.

The goals of ANL's experimental work were to capture nuclear data (using critical assemblies) and calculating the properties of their proposed design by developing simplified analytical techniques. Materials studied in the critical assemblies included W-Re and W cores with uranium metal and simulated UO_2, and reflectors of alumina (Al_2O_3) and BeO. These assemblies provided evidence that the proposed core designs could maintain criticality, albeit with high neutron leakage due to its compact size. At the time of the program's cancellation, a multi-purpose vacuum furnace facility was being developed to evaluate material structural behavior at high temperatures (sketched out in Figure 8).

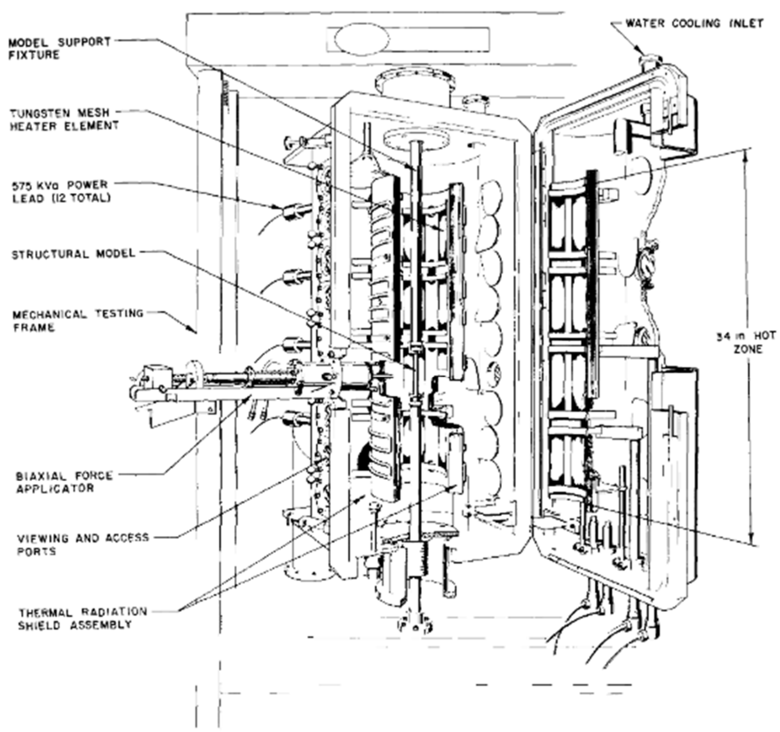

Figure 8: Sketch of ANL's high temperature vacuum furnace design, under construction at the time of program termination (Water cooled, tungsten mesh heaters) (Argonne National Laboratory, 1967)

ANL also developed two flowing hydrogen loop experiments to test fuel elements, with one small loop and one large loop. The 50 kW loop could fit smaller specimens with 7 cooling channel holes (smaller than the full element cross-section), and the larger 1000 kW loop could fit short sections of the full cross-section. The testing campaign goals were to conduct steady-state hot hydrogen runs for 1-2 hours, conduct thermal cycling hot hydrogen runs on the order of one hour, and conduct in-pile rapid nuclear transient testing of small fuel element specimens. Both loop heaters (sketched out in Figure 9) experienced multiple failures as the Re end plug thermally expanded, leading to only limited data collected and the large loop disassembled for storage. The last large loop run lasted 6 minutes, providing a sample temperature of 2543 K with no evidence of creep-related failure in the sample. For in-pile testing, the program developed an evacuated capsule, with Ta-sheathed W-Re thermocouples and thorium oxide insulation, for irradiation of partial fuel elements with 7 representatively sized cooling channels in the Transient Reactor Test (TREAT) facility. Due to uneven vapor coating of the 7-hole specimens, there is considerable temperature variation in the recorded surface temperatures of the fuel elements. However, none of the eight specimens cracked or spalled during the tests, which ranged from 0.2 to 3 seconds in total.

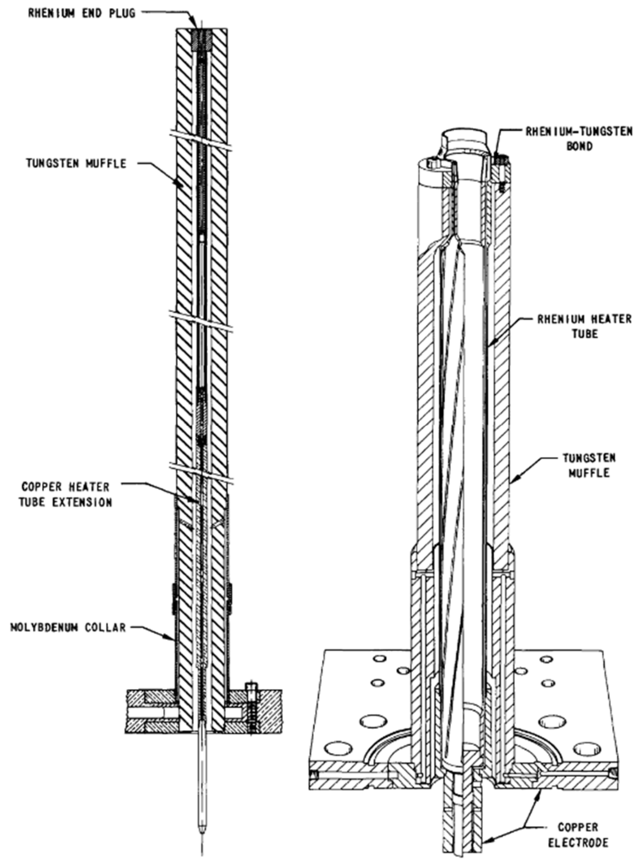

Figure 9: Sketch of heater system for ANL's small and large hydrogen test loops (Argonne National Laboratory, 1967)

The results of ANL NR's static, dynamic and in-pile tests on wafers and other partial fuel element specimens demonstrate initial confidence in the selected materials' performance at high temperature cyclic operation. The critical experiments performed indicated the proposed reactor core could maintain criticality, and that neutron leakage would play the largest role in reactivity control. The ANL program demonstrates that methods development and analysis can be done in parallel with experimental testing of fuel elements/sub-elements, and that gathering data proving that these specimens will meet their performance requirements is necessary to obtain before proceeding to fuel bundles/assemblies testing.

2.5. Space Nuclear Thermal Propulsion Program

The SNTP program (1987-1994) was a US Department of Defense undertaking, that began developing a Particle Bed Reactor (PBR) nuclear rocket engine for missile defense purposes (Lieberman, 1992). The project then known as Timber Wind began its first of three phases in 1987 with sponsorship from the Strategic Defense Initiative (SDI, or "Star Wars"), and completed its preliminary engine design in 1989 (Haslett, 1995). Following this, and the rearrangement of the international political landscape with the collapse of the Soviet Union in 1990, the program was transferred to the US Air Force (USAF) and its focus shifted to more general space missions. Phase Two of the program was focused on a ground demonstration of a prototypic PBR rocket engine but did not see completion due to the reduction of program funds beginning in 1992, and ultimate cancellation in 1994. Phase Three would have seen a flight test of the SNTP engine using a launch vehicle rocket. The program was on track to conduct a ground test in 2000 before the program's cancellation (Haslett, 1995).

The SNTP program's Phase I goal, under management of the SDI office, was to design a 2nd stage NTP engine for an ICBM interceptor (Haslett, 1995). The PBR concept involves containing a pile of fuel particles within two cylindrical containers called frits, with propellant fluid pumped through the particle bed to gain heat and produce thrust upon exiting the rocket (Ludewig et al., 1996). Timber Wind's development approach was aggressive, focused both on a design study of the engine's requirements (~ 2973 K exit temperature, high power density) and experimental testing within a short timeframe. In-pile testing of fuel particles was carried out at Sandia National

Laboratories' (SNL) Annular Core Research Reactor (ACRR). These particles were tested in a series of Particle Nuclear Tests (PNTs) and Particle Heating Tests (PHTs) (Allen, 1993). The goal of these fuel particle tests was to qualify fuels for the PBR design before moving to the subsystem/reactor level. PNTs 1-5 subjected >200,000 particles at temperatures from 1800-3000 K and 100-600 seconds. PNT 3 and 4 tested particles to failure and found the uranium carbide melts between 2700-2800 K (leading to failure in 5 minutes), which indicated that the baseline particle temperature limit is ~2500 K (Haslett, 1995).

As Timber Wind wrapped up this phase and began to transition to Phase II, the SDI office decided to broaden the scope of the engine to include missions to Low Earth Orbit (LEO) and deep space, where the PBR stage could transfer payloads between LEO and Geosynchronous Orbit (GSO). After the USAF took over in Fiscal Year 1992, Project Timber Wind was renamed the SNTP program and restructured as a technology demonstration program with a lower program risk vs. the previous aggressive development strategy. Critical experiment tests began at SNL to validate neutron transport code results, and Nuclear Element Tests (NETs) of single fuel elements began in the ACRR (Haslett, 1995). NET elements (depicted in Figure 10) weren't quite the same as demonstrator engine elements but were meant to address design concerns. These slight dissimilarities were not as great of concern as in previous NTP programs with prismatic elements since the particle bed fuel elements are less geometrically complex. The NET 1.2 was the only experiment completed before program cancellation, and power anomalies in the hot frit due to cracking were identified during Post-Irradiation Examination (PIE) in late 1993 (Haslett, 1995). These cracks were likely due to excess hoop and thermal stresses on the hot frit wall near the end fitting interface.

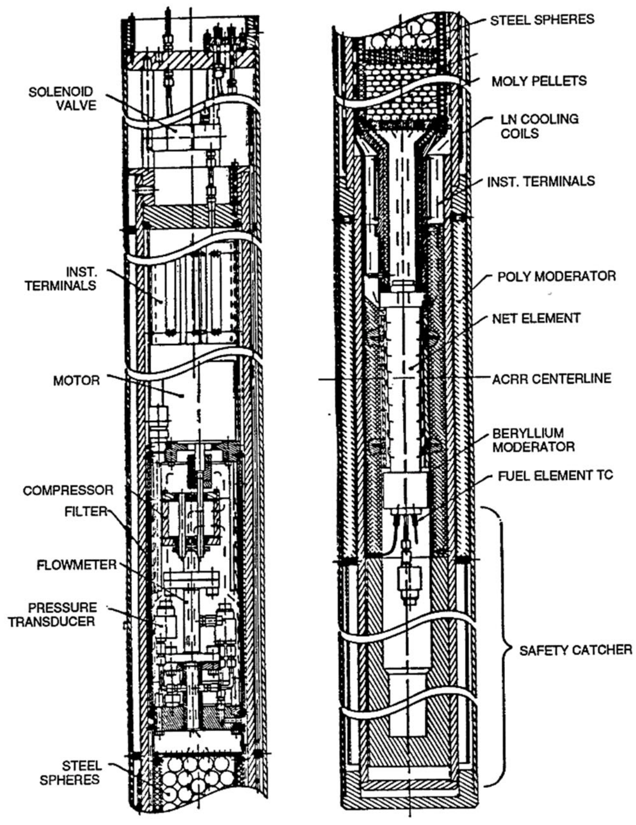

Figure 10: SNTP's NET Experiment Schematic (Haslett, 1995)

A number of tests and facilities were planned before the SNTP program's cancellation. To provide data on transient thermal stresses, tests of PBR elements in TREAT were proposed (Todosow et al., 1993). Plans were made to test validated NET elements in the Particle Bed Reactor Integral Performance Tester (PIPET), a nuclear test bed to be built at either the Saddle Mountain Test Station in Nevada (Figure 11) or at the Idaho National (Engineering) Laboratory (Allen et al., 1993). PIPET's design featured a driver reactor core to provide radiation to samples in the test bed, allowing for a testing progression from bare prototypic elements to moderated elements and then a core assembly. This ground test facility needed to meet standards from the 1969 National Environmental Policy Act (NEPA) among other requirements, and costs for the facility began to grow. While the necessary temperatures and pressures of a demonstrator engine require a ground test facility, these costs proved to be too much and led to the program's cancellation.

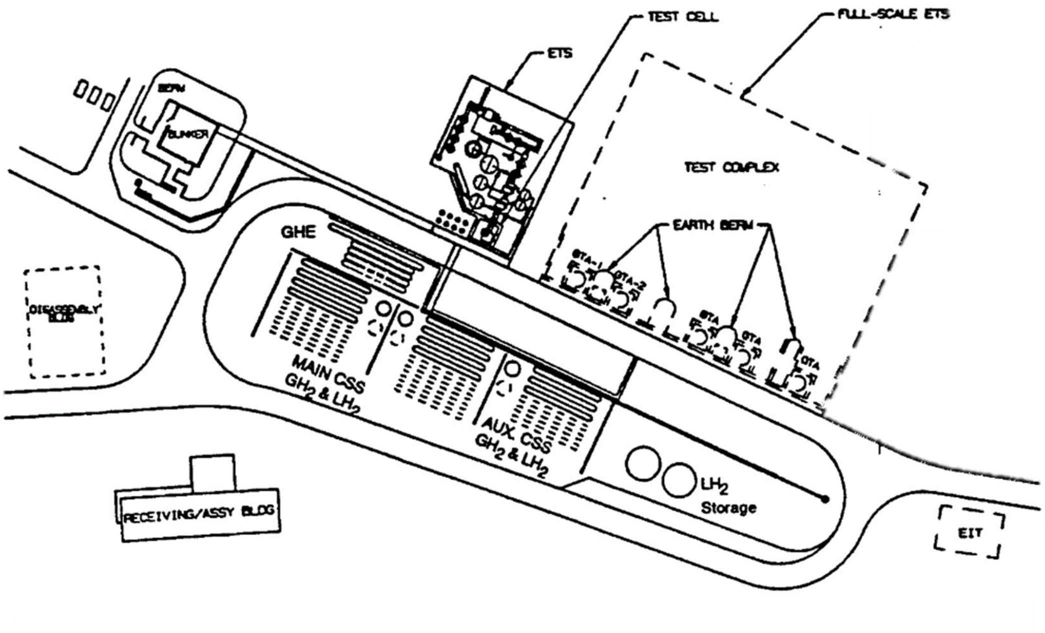

Figure 11: SNTP's Planned Ground Test Facility at the Nevada Test Site (Haslett, 1995)

The SNTP program highlights the significant changes in development landscape between the NERVA era (~1960-1973) and the modern era (1989 - present). Despite both the shifting program goals and perennial funding challenges, the program made significant technical headway on the PBR concept and on NTP testing in general. In particular, the stepwise planning of tests provides a useful framework for structuring fuel and reactor qualification in a modern NTP program, where engine subsystems and reactor subsystems can be qualified in parallel and fuel development can begin with single elements (subscale and full scale) before proceeding to subscale assemblies.

3. Results & Discussion

3.1. Historic Fuel Qualification Testing Program Tasks and Test Conditions

Table 2 provides a high-level summary of the fuel testing activities surveyed from each historic NTP program. Tests planned before cancellation were also included to give a sense of direction for each program at their end-of-life points. A common theme throughout each historic NTP program is the need for testing of fuel elements to occur in parallel to the development of manufacturing processes to enable informed optimization of the manufacture process. In the Rover/NERVA and Pluto programs, fuel performance was primarily evaluated using ground reactor testing. This allowed for fuel performance under prototypic conditions to be evaluated immediately. However, ground reactor testing required extensive engineering, complex reactor operations, and production scale reactor manufacture and assembly. While this approach allowed for direct testing of fuels under prototypic conditions, it was an expensive and time-consuming process and often required subsequent separate effects testing to better resolve fuel form failure modes. The Pluto program reports consistently indicated that focused work on reactor modeling and simulation, critical experiments, as well as materials manufacture and testing were pursued in parallel, demonstrating the benefit of crosstalk between different activities. Test data gathered from experiments could be used to validate models; fuel performance data proved the reactor was capable of satisfying performance parameters and that manufacturing processes were well optimized. Similar to Rover/NERVA, Pluto also heavily relied on reactor testing to verify component performance and provide a proof-of-concept for wholly new NTP systems for space or ramjet operations that had not been previously demonstrated. Both programs revealed that reliable and robust fuel performance was required in order to allow the reactor to remain fully functional and meet performance requirements. Structural failure of fuel, due to high temperature operation, thermal shock during transients, or thermal cycling, could lead to ejection of fuel material from the core and loss of reactivity. Undesirable corrosion effects or high temperature instability (localized melting, selective vaporization of materials, or change in material composition) similarly could lead to loss of reactivity due to loss of material through corrosive interaction or local failure of the fuel element.

The GE 710 and ANL NR fuel development programs showed a divergence from this original fuel testing methodology by demonstrating fuel manufacture and performance in an incremental manner. Unlike the Rover/NERVA and Pluto programs, the underlying proof-of-concept of a NTP system had already been demonstrated, and fuel performance was determined to be a limiting factor to reactor lifetime and functionality. The approach used under these programs began with subscale fuel element manufacture and separate effects testing (both nuclear and non-nuclear environment testing). Testing data from these activities could be used to optimize fuel design and manufacture techniques more affordably than ground reactor testing. Although separate effects testing does not demonstrate fuel performance under full integrated effects conditions expected for prototypic operations, the approach does allow for initial identification and isolation of failure modes early in the program. It also allows for test data to be gathered to validate modeling and simulation activities. Therefore, the separate effects approach is effective for low TRL (< 5) advancement. In the GE 710 program, future fuel testing activities planned included demonstration of fuel performance in a dynamic in-pile loop which subjected fuel elements to a combined nuclear environment with a working fluid.

The SNTP program underscored the importance of developing a robust plan for ground testing, which must meet environmental regulatory constraints while also demonstrating the necessary subsystem interactions that will take place at prototypic conditions. Because the environmental regulatory landscape has changed significantly since Rover/NERVA, the cost of SNTP's ground testing facility proved to be significantly challenging. This does not weaken the case for a subscale testing facility however, for its abilities to enable higher TRL advancing qualification tests (subscale assemblies, reactors, and integrated reactor-engine systems). Instead, this simply makes it plain that significant resources must be devoted to this facility's design and planning early, in order to provide useful experimental results in a timely manner. Testing performed under the SNTP program included early non-nuclear high temperature testing of fuel particles which progressed to in-reactor testing of fuel particles in a bed (~10^4 particles) in a static He and He-H_2 atmosphere. In-reactor testing of fuel element frits, via in-pile hydrogen flow loops, allowed for exposure of fuel particles to representative hydrogen and irradiation environments, although the exact flow and power density conditions (compared to the operational system) were not matched. This approach allowed for fuel to be tested under combined effects conditions without the assembly of a NTP ground test reactor, and allowed for an understanding of failure modes due to fuel assembly structural performance and a combined effects environment.

By far the most common tests performed during historic programs were separate effects testing: non-nuclear thermal cycling and steady-state irradiation tests, which were accompanied/substituted for transient irradiation tests to a lesser extent. These tests are seen as the most important precursors to reactor demonstration testing, since these tests when performed at prototypic temperatures, fluxes, powers etc., demonstrate whether a fabricated fuel element will fail or not. Although it is possible to begin testing fuel assemblies without knowing their constituent elements' prototypic mechanical/vibrational response, it is crucial to confirm that the fuel's response to the hydrogen and nuclear environment is going to be acceptable prior to testing fuel assembly bundles. Although thermal shock testing was utilized in the Pluto program to great effect, it would be possible to evaluate fuel response to thermal stresses using a transient irradiation test as well. Additionally, irradiation testing of fuels should be first conducted with a prototypic neutron flux before moving to testing reactor scale assemblies. This is because a fuel element's material response to prototypic neutron fluxes and power densities must be understood and experimentally validated before being combined with other elements, in order to buy down risk associated with unexpected failure due to element-element interactions. Finally, prototypic fuel elements must be used as fabricated for safety testing and critical experiments, since non-prototypic elements will not effectively validate the neutronics or safety system designs for an NTP system and introduce additional risk for future subscale tests.

Table 2: Summary of fuel development tests performed or planned for historic NTP programs

Test Type	**Test Description**	**Test Objectives**	**Variable Range Explored**	**Test Article Description**	**Related Program**	**Performed or just Proposed?**
Mechanical Loading	1) High temperature elastic modulus measurement 2) Fixing one end of a fuel element support plate, applying torque	1) Determine decrease in elastic modulus after heating elements for extended periods of time 2) Determine structural stability of support plate, fuel element clamping studs	1) 863 –1073 K, 2 –23 hours 2) <16,000 lbf applied at the free end	1) BeO tubes, 10 without UO_2 (1.905 cm OD, 0.635 cm ID, 7.62 cm length) 2) Aluminum (6061-T6) plate with SS304 (and Inconel-X) clamping studs	1) Pluto (Tory II-C) 2) ANL NR	Performed (1, 2)
Vibrational Testing	Fuel elements assembled into a shaker device and vibrated at high frequencies	Determine vibrational modes, evaluate structural stability of fuel elements under dynamic loading	5–3000 cycles/s, 1–163 "fuel" elements	Steel rods	ANL NR	Performed (ANL NR)

Thermal Shock Testing	Rapidly heating a fuel element to examine the material's thermal stress response	Determine if and at what temperatures fuel/moderator elements will fracture from thermal stresses	<2033 K, 3 times for 2–3 minutes in a "blowpipe" furnace with a graphite heater blowing helium	70 BeO tubular elements (few failed except at 2–3 times expected temperatures)	Pluto (Tory II-A)	Performed (Pluto)
Non-Nuclear Static Flow Thermal Cycling	Non-nuclear heating of a fuel assembly to high temperature, maintaining temperature for a period of time and then cooling of the fuel assembly in a repeated (cyclic) pattern. A hydrogen (or other working fluid) environment may be present but is not actively flowing.	Verify thermodynamic stability and mechanical integrity of reactor materials under high temperatures Verify material resilience to fatigue under repeated high heating and cooldown	1) 1305–1700 K, 216.5–635.4 W/cm, to failure (first cracked in 52 s, second cracked, time unknown due to detector malfunction, third intact) 2) <3278 K vacuum furnace 3) 672–1922 K, 98,685 total hours → 368 cycles 4) 20,000-hour life demonstration 5) He, He-H_2 high temperature testing	1) BeO tubes, 10 without UO_2 (1.905 cm OD, 0.635 cm ID, 7.62 cm length) 2) Partial length, fuel elements 3, 4) Partial length fuel element, W-based or Ta-based clad 5) multiple fuel particles	1) Pluto (Tory II-C) 2) ANL NR 3, 4) GE 710 5) SNTP	Performed (1, 3, 5) Proposed (2, 4)
Non-Nuclear Dynamic Flow Thermal Cycling	Non-nuclear heating of a fuel assembly to high temperature, maintaining temperature for a period of time and then cooling of the fuel assembly in a repeated (cyclic) pattern. A hydrogen (or other working fluid) flow is present to transfer heat from the test article. Conducted with an experimental test loop	Verify thermodynamic stability and mechanical integrity of reactor materials under high temperatures and representative non-nuclear environment. Investigate fluid interactions with structural materials, specifically negative effects like corrosion.	1) 0.555 standard cubic meters/minute, 293–2723 K, 40.3–613 kW, 12 hours & 16 cycles - 6 minutes 2) 1089–1922 K, 15,699 hours → 48 cycles	1) Partial length, partial cross section 7-channel fuel elements 2) Full length fuel element, Ta-based clad	1) ANL NR (Small, large H2 test loops) 2) GE 710	Performed (1, 2)

Steady-State Nuclear Testing, Representative neutron spectrum	Exposing test elements/subsystems to a steady source of neutrons similar in energy distribution, flux, or fluence to that in an operating NTP fuel assembly	Verify mechanical integrity of reactor materials and irradiation effects under nuclear environment Verify fission product retention and/or inventory (e.g. below 1% release)	1) <1811 K, 121,066 hours → 231 cycles 2) <2222 K exit temperatures, 937 and 882 MW_{th}, 8 and 2.5 minutes at full power 3) <2444 K exit temperatures, 1450 and 588 MW_{th}, 30 and 2.5 minutes 4) 2000, 4082, 1280 and 3500 MW_{th}, 32, 12.5 and 30 minutes 5) <2556 K exit temperature, 508 MW_{th}, three 20-minute cycles 6) <2444 K exit temperature, 44 MW_{th}, 108.8 minutes total → 4 cycles (NF-1) 7) 1800–3000 K, 100–600 s (SNTP Particle Nuclear Tests 1–5)	1) Partial length fuel element, W-based or Ta-based clad 2) Pyrolytic carbon-coated UC beads in graphite matrix with NbC coating 3, 4) Pyrolytic carbon-coated UC beads in graphite matrix with NbC coating and Mo overcoat 5) Matrices coated in ZrC and elements interspersed with ZrH tie tube support rods 6) 47 (U,Zr)C-carbon composite elements & a seven-element cluster of single-hole pure (U,Zr)C carbide 7) Cercer fuel particles	1) GE 710 2–6) Rover/NERVA (Kiwi-B4E, Phoebus-1B, 2A, Pewee-1, NF-1) 7) SNTP (Particle Nuclear Tests 1–5)	Performed (1–7)
Transient Nuclear Testing, Representative neutron spectrum	Exposing test elements to a sudden short-lived source of neutrons similar in energy distribution to that in an operating NTP fuel assembly during start up or other operational transients	Verify mechanical integrity of reactor materials under nuclear transient	1) 1073–3023 K, 0.2–3 s 2) 302–3850 MW_{th}, 0.04–0.139 s, 1123–3623 K 3) 3–60 s, 0.09–1.6 MW/L 4) 150–2300 K H_2 temperature, 10 s/2 cycles 5) 10–20 MW/L, 5–10 s	1) Partial length, partial cross-section (7-channel) cermet elements 2) Shelf (25% UO_2, 75% UC_2) surrounded by graphite in a helium-filled, Stainless-Steel autoclave 3) Unknown, information at Sandia National Laboratories 4, 5) Cercer fuel particles contained in a graphite/NbC hot frit and a Stainless-Steel cold frit	1) ANL NR (TREAT) 2) Rover/NERVA (TREAT) 3–5) SNTP (Pulse Irradiation of a Particle Bed Reactor Element 1–7, Nuclear Element Test 1.2, TREAT)	Performed (1–4) Proposed (5)

3.2. Historic Reactor Testing Program Tasks and Test Conditions

Table 3 provides a high-level summary of the reactor development tests performed or proposed by historic NTP programs. Since fewer historic programs progressed to the point of full scale reactor testing, most of the information available is for the Rover/NERVA and Pluto programs. The testing included in Table 3 can be largely grouped into three categories: flow testing (cold or hot), critical testing, and reactor powered operations tests. Flow testing includes flow of a heated (hot) or non-heated propellant through a fully assembled reactor or mockup reactor. This allows designers to understand fluid-structural interactions expected within the reactor subassembly at the appropriate scale. Reactor tests for the Pluto program primarily focused on cold and hot flow testing, due to the focus on understanding fuel-air interactions during ramjet operations. Cold and hot flow testing provides risk buydown against unexpected reactor performance degradation if the coolant/propellant causes failure in any structural materials.

Critical experiments, including zero power critical experiments, allow for the generation of reactor physics or nuclear data needed for model verification. Past zero power critical experiments have taken representative critical assemblies or fully assembled reactors to a critical condition while reactor power production is kept at zero. These are an important precursor test to full power reactor testing because it allows for initial validations of predicted reactor physics behavior. Without that experimental validation of core reactor physics (as predicted from computer modeling), significant risk is present in testing the full reactor core at nominal operating conditions (due to uncertainty in material reactivity worths and power distributions). Zero power critical experiments can also provide information related to reactor operations, including dynamic reactor response due to different temperatures or component orientations. Numerous zero power tests were performed on the Tory II-A and II-C, as well as the Kiwi series, NF-1 and the SNTP PBR to evaluate their core neutronics as compared to predicted results. Additional critical testing to verify reactor behavior under design basis accident scenarios, such as those planned for Pluto or similar to Kiwi TNT, can be performed to provide additional confidence in the safe operation or launch of the NTP reactor.

The final set of tests include reactor powered operation tests. This testing may be performed through either reactor subsystem testing (no engine interface) or integrated reactor-engine testing. Under project Rover, significant ground reactor testing was performed. Early Kiwi reactors were tested without any engine hardware, where simpler fluid feed systems provided the hydrogen propellant into the core and heated hydrogen vented to open air. Throughout the Kiwi test series, reactor design progressed in complexity to nearing that expected of the eventual operational system. This testing allowed for reactor operations data to be generated to validate reactor physics models, component level performance (such as fuel) under prototypic conditions to be verified, as well as demonstration of reactor manufacture and assembly techniques at a prototypic scale. Under SNTP, reactor powered operation tests were also planned using a flexible test assembly which would allow for different reactor core assemblies to be tested using a surrounding driver core to simulate a fully assembled reactor (Particle Bed Reactor Integral Performance Tester, PIPET). While this testing was never performed, it is an alternative approach to demonstrate reactor operations and generate component performance data under prototypic conditions at a reduced scale. Under NERVA, similar data was generated; by testing an integrated reactor-engine system, reactor components were subjected to the conditions expected during the operational system and all engine operations could be experimentally verified.

Table 3: Summary of reactor development tests performed or planned for historic NTP programs

Test Type	Test Description	Test Objectives	Variable Range Explored	Test Article Description	Related Program	Performed or just Proposed?
Cold Flow Testing	Cryogenic/room temperature fluid pumped through reactor core	Evaluate fluid-structural interactions with components	<342 pulses/s	Un-fueled or as built reactor	1) Rover/NERVA (Kiwi Cold Flow tests) 2) Pluto (Tory II-A)	Performed (1, 2)
Hot Flow Testing	Hot fluid pumped through reactor core or unheated fluid pumped through a heated (simulated) reactor core	Evaluate corrosion effects and fluid-structural interactions with components, evaluate thermal response of reactor materials	300–1514 K, 40 MW_{th}, 103 pulses/s	Un-fueled or as built reactor	Pluto (Tory II-A)	Proposed (Pluto)
Zero Power Critical Experiments	Bring the reactor (or representative assembly) critical while keeping fission heat generation at a minimum	Evaluate neutron population/power distribution, evaluate component worths, evaluate reactivity of the reactor.	1) 200–1800 pulses/s, 1 kW_{th}, 1.33 hours 2) 107–283 L core volume, 192–494 kg critical mass 3, 4) Unknown	1, 2) Mockup, as built reactor, or subscale reactor 3) U-W cermet with Al/BeO/Alumina reflector 4) Unknown, information at Sandia National Laboratories	1) Rover/NERVA 2) Pluto (Tory II-C Run 87) 3) ANL NR (Critical Experiments 1–9) 4) SNTP	Performed (1, 2, 3, 4)

Critical Tests for Design Basis Accidents and Control System Demonstration	Reducing the coolant flowrate and temperature to reactor core operating at full power	Evaluate reactor safety under thermal stresses above design point	170 MW_{th}, 1644 K, 197.3 kg/s, 477 K air inlet, 90 s total	Un-fueled or as built reactor	Pluto (Tory II-A)	Performed (Pluto)
Reactor Ground Tests	Full power critical experiments at various power/thrust levels	Demonstrate steady-state operation of reactor under prototypic operation, reliable operation of control systems Gather performance data to validate previous design work and separate effects tests	1) 200–1260 pulses/s, 313 MW_{th}, 750–1405 K chamber temperature, 1.75 hours 2) 200–1660 pulses/s, 485 MW_{th}, 745–1566 K chamber temperature, 1 hour 3) fast start-up: 1644 K, 1800 pulses/s, 480 MW_{th} in 1 minute, hold for several minutes 4) 548–1096 MW_{th}, 6–46 minutes → 4 cycles 5) <1120 MW_{th}, 14.5, 15.5 and 62 minutes 6) 200–2000 s, 1–75 MW/L	Mock up, as built reactor (1–5), or subscale reactor (6)	1–3) Pluto (Tory II-C Run 88, 89) 4, 5) Rover/NERVA (NRX-A2 & A3, A5 & A6) 6) SNTP (Particle Bed Reactor Integral Performance Tester)	Performed (1, 2, 4, 5) Proposed (3, 6)
Integrated (Engine-Reactor) System Testing	Full power critical experiments with engine hardware at nominal power/thrust levels	Demonstrate repeated operation of reactor with desired performance	1) 1140 MW_{th}, 2272 K chamber temperature, 105 minutes total → 24 cycles 2) 100–1000 s, 20–60 MW/L	As built reactor, or subscale reactor with engine integration	1) Rover/NERVA (XE Prime) 2) SNTP (Ground Test Article Engine Test)	Performed (1) Proposed (2)

3.3. NTP Reactor Development Program and Facilities Recommendations

Using the information gained through this historic NTP program review, the tests used to develop NTP fuels and reactors have been compiled into a flowchart, shown in Figure 12. Each swim lane is meant to identify a category of test (manufacturing, nuclear environment, non-nuclear environment, physics and control). These categories were chosen based on the broad kinds of information that their tests can provide for NTP fuel/reactor qualification, with manufacturing demonstration feeding in as necessary to advance the size of test articles. The symbols in each test box indicate the size of test article intended for that test, with sizes generally increasing from left to right. The arrows illustrate what test results are considered prerequisite for other tests, informed by the literature. Each test is also matched with a TRL rating, determined based on the achievements of historic tests performed and the resulting information gained from that test. TRL descriptions from (Frerking and Beauchamp, 2016; JANNAF Spacecraft Propulsion Subcommittee, 2019; Mankins, 2009, 1995) are used to evaluate these test TRLs, and the TRL ratings for each historic program.

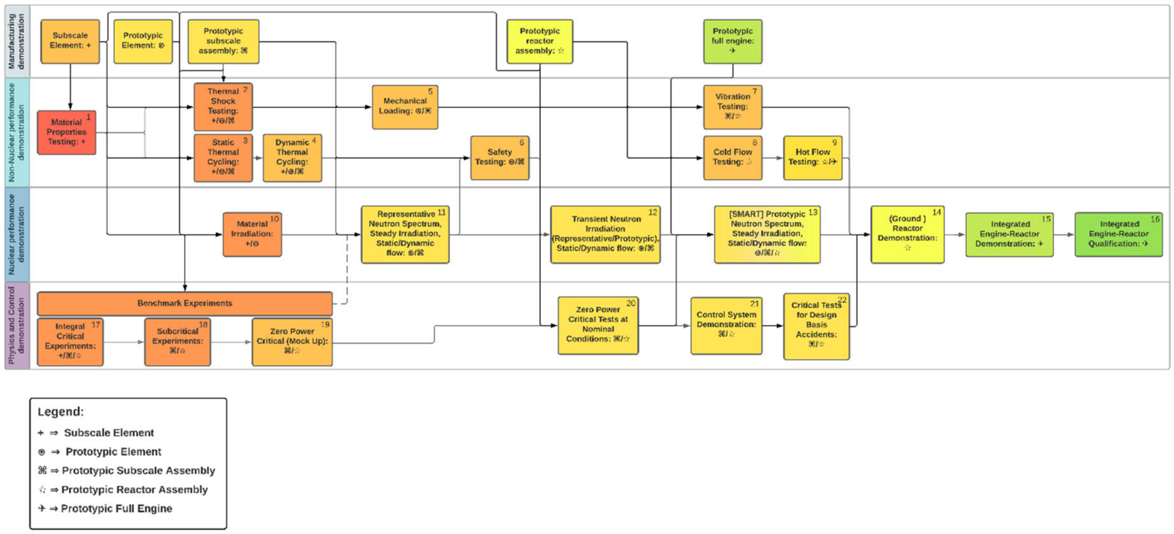

Figure 12: Compilation of qualification tests performed by historic NTP programs, grouped by test category and expected/actual test progression

NTP reactor maturation is highly dependent on demonstrating subsystem performance under prototypic operating conditions. There are two important aspects to the development of NTP reactor components: manufacture or assembly at the appropriate scale (component level geometries as well as production rates) and testing to demonstrate the reactor subsystem and its critical components are capable of meeting performance requirements under NTP operating conditions. Historic testing programs have shown that the different aspects of this environment important to match, i.e. comparable to those in a full scale operational NTP engine, during demonstration testing include component temperature ranges, pressures and mass flow rates of the circulating propellant, the irradiation fluxes, and operating lifetime (including number of transients). Historic development programs have also demonstrated overall NTP reactor feasibility and identified primary reactor development challenges. Therefore, it is possible and expedient to develop components and demonstrate material performance through incrementally more complex manufacture and testing activities, beginning with laboratory scale manufacture activities and separate effects testing progressing eventually to prototypic scale assembly tests under combined effects conditions. This approach was proposed in the GE 710, ANL, and SNTP programs and allowed for more affordable and rapid development of fuel forms, due to the ability to iteratively develop fuel forms by allowing for performance data to inform manufacture activities. Furthermore, this approach is anticipated to provide the testing data desired for validation of models used to design both fuel and reactor systems and is also congruent with recommendations for accelerating modern fuel qualification activities (Terrani et al., 2020). If testing, modeling, and simulation are used in this way, the required testing program can be minimized so that focused experiments may be planned which confirm model predictions. This approach will require that existing fuel performance models, reactor multi-scale, multi-physics analyses, and performance databases be adapted for NTP fuel and reactor designs. Subscale separate and combined effects testing should aim to validate adapted models and expand existing databases to cover the range needed for NTP reactor operation. Beyond component level testing, to improve the maturity of the NTP reactor and reduce risk ahead of an NTP engine-reactor demonstration, a reactor core assembly should also be tested to show functionality and validate models at the prototypic scale, including: reactor physics, fluid-structural interactions, and thermal-structural response under prototypic conditions.

Reflecting on the compiled list of tests in Figure 12, a flowchart of fuel and reactor qualification tests was made to illustrate the recommended progression of tests en route to successful NTP engine demonstration (Figure 13). Because of the progress related to fuel manufacturing and separate effects testing in modern NTP development programs, the flowchart is focused on tests that will bring modern NTP programs closer to fuel and reactor qualification while minimizing risk from knowledge gaps. Most important to buying down risk to reactor qualification is validating performance in a prototypic combined effects environment, including: hot hydrogen environment (flow rate, thermal cycling temperatures, and pressures), nuclear environment (power density and total fluence), as well as material response to thermal/nuclear transients (including thermal shock) under all designed operation modes. Therefore, reactor qualification will require testing of prototypic scale fuel assemblies in a combined effects environment. There is currently no facility capable of conducting such tests. PIE capabilities are also needed to characterize the fuel after testing to confirm fuel integrity following integrated effects testing and confirm fuel forms do not exhibit unacceptable compositional or property evolution. Capability to gather data related to fission product inventory, material activation, and fission product release is also desirable for informing future integrated system testing and related concept of operations. Future NTP development programs would greatly benefit from such facilities to reduce risk prior to a reactor demonstration. The remaining residual risks to fuel performance beyond a combined effects demonstration include inter-element effects due to interaction of fuel assemblies with each other in the reactor and specific variations in the environment that may result due to the engine interface (such as fluid dynamics or vibrations from turbopump operation). Testing subscale fuel assemblies with a ground test reactor can reduce this first residual risk and engine-reactor testing will resolve the final risk related to fuel performance during operation.

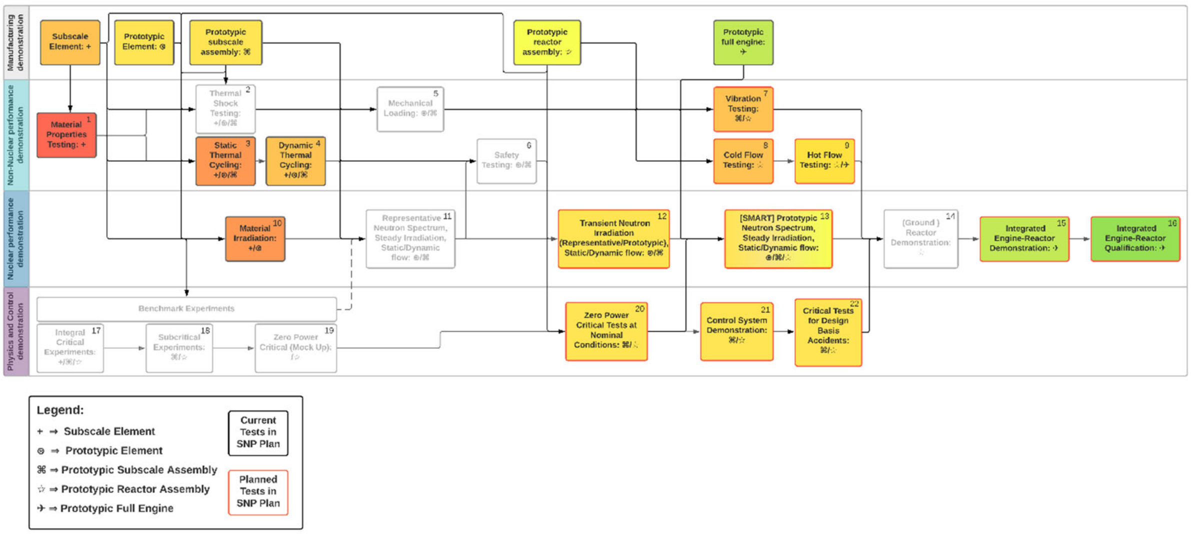

Figure 13: Compilation of qualification tests performed and planned for the NASA SNP program

To qualify nuclear fuels and reactors for NTP systems, they must be tested in prototypical environments comparable to those which the reactor components would experience in a full scale NTP engine (Werner et al., 2019). Currently, experimental capabilities for NTP qualification in the US are limited to separate effects testing (both non-nuclear/out-of-pile and nuclear/in-pile tests) of individual components or subscale components (Palomares et al., 2020). Therefore, improvements to experimental facilities will be needed to support future qualification of reactor subsystem components and later the fully assembled NTP demonstration engine. Further, once fuel performance has been demonstrated on a component level, there is a level of technical risk that remains related to fuel assembly interactions within the reactor core. Guidance from historic NTP programs suggests that an intermediate, subscale test facility for NTP subsystems is useful to advance NTP reactor development past the component level; this approach mitigates risk that would be involved in moving from current capabilities to a full NTP engine demonstrator. A Subscale Maturation Advanced Reactor Technologies (SMART) facility will mitigate risk to NTP reactor development programs by enabling testing of fuel components under integrated effects environments. With an effluent treatment system or with a contained flow loop, subscale fuel assemblies could be tested with a driver core similar to the proposed PIPET experiment in SNTP, or a test loop in an existing reactor.

In order to prepare for reactor testing beyond the subscale, a new facility capable of performing control system demonstration, design basis accident scenarios and safe handling during assembly/disassembly may be necessary. This facility can be later expanded to test stands for integrated tests with engine subsystems, and facilities for PIE to allow for more rapid evaluation of system performance. This new facility is required because currently there are no facilities which can provide the combined prototypical conditions (heat, pressure, flow rate, neutron flux etc.) for an entire core assembly. The location of a ground test facility for full scale reactor-engine testing wouldn't necessarily need to be dependent on proximity to an existing reactor or driver core, since at full scale the reactor could provide its own particle fluxes and heat at the level required to test reactor components under prototypic conditions and would only require accompanying flow injection and effluent treatment systems to generate the full set of operating conditions. Because of the long lead times and expense that will come with this facility's development, test objectives and the testing program should proceed in parallel to SMART facility development in order to reduce risk in bringing NTP reactors to full qualification within SNP's desired timeline.

4. Conclusions

Due to the unique operating conditions of an NTP reactor, the history of NTP reactor development centers around achievable testing activities based upon available facilities and their limitations. Since an NTP reactor uses a hydrogen working fluid, extremely high-power densities, and fast thermal transients to produce the prototypic testing environment for fuels, components and subsystems, new facilities development often has been needed to support NTP reactor maturation beyond TRL 4. Developing new testing facilities often involves significant expense, thus a lower cost alternative is modification of existing facilities. While only an entirely new facility may be able to produce the entire suite of prototypic conditions in an NTP system, separate effects can allow for initial component level testing and data to be generated for modeling validation. This testing can be performed with existing or slightly modified facilities.

Modeling and simulation may be used in tandem with separate effects testing to predict fuel performance under combined effects conditions, such as that expected during operation. This approach allows for initial screening of components and identification of any performance limits that preclude feasibility of such a concept for the envisioned use case. This approach also buys down risk associated with attempting full scale reactor/engine tests without rigorous fuels/components testing in all relevant conditions without an established performance database.

The main challenge for NTP reactor and fuel development moving forward is related to enabling the more complex testing environments desired for improving TRL beyond preliminary technology development (TRL 4). This includes prototypic, combined effects testing (irradiation and hydrogen environment) of engineering scale (full-sized or segments of) fuel and moderator elements as well as PIE of these elements to provide material performance data to validate multiphysics models. These knowledge gaps should be addressed before moving to reactor and engine qualification to increase confidence in meeting testing objectives. Some of the most significant outstanding risks which may impact reactor-engine performance and functionality include unknown interactions between elements and the impact of those interactions on the operating environment (including power and stress distributions within the reactor). To meet this need, a Subscale Maturation of Advanced Reactor Technologies (SMART) facility can mitigate risk to NASA's SNP program by enabling integrated effects testing of NTP fuel assemblies. SMART can further fuel qualification for NTP systems by demonstrating element performance under integrated effects conditions as well as element-element interactions. This testing data can build upon the fuel performance data obtained from separate effects testing, predictive computational modeling, and manufacturing process development. Crucial to fuel and reactor qualification are prototypic test conditions which capture the hydrogen environments (temperature, pressure, flow velocities) and irradiation environments (power density) over total component lifetime. A SMART facility can be designed to provide prototypic irradiation in a combined effects environment to a subset of an NTP reactor to improve the TRL of the NTP reactor subsystem. For verification of reactor subsystem performance when integrated with the non-nuclear engine, a new ground testing facility could be used to demonstrate repeated, safe operation of the full core at prototypic operating conditions.

Historic programs underscore the importance of integrated system testing, since only after reactor operation at prototypic conditions have been established with a prototypic engine interface can NTP systems advance to TRL 7 and beyond (Aerojet-General Corporation, 1970b). Ground testing provides full system validation of performance predicted by models in a way that separate and subscale testing cannot. In order to expedite reactor testing and subsequent qualification, a ground testing facility must be built that can house reactor assembly/disassembly equipment, a test stand allowing for integrated reactor-engine tests, and accompanying experimental apparatus to verify prototypic conditions are achieved during tests.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

William Searight: Conceptualization, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Kelsa Palomares:** Conceptualization, Investigation, Writing - original draft, Writing - review & editing, Supervision. **James Werner:** Writing - review & editing. **Michael Todosow:** Writing - review & editing. **Katey Lenox:** Writing - review & editing.

Acknowledgements

This work was supported by NASA's Space Technology Mission Directorate (STMD) through the Space Nuclear Propulsion (SNP) project. William Searight and Kelsa Palomares were funded under Contract No. 80LARC17C0003 Task No. 10.022.000. The authors wish to thank the members of the SMART team: Katey Lenox (INL), Douglas Burns (INL), James Werner (Walsh Engineering), Michael Todosow (BNL) and Robert O'Brien (INL), as well as Isabella Rieco (UW), for their support and helpful feedback. The SMART team also thanks the Department of Energy for their support. The opinions expressed in this work are solely those of the authors and do not necessarily reflect the views of the National Aeronautics and Space Administration or the Department of Energy.

Authors' Note

Effort has been made to convert all original English/Imperial quantities to SI quantities, with force (lbf) being the exception. This exception was made in order to make historical rocket concepts more directly comparable to modern designs, since the lbf is still used as the unit for engine thrust requirements.

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