

Steps in the Development of Nuclear Thermal Propulsion Fuels

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Abstract—As a result of recent increased interest in Mars exploration and other deep-space missions, the idea of a US Nuclear Thermal Propulsion (NTP) system has been rekindled, and the feasibility of such a program will be revisited. Making and qualifying an NTP fuel that meets mission performance requirements is an essential first step. Graphite fuels and ceramic metal (cermet) fuels are of particular interest since these fuels have shown significant advantages over other fuel types. This paper will address the history of NTP fuel fabrication technology as related to the Nuclear Engine for Rocket Vehicle Application, GE 710, and ANL nuclear fuel program, as well as recent efforts in recapturing heritage fuels and developing new NTP fuels. Substantial experimental databases and supporting documentation exists for the graphite composite fuel option. Some irradiation and high temperature test data is available for cermet fuels, but cermet fuels were never tested in prototypic NTP conditions. A first step in the development effort will be a fuel fabrication recapture effort to provide samples to show that the technology works and that the performance of the fuel is acceptable. Advances in fuel fabrication, materials processing, and coating technology are expected to improve and/or enhance future fuel development, maturation, and certification efforts. The current plan is to perform non-nuclear, separate-effects, and integrated tests to provide additional test data and insight into the capabilities of each fuel and to use that data to evaluate potential performance within an NTP engine stage.

Recently, interest has focused on development of engines with thrust levels of approximately 25,000 lb and a targeted Specific Impulse (Isp) of ~900 s. To achieve these performance parameters, an NTP reactor must heat a specified flow rate of hydrogen propellant (used because it has the lightest molecular mass and is the best performing propellant) to temperatures of 2,700 K or more. The reactor fuel must operate at higher temperatures to transfer heat to the propellant but it must not exceed its melting temperature or the melting temperatures of the surrounding reactor/rocket components. For this reason, nuclear fuels with melting temperatures exceeding 2,900 K are considered for NTP applications and are operated to within ~100 K of their melting temperature. The total power required to heat the propellant to the desired temperature can be independent of reactor size. Increasing the fission power density within the reactor fuel allows the reactor to be smaller while still achieving similar power levels, which is advantageous for flight systems. Similar to melting temperatures, different fuel forms (composition and shape) generally have different allowable fission power densities.

In 2014, an interagency Nuclear Cryogenic Propulsion Stage Fuel Evaluation Committee, consisting of NASA and US Department of Energy (DOE) members, evaluated several nuclear fuels in order to identify the most promising for Nuclear Thermal Propulsion (NTP). The study was focused on Highly Enriched Uranium (HEU) graphite fuel and HEU cermet fuel. The nuclear fuel contained within these base materials is Uranium-235 (U-235). The ratio of the U-235 to the total uranium within the fuel is the enrichment. HEU is generally considered to be any enrichment where U-235 makes up greater than 93% of the total uranium. By definition, Low Enriched Uranium (LEU) is less than 20% U-235. HEU is typically considered for space power applications because it can be used to make small reactor systems. The balance of uranium in the fuel that is not U-235 is mostly U-238, which is chemically identical to U-235 but is not reactive in the nuclear sense (it is nonfissile). However, U-238 does have important nuclear characteristics that can influence reactor design and operation. LEU has different regulations with respect to handling and safeguards than fuel with enrichments above 20%.

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1. INTRODUCTION

For Nuclear Thermal Propulsion (NTP) systems to be successful, many issues must be investigated and overcome. Engine performance must be acceptable for the mission architectures being considered. This performance generally relates to overall engine thrust, specific impulse, and mass.

Both graphite and cermet HEU fuels have the potential for use in NTP engine concepts. However, to date, analysis suggests that comparable HEU cermet-fueled concepts require core fission power densities to be as much as three times higher than in a comparable graphite fueled system and require as much as seven times the amount of U-235 [1]. Performance data available for cermet fuel in reactor environments is limited to values well below the temperature and fission power density needed for NTP reactor systems. Graphite fuel was demonstrated in numerous NTP reactors of various sizes and configurations during the Rover and Nuclear Engine for Rocket Vehicle Application (NERVA) programs of the 1950s, 1960s, and early 1970s. Thus, with demonstrated performance near or beyond that needed for Mars missions, the greater chance of success and lower cost for successfully developing NTP systems (at least in the near term) was deemed by DOE to reside with the use of graphite-based composite fuels. This position was, in part, a response to the scheduling issues associated with a prescribed early demonstration flight and a proposed mid-2030s launch date. The DOE does, however, recognize the potential of cermet fuels. Cermet fuels are recommended as an alternate fuel rather than a primary fuel because of their limited experience base and unproven performance in NTP conditions. Cermet fuels are thought to require longer development, characterization, and qualification times, in addition to the need to develop a corresponding reactor core support structure.

NTP fuel forms from graphite or cermet materials can generally be categorized into a two by two matrix, as shown in Table 1.

Table 1. Leading fuel forms for NTP systems and their characteristics

	Graphite	Cermet
Thermal spectrum	Graphite is the moderator. HEU is the preferred fuel but LEU systems are possible.	Moderator must be added. Parasitic neutron absorption may require control through isotopic selection of tungsten. LEU systems may be possible.
Fast spectrum	Not viable.	Must be HEU.

The NTP project funded NASA’s Science Technology Mission Directorate (STMD) and its Game Changing Development (GCD) program has a current emphasis on the examination of cermet fuels, with an added emphasis on investigating whether LEU-NTP systems could be developed at lower lifecycle costs. Potentially, LEU reactor systems could be commercially provided to NASA by industry in a joint government/industry effort. LEU systems may offer increased handling flexibility (i.e., less security needed and thus lower security costs) and a potentially easier path to

commercialization compared to HEU systems.

NTP reactor development, regardless of fuel technology, will progress through a series of development, demonstration, and qualification efforts that could include the following development tasks:

- fuel development and preliminary qualification;
- core component and subsystem development, testing, and qualification;
- core design;
- fuel and component testing under prototypic conditions and production qualification;
- development and qualification of fuel and component fabrication facilities;
- development and qualification of nuclear testing facilities;
- core low-temperature, zero-power testing, full flow testing;
- launch vibration qualification;
- core elevated temperature, zero-power critical testing;
- startup, transient, and full-power reactor testing with facility-controlled coolant flow;
- reactor post-test examination and design change modifications;
- first generation reactor integration and operation with engine stage;
- flight system design qualification testing; and
- flight article acceptance testing
- flight.

2. FUEL RESEARCH SUMMARIES

All graphite-based fuels—whether HEU or LEU—are used to make a “thermal” reactor. In a thermal reactor system, the neutrons are slowed due to atomic level interactions with the moderator material, which is typically composed of lighter elements (such as carbon or hydrogen) that do not absorb a significant percentage of neutrons. At lower energy levels, neutrons are more likely to interact with U-235 and produce fission. An LEU cermet system also requires moderation, and so moderating material must be added to a cermet core. Thus, LEU cermet cores are generally bigger than HEU cermet cores. Unprotected thermal NTP reactors will generally go critical in a water immersion event, whereas “fast” reactors are easier to design so that they remain subcritical in water immersion events. This potentially simplifies the safety case for fast reactor systems. Within an NTP system, the reactor coolant and the rocket propellant are the same hydrogen inventory. Hydrogen is an effective neutron moderator, thus its insertion into the core can result in significant positive reactivity, which—in an already thermalized system like the graphite systems and LEU cermet systems—can lead to overpower events.

Graphite-based fuels are advantageous because they are common in reactor design and have been demonstrated in complete reactor cores near the performance levels required

for the relevant NTP systems. The fuel formulation and reactor core structure are largely known, and reactors that can produce engine systems of the size of interest to current NASA Mars mission architectures have been successfully built and operated beyond, at, or near most necessary operating points. [8].

Coated particle graphite fuels were studied extensively from 1955 to 1975 and were a leading fuel technology because of their greater experience base, lower thermal neutron absorption cross section, and ease of fabrication. Graphite fuels are being developed and studied for commercial high-temperature reactor applications today [2]. Composite fuels, in which carbide-based ceramic fuel is mixed within a graphite matrix, were considered a “drop-in” replacement to coated particle graphite fuels used in the Rover/NERVA reactors in configurations similar to that shown in Fig 1.

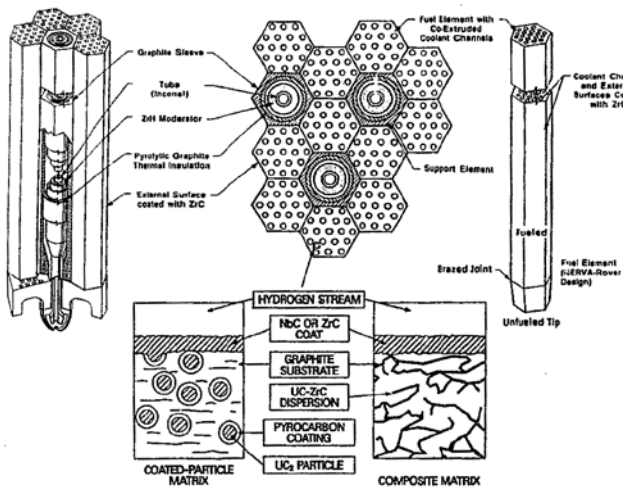


Fig. 1. Schematic of coated-particle fuel and composite fuel as used within the core of NERVA reactors.

These composite fuels were tested under representative reactor conditions in the Nuclear Furnace-1 (NF-1), [3], which was a reactor designed to test fuel to the necessary operating conditions but was not a standalone NTP reactor. Westinghouse also performed full-length, externally-heated tests at approximately 2700 K (but not in an irradiation environment). The composite fuel form was to be tested in an NTP reactor, but the program was cancelled prior to the test. In follow-up reactor concept development efforts, such as the Small Nuclear Rocket Engine (SNRE) [4], zirconium hydride (ZrH) tie tubes were inserted into composite fuel cores for additional neutron moderation, which allowed for smaller cores. The SNRE concept was predicted to produce 16,400 lb of thrust at a specific impulse (Isp) of approximately 900 s but the system was never built. A schematic of the SNRE is shown in Fig 2. Liquid hydrogen from a tank flows through a regeneratively cooled nozzle, where it is vaporized and pre-heated before passing through the core tie-tubes and finally through the reactor fuel where it is heated and ejected

out of the nozzle to create thrust.

During the Rover/NERVA programs, fuel elements experienced cracking of the protective zirconium carbide (ZrC) coating on regions of some of the inner coolant channels of graphite-based coated particle-fuel elements, and this issue was never fully addressed. Graphite composite fuels have a higher thermal expansion coefficient than graphite particle fuels, making them, in theory, a better match for the expansion of ZrC. However, the NF-1 composite fuel irradiation tests resulted in cracking on the protective coating and within the composite fuel matrix of some elements under those particular test conditions. Additional coating options, including the use of multiple layer coatings, are being pursued to ameliorate the coating cracking issue but they have yet to be implemented and tested.

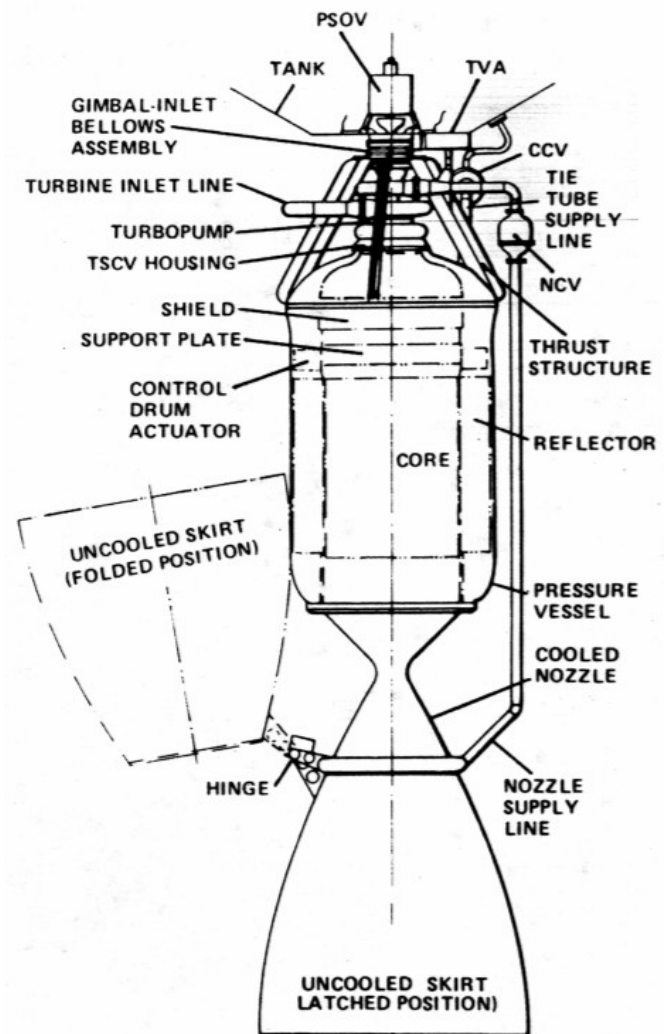


Fig. 2. Diagram of SNRE.

Cermet fuels have been made in a number of compositions and forms. However, these metal and ceramic composite fuels generally have less fabrication pedigree because none of them had extended development or demonstration efforts. There is limited operational experience with cermet fuels in a

reactor environment and that is generally as irradiation samples at conditions below those required for NTP systems. Previous analyses suggest that, in order to produce competitive engine designs, cermet fuel systems will have to operate with peak power densities 2–3 times higher than required for graphite-based systems [1]. Thus, if a cermet NTP system is to be developed, a fuel will have to be created, characterized, incorporated into a structural design, and qualified for service at the higher power densities. The majority of cermet fuel research was carried out through two rocket programs: the GE-710 [5] Program and the Argonne National Laboratory (ANL) [6] Nuclear Rocket Program. The GE-710 fuel and system were designed for higher thrusts (25,000 lb and above) and did not scale favorably to lower thrust scenarios. The ANL-200 fuel, on the other hand, scaled down favorably to lower thrusts (10,000 lb), but did not scale well to higher thrust scenarios.

Cermet fuels were tested in the Oak Ridge Research Reactor and Low Intensity Test Reactor. Approximately 50,000 hours of test data were collected [7]. However, the temperatures were limited to ~ 900 K, and the power densities were limited to ~ 0.4 MW/l. Also, the irradiation tests were not conducted in a relevant hydrogen environment. Relevant irradiation tests (in a hydrogen environment) may be needed for the qualification of any NTP fuel and will be difficult to achieve in currently available research reactors. Some limited recent progress has been made toward developing a cermet NTP fuel, and a new effort is under investigation within the current NTP program in NASA.

3. LEU REACTOR SYSTEMS

NASA is currently considering the use of LEU cermet NTP systems. This activity includes 1) analytical comparison of LEU cermet systems to competing HEU graphite systems, 2) affordable demonstration of the required material modifications to make a viable LEU cermet system, 3) fuel fabrication and performance demonstration, and 4) evaluation of any potential programmatic differences between LEU cermet systems and heritage graphite systems that could result in cost savings.

For LEU cermet NTP systems to be successful, additional issues must be considered. Cermet fuels contain high-temperature refractory materials (often molybdenum or tungsten) that may require isotopic tailoring to improve neutron economy. Thus development for LEU cermet may be contingent upon the ability to isotopically tailor refractory metals to the levels needed large quantities in an affordable manner.

Handling of HEU and operation of HEU reactors in the United States is generally limited to government and occurs within highly controlled and secure environments under strict operating protocols. The use of an LEU fuel could potentially avoid some of the costs associated with security, and it may also present more opportunity for greater industry participation, which could potentially reduce lifecycle costs. The safety requirements for LEU and HEU reactors that are

to be operated on Earth for testing and qualification purposes, however, are the same and are derived largely from the inventory of fission products that could be released in an accident scenario. Terrestrial reactors typically require either 1) containment, in which the fission products are retained within a pressurized and sealed surrounding structure or 2) confinement, in which fission products are held or delayed in a manner that allows an eventual, acceptable release to the environment or 3) have limited operation so that hazardous levels of fission products are never permitted to build up in the core. Commercial reactors in the United States have large containment buildings because they can have large radioactive inventories. NTP systems, on the other hand, will have limited operational time and therefore much less radioactive inventory. They could potentially be operated without a containment structure, but they may still contain a significant amount of radioactive material that must be controlled to ensure any releases to the public and the environment remain within regulatory limits. Test facility requirements will ultimately depend on the reactor configuration, operating plan, and location. Creating facilities in which reactor cores can be handled, reactors can be constructed and operated, and reactors can be disassembled and inspected after operation—all while appropriately storing fresh or radioactive nuclear material and managing all waste streams—is a complex undertaking. An affordable program will have to carefully consider these costs and decide when and how to use existing infrastructure or whether to make new investments.

The safety environments of both space and nuclear industries have changed considerably since the days of the Rover/NERVA projects, and combining cryogenic hydrogen-handling operations with reactor operations will be a significant challenge for either HEU or LEU NTP systems. It is anticipated that less reactor experimentation will occur compared to the Rover/NERVA programs due to higher costs, lower budgets, and stricter testing protocols. NASA and DOE are collaborating to understand and address the challenges of such a program. Fortunately, emerging capabilities can be brought to bear on NTP development to ensure that progress can be made with increased confidence early in the development activity with less experimentation. Examples include advanced modeling and simulation, coupled multi-physics analysis, and—potentially—additive manufacturing (3-D printing) to decrease component fabrication cost while increasing fabrication repeatability. However, physics models and relevant benchmarking data do not exist for many important phenomena, with perhaps the most significant being fuel performance. Therefore, a robust fuel development and testing approach is needed.

4. CONCLUSION

The possible paths to develop an NTP capability are being compared within the STMD NTP project during FY 2017. Progress towards realizing an NTP flight system will require a series of development and demonstration activities. This process must also include planning for industry participation (procurement strategy) and preparing regulatory agencies for

approval of a reactor concept well outside of their normal experience base. Additionally, qualified nuclear facilities and experienced design and operations teams from both the reactor and rocket industries will have to be put in place. DOE concluded from the previous NTP studies that graphite composite fuels are ahead of cermet fuels and carry less programmatic risk for near-term NTP development, demonstration, and operation. However, cermet systems are currently being investigated, with an emphasis on LEU cermet systems, to determine whether they offer significant programmatic benefits. Issues associated with LEU cermet systems, including fabrication and performance verification of fuel, comparison of reactor and engine performance, and whether LEU systems offer cost advantages over HEU systems, are being considered. Scheduling remains an important additional consideration assuming that a space reactor will be necessary for a manned mission to Mars in the mid-2030s. NTP systems are complex systems, and carefully coordinated efforts among industry and multiple government agencies will be required to mature this technology to flight.

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BIOGRAPHY



Lou Qualls graduated from the University of Tennessee with a Ph.D. in nuclear engineering in 1991 and is currently a Distinguished Researcher at Oak Ridge National Laboratory. He supports the Department of Energy (DOE) in collaborations with NASA related to space power applications.



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