Recapturing NERVA-Derived Fuels for Nuclear Thermal Propulsion

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The Department of Energy is working with NASA to examine fuel options for Nuclear Thermal Propulsion applications. Extensive development and testing was performed on graphite-based fuels during the NERVA and Rover programs through the early 1970s. This paper explores the possibility of recapturing the technology and the issues associated with using it for the next generation of nuclear thermal rockets. The issues discussed include a comparison of today's testing capabilities, analysis techniques and methods, and knowledge to that of previous development programs and presents a plan to recapture the technology for a flight program.

Nomenclature

DOE	=	Department of Energy
DU	=	depleted uranium
LASL	=	Los Alamos Scientific Laboratory
NASA	=	National Aeronautics and Space Administration
NbC	=	niobium carbide
NERVA	=	Nuclear Enginer Rocket Vehicle Application
NF	=	Nuclear Furnace
NTP	=	nuclear thermal propulsion
UO_2	=	uranium dioxide
UC	=	uranium carbide
ZrC	=	zirconium carbide

I. Introduction

THE United States began development of nuclear thermal propulsion (NTP) rockets in the early 1950s and continued through the early 1970s. America is still discussing ambitious missions that will take human explorers to Mars or Near Earth Objects, and nuclear thermal propulsion provides unique and important capabilities that can make those missions successful and affordable. The fuels developed and tested for the NTP program were ^{235}U in a graphite matrix. These fuels evolved quickly from the simple uranium and carbon fuel mixtures that experienced a large number of failures to the sophisticated coated composite fuels that performed well during extended operation at temperature and through multiple restarts. The composite fuels are no longer being made, and time is limiting access to the people and equipment that made them. A starting point to recapturing NTP is recreating the fuels that made the early reactors successful. NASA and the Department of Energy have begun this process and are also looking at modern capabilities that could potentially improve the fabrication process and perhaps fuel performance.

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II. Fuel Development History

The original ROVER program began in 1953 as a backup technology to chemical intercontinental ballistic missile technology. Initially, Los Alamos Scientific Laboratory (LASL) ran the KIWI program, and Lawrence Livermore Laboratory operated the TORY program in parallel efforts. The KIWI program was ultimately chosen for futher development, and the Los Alamos activity became the ROVER program. The main phase of the ROVER program began in 1955 under the joint direction of the Atomic Energy Commission and the United States Air Force.

Eight ground-based reactors were tested under the KIWI program. The KIWI-A reactor used uncoated graphite fuel plates protected by an unfueled graphite layer. The resulting core was approximately 18 inches in diameter and 54 inches long. The reactor ran for 5 minutes and reached a peak power level of 70 MW(t). Post-test examination showed that some of the KIWI-A fuel elements reached temperatures in excess of 2889 K so the KIWI-A' and KIWI-A3 reactors used cylindrical fuel elements with four internal coolant channels in an effort to reduce element temperature. This fuel still showed evidence of blistering, corrosion, and transverse cracking, and the tests demonstrated the need to limit tensile loads on graphite structures within the core. The A series of KIWI tests established the viability of the concept but clearly demonstrated the need for better fuel.

The KIWI-A series was a 100-MW(t) class of reactors. The KIWI-B series was a 1000-MW(t) class that began operation in the fall of 1961. The KIWI-B reactors used pyrocoated fuel particles in a graphite matrix with the exception of KIWI-B4E, which used 50–150 micrometer diameter UC_2 particles. In the B series, six hexagonal fuel elements were supported by a central, nonfueled tie-rod element. In this configuration, dynamic flow instabilities in the gap between adjacient fuel clusters resulted in vibration that led to broken fuel elements.

In 1967 the Phoebus IB reactor operated at approximately 1500 MW(t) for a planned run time of 30 minutes, and post-test examination showed excellent core condition. This test demonstrated a power density approaching 1 MW per fuel element for a duration relevant to deep space missions. The Phoebus 2A reactor used a two-pass tie-rod system in a core with 4068 52-inch-long fuel elements. The fuel elements were UC_2 pyrocoated particles in a graphite matrix. The outer surface of the elements was protected by a NbC-Mo coating. It was the largest propulsion reactor tested and achieved a maximum power level of approximately 4100 MW(t). The fuel elements from the reactor each showed a mass loss of 10 to 13 grams per element after four high power runs of approximately 12 minutes. By the end of the Phoebus tests, a mature core structure design was demonstrated in which fuel elements did not break, although they did experience mass loss.

The PEWEE-1 reactor was designed as a testbed for advanced fuel elements for the Phoebus and NRX reactors. Fuels coated with NbC and ZrC were tested in PEWEE-1 for a total of 40 minutes at power levels of approximately 500 MW(t). Fuel elements produced power levels of 1.2 MW(t) per element, and the core had an average power density of approximately 5200 MW(t)/m³. Though it did experience core damage, this smaller reactor achieved a record exhaust temperature of 2550 K. Post-test examination of the fuel demonstrated that the ZrC-coated elements performed better than the NbC-coated elements. A propulsion system based on the PEWEE-1 reactor could be used to generate a 25,000 pound thrust class rocket, which would be directly applicable to missions being considered by NASA today.

The Nuclear Furnace (NF-1) reactor was a 44 MW(t) reactor testbed used to test advanced hexagonal elements. Forty-nine fuel element cells were tested. Forty-seven of those were (U,Zr)C-graphite "composite" fuel with a carbide content of 30% to 35% by volume. Testing of these elements demonstrated that matching the thermal expansion of the coating and the matrix reduced coating cracks and limited carbon mass loss; however, the ZrC coatings showed some susceptibility to radiation damage. The other two fuel element cells contained (U,Zr)C solid solution with a carbide content of 100%. These elements were impregnated with 0%, 3%, or 8% Zr. These fuel elements showed transverse and longitudinal fractures but no fragmentation. The 8% Zr elements showed the least amount of fracture. NF-1 is significant because it operated in a closed loop effluent cleanup system to retain fission products. This technology could potentially be used to test modern NTP reactor concepts.

The Nuclear Engine for Rocket Vehicle Application (NERVA) program was focused on the development of a reusable flight-rated propulsion system based on technology developed in the ROVER program. The NRX reactors were developed to demonstrate that the KIWI-B series reactor structure could be adapted to launch and flight conditions. The NRX-A2 reactor closely resembled the KIWI-B4E and operated for 6 minutes. The test resulted in no broken fuel elements; however, incipient corrosion was observed around the core periphery. NRX-A3 was the first reactor to use externally coated fuel elements around the periphery, which eliminated the corrosion for the short 15 minute test. The NRX-A4 was the first reactor coupled to major engine components and was operated in 1966 as part of the NRX/EST test. The engine was started 11 times and operated for a total of 29 minutes at full power. The elements suffered significant corrosion in the mid-band region of the core, and 528 were broken. NRX-A5 was tested in two 30-minute runs at 1120 MW(t) and showed that in-core corrosion resulted in a nontrivial loss of

reactivity ($2.2) after 40 minutes of operation. The NRX-A6 doubled reactor power and test duration with a 75%–80% reduction in the fuel element corrosion rate, which was attributed to improved channel coating techniques, better dimensional control across the flats, better regard to matching the coefficient of thermal expansion between the coating and matrix, and a flattened core power distribution.

III. Composite Fuel Development

The reactor concepts developed by LASL used pyrocarbon-coated UC_2 spheres in a graphite matrix. NbC and ZrC coatings were used on the exposed surfaces of the elements to minimize carbon loss due to reaction with the hydrogen coolant/propellent; however, appreciable mass loss occurred. Two approaches to this problem were developed. In one effort, an all-carbide fuel element of uranium/zirconium carbides in solid solution and substoichiometric in carbon was developed. The continous carbide phase was expected to reduce the reactions with hydrogen because the carbon is chemically bound. ZrC or NbC surface coatings were still required. The other approach was the use of a carbide/graphite "composite" matrix as opposed to the original graphite matrix.

Forty-seven of the 49 cells tested in the NF-1 were the (U,Zr)C-carbon "composite" fuel elements. The remaining two cells were pure (U,Zr)C carbide fuel elements with a single internal coolant channel. These "composite" and "carbide" elements were run in the NF-1 at full power for a total of 109 minutes. The reactor operated with a peak fuel exit temperature of 2222 K and an average power density of 4500–5000 MW/m^3 with matrix temperatures of 2500 K. The composite fuel was reported to have achieved better corrosion performance than was observed in the graphite matrix fuel used in Phoebus reactors; however, it was found that composite fuel was susceptible to irradiation damage and that mass loss occurred where this damage was present. It was concluded that the composite elements would perform for at least two hours, and perhaps four to six hours, in a nuclear propulsion reactor in the temperature range of 2500 to 2800 K. The carbide fuel elements cracked extensively near the center of the reactor where the peak power density approached 4500 MW/m^3. This cracking is due to the relatively poor thermal conductivity of the carbide matrix. It was thought that carbide fuel would be acceptable for lower power densities (3000 to 4000 MW/m^3) but could potentially perform for several hours at temperatures ranging from 2800 to 3200 K with a possible maximum temperature approaching 2900 K.

A. Post ROVER Efforts

There has been minimal actual fuel development effort directly related to NTP fuels since the early 1970s. Advanced fuel development efforts were to continue in the late 1980s and 1990s under the Air Force Space Nuclear Thermal Propulsion (SNTP) program. Three coated particle fuel concepts were investigated for short duration burns at temperatures approaching 3000 K: the infiltrated kernel particle fuel, the mixed-carbide particle fuel, and the interstitial dispersoid particle fuel. However, the program was cancelled in 1993 before significant work was completed. In 1991, a NASA panel was established to evaluate the current state-of-the-art for nuclear propulsion fuels and concluded at the time that composite fuels were the best technological choice for engine development. Westinghouse Electric Corporation developed an engine concept called the ENABLER based on composite fuel. The report concluded that composite fuels could attain exhaust temperatures of 2700 K for several hours, enabling designs with specific impulses approaching 925 s. This capability was adequate for the desired missions and was technically achievable.

Issues related to the loss of material along the elements were thought to be a result of the application of a uniform coating thickness, but different mechansims account for the losses along an element length. It was speculated that altering the coating along the length of the element could allow coatings to be tailored to resist specific failure mechanisms.

Binary and ternary carbide fuels were considered, but the materials are brittle and difficult to shape. It was believed in 1991 that progress on the fabrication of such fuels could potentially allow them to be a credible candidate for a future mission. However, little development has occurred since then. Thus, the report concluded that composite fuel was the better baseline fuel for recovery and development and that the application of advanced coatings was a promising way to enhance performance.

In 2007, a joint NASA/DOE team reviewed candidate NTP fuel options and concluded that the two most promising graphite fuel forms were coated UC_2 particles in graphite and "dispersed" solid solution (UC-ZrC) in graphite "composite" form. This work was not published.

In 2009, the Los Alamos National Laboratory explored the ability to produce a simplified composite fuel form. There was some reported difficulty finding raw materials as originally specified, and some substitutions had to be

made. Results indicated that simply following processes and procedures available in the literature would not be sufficient to recreate the fuel. A learning curve is assocated with extrusion and curing, and this effort to some degree will have to be repeated for each fuel mixture and shape. The effort pointed to the need to have the flexibility to perform many mixings, extrusions, and heat treatments to optimize performance with substituted materials. Many of the original presses and furnaces used for the larger scale productions of the ROVER program are no longer available, nor well sized for the smaller, high throughput development effort deemed necessary to recapture the desired fuel characteristics.

IV. Recapturing NERVA-like Fuel

New, slightly altered fuel element mixtures will have to be developed and tested experimentally. Because so much time has passed since the original fuels were developed, and owing to the fact that future development efforts initially will be smaller in scale (budget and focus), it is recommended that recovery efforts begin with the establishment of smaller scale extruders and furnaces that can be used to rapidly produce a large number of extrusion samples. It is important that this capability be established in locations that do not have excessive operational overhead costs associated with them so that significant progress can be made with limited budgets. Fabrication would be relocated for production once the process has been developed. It is recommended that a furnace capability be established that would allow extrusions to be heat treated to temperatures approaching 3073 K (required as the final step to make some forms of composite fuel). This extrusion and furnace capability would be used to systematically produce prototypic NTP fuel loaded with depleted uranium. The prototypes would have a prototypic cross section, but perhaps reduced length. Fuel forms that match historical performance parameters will be carried forward to the coating process.

The ability to control the application coatings has evolved since the ROVER program, and it is thought that more consistent coatings can be produced. Coated particle fuel development has also generally benefited from considerable development effort for use in graphite-based, gas-cooled reactor fuels. The SiC coating used in those fuels could potentially be replaced with a higher temperature coating such as NbC or ZrC. Improved coating techniques and particle manufacturing techniques will be investigated as part of composite fuel recovery.

Coated elements will be subjected to nonnuclear, hot hydrogen flow testing. Successful element and coating combinations will then be irradiated at temperature in an existing test reactor, such as HFIR or ATR. Once the process has been validated through post-irradiation testing, the process will be expanded to make full-length elements for testing in an NTP reactor configuration.

V. Conclusion

The fuel development effort of the ROVER/NERVA programs quickly evolved to a baseline fuel form that performed well in reactor tests. Several reviews since the termination of those programs have recommended the recovery of the composite fuel form as a preferred technology path to recapturing NTP. These fuels will allow reactor concepts with 2700 K exhaust temperatures with specific impulses approaching 925 s that could operate for two hours and perhaps for four to six hours. It is not possible to use the original equipment or the exact mixtures to recapture composite fuel. It is recommended that smaller scale equipment be commissioned to allow cost-effective production of numerous shortened fuel elements from the new, slightly altered mixtures to develop fuels that match historical performance criteria. Better fuel performance based on advanced coated particle technology will be evaluated with this equipment. Specifically, the ability to tailor surface coatings along the length of an element to account for different failure mechanisms will be investigated. Successfully coated elements would be tested in hot hydrogen flow tests, and promising candidates would then be irradiation tested.

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