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STUDY OF A TRICARBIDE GROOVED RING FUEL ELEMENT FOR NUCLEAR THERMAL PROPULSION

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Deep space exploration, especially that of Mars, is on the horizon as the next big challenge for space exploration. Nuclear propulsion, through which high thrust and efficiency can be achieved, is a promising option for decreasing the cost and logistics of such a mission. Work on nuclear thermal engines goes back to the days of the NERVA program. Currently, nuclear thermal propulsion is under development again in various forms to provide a superior propulsion system for deep space exploration. The authors have been working to develop a concept nuclear thermal engine that uses a grooved ring fuel element as an alternative to the traditional hexagonal rod design. The authors are also studying the use of carbide fuels. The concept was developed in order to increase surface area and heat transfer to the propellant. The use of carbides would also raise the operating temperature of the reactor. It is hoped that this could lead to a higher thrust to weight nuclear thermal engine. This paper describes the modeling of neutronics, heat transfer, and fluid dynamics of this alternative nuclear fuel element geometry. Fabrication experiments of grooved rings from carbide refractory metals are also presented along with material characterization and interactions with a hot hydrogen environment. Results of experiments and associated analysis are discussed. The authors demonstrated success in reaching desired densities with some success in material distribution and reaching a solid solution. Future work is needed to improve distribution of material, minimize oxidation during the milling process, and define a fabrication process that will serve for constructing grooved ring fuel rods for large system tests.

I. Foreward

Propulsion systems that derive their power from nuclear reactions have been conceptualized for many decades. Serious efforts to develop this technology were made in both the United States and the Soviet Union. The most well-known program was that of the Nuclear Engine for Rocket Vehicle Application (NERVA) that was a joint effort of the U.S. Atomic Energy Commission and NASA. Several engines were built and tested under this program in order to develop this technology for a manned mission to Mars. This work ran until the early 1970's.[1,2] The reactors of the NERVA engines consisted of fuel elements formed into hexagonal rods with cylindrical flow passages through which propellant was flowed. The nuclear fission reactions heated the material in the rod and the heat was transferred to the propellant. This type of nuclear propulsion is called nuclear thermal propulsion (NTP). Later, particle bed reactors were considered in a defense project called Timberwind. This reactor geometry flowed propellant through a bed of spherical fuel "particles" to greatly increase surface area and thus heat transfer. This design showed promise for significantly improving thrust to weight ratios and specific impulse compared to the NERVA engines. It suffered; however, from nuclear thermal instabilities.[2]

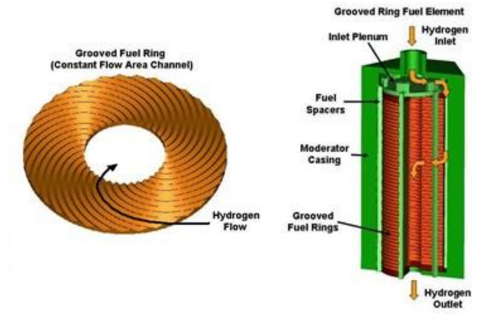

Figure 1. Illustration of a grooved ring fuel element

Recently, there has been a renewed effort to develop NTP as NASA has been working seriously toward manned Mars mission planned for the 2030's. Much of the fuel fabrication and engine modelling efforts have been focused on the tungsten and graphite based fuel elements in hexagonal rod geometries. Cermet and Graphite based fuels are being studied for fuel element fabrication. This work has been moving toward the hexagonal rod geometry. The authors of this paper have been working on a center innovation fund project to investigate an alternative fuel element geometry proposed by Dr. Bill Emrich at Marshall Space Flight Center, a co-author of this paper. This concept is centered on the idea of increased surface area and heat transfer to the propellant, much as particle bed reactors do, while eliminating the thermal instabilities by creating a defined flow path. This concept is known as the grooved fuel ring element. The idea is to build a fuel element from a stack of washer like rings. Each ring has grooves cut into the surface to allow propellant, constrained by an outer structure, to flow through the grooves to the center where it can flow down and out of the reactor. This provides a large increase in surface area which is directly proportional to heat transfer. These elements would be put together to make up a reactor much in the same was as traditional elements do. Figure 1 illustrates the concept.

In addition to the alternative geometry, the authors are investigating the use of mixed carbide fuels. These fuels are composed of fissile uranium carbide (UC) the fuel and additional refractory metal carbides (e.g. niobium carbide (NbC) and zirconium carbide (ZrC)) in solid solution to increase the melting temperature of UC. The Soviet Union conducted tests of carbide fuels and reached reactor temperature greater than 3000 K.[1] A combination of carbide materials has the potential to allow maximum fuel operating temperatures in the vicinity of 3500 K. This is in contrast to the lower temperature limitations of other fuel forms. The use of carbide fuels could allow the reactor to run at higher temperature and provide more thrust and specific impulse to the propulsion system.

In order to develop this alternate geometry carbide fuel element, data is needed to develop the fabrication process, understand the fuel's performance in a hot hydrogen environment and characterize material properties. This has been the primary goal of the work discussed in this paper. Past work has been studied to provide the foundation for this work.[3,4,5,6] Additionally, modeling has been done to understand the neutronics, fluid, and heat transfer processes in such a reactor. Model results have been used to guide material selection and fabrication experiments. Processes and results to date are discussed in this document.

II. Modeling and Experimental Design

A series of models were constructed in order to guide the decisions that would drive the design of material fabrication experiments. The modeling conducted included neutronics and reactor design as well as thermal and fluid modeling. In addition to the models, carbide material properties were studied for material experiment selection.

Monte Carlo N-Particle code (MCNP) was used to model the grooved ring fuel element reactor design. A concept reactor was modeled and adjusted to couple with the study of different carbide materials combinations. The changes in neutron cross section and melting point of materials greatly influenced the size of the fuel elements, the quantity of uranium carbide (UC) required for reactivity, and the overall melting point. For example tantalum carbide has a very high melting point, but also a high neutron cross section. The high cross section requires additional UC, which has a much lower melting point, to compensate. As one can see, the material selection is tightly coupled with several reactor parameters. A tricarbide mix of niobium carbide (NbC) and zirconium carbide (ZrC) with vanadium carbide (VC) acting as the UC surrogate were chosen for the tricarbide mixture to be used in experiments. The combination of NbC, ZrC, and UC give a reasonable balance between overall melting point and reactivity. One can see the difference in neutron cross section between materials in Figure 2.

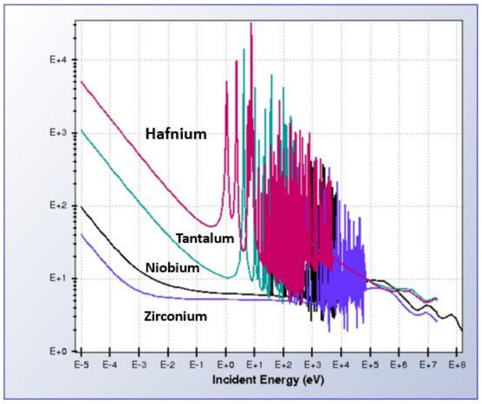

Figure 2. Cross section of materials of interest

A high level model of a grooved ring fuel element was also built in Comsol to verify the concept of the fluid flow through the element. For simplicity radial grooves were used, although more complex geometries could be created. The Comsol model showed that the concept can successfully drive laminar flow of propellant around the cylinder, through the grooves and then out the center passage. Volumetric heating of the fuel transferred heat to the propellant as expected and successfully heated the propellant.   The model showed that the concept of a grooved ring fuel element used to increase heat transfer over traditional element geometries works as expected.

III. Fuel Element Fabrication

The process of constructing a fuel element of a combination of carbide compounds is not well understood. Historically research has shown that they are prone to cracking and are brittle. The high melting point also increases the difficulty. The authors conducted a test series to try and identify a practical method for fabricating tricarbides for nuclear fuel element application.

First, the carbides to be applied in experiments were determined. Niobium carbide and zirconium carbide were chosen due to their neutron cross sections and melting points. Vanadium carbide (VC) was chosen to act as surrogate for UC since it has a similar crystal structure.

Materials were obtained in the form of powder on a nanometer scale size. Experiments were performed with powder without further processing, with sifting to remove larger particles, and with milling to reduce particle size and create a more uniform size distribution.

Experiments employed spark plasma sintering, also known as direct current sintering. The powder mixture was placed into a die in which spark plasma sintering was used to form a continuous solid tricarbide material for inspection. Many variables were adjusted to approach a material with a high density and good material distribution. It was found that higher sintering temperatures, on the order of 1600 °C, longer dwell times at max temperature, and fast cooling, on the order of 200 °C/min, led to carbide samples reaching densities in the range of 95% of theoretical density. Additionally, it was found that sifting the powders to remove larger particles resulting in improved material distribution. It is concluded that overall smaller particle size in the powders will yield improved distribution of materials. It is expected that milling the powders can result in the best distribution of materials of the samples studied.

Limited progress was made in attempting to fabricate the grooved ring geometry due to cost and schedule restraints. This is planned as a future effort for FY18.

IV. Material Characterization

Further work was done to characterize the sintered carbides and evaluate them for use in a nuclear fuel element for nuclear thermal propulsion. Through these measurements the authors also hope to gain understanding into how they will perform in the reactor environment and the resulting overall engine performance.

First, thermal diffusivity measurements were attempted. For reasons as yet unknown the samples measured disintegrated at relatively low temperatures. Investigating the cause is planned as future work.

Several samples were placed in a hot hydrogen environment similar to what would be seen in the reactor of a nuclear engine. It is important to measure how the carbides react to the hot hydrogen, such as through mass loss, and determine any changes in structure.

The hot hydrogen environment tests were conducted at Marshall Space Flight Center in the Compact Fuel element Environmental Test (CFEET) system. It has a 50 kW induction power supply and two color pyrometers for temperature measurements up to 3000 °C. It is designed to flow hydrogen across subscale fuel materials for testing at high temperatures for up to ten hours.

The first sample was run at relatively low temperatures to see if it would fall apart as in thermal diffusivity testing. This was not the case. The sample ran at 2000 K for 30 minutes and experienced no loss of structural stability. Subsequently, 3 samples were run at 2250 K for 30 minutes. X-ray diffraction analysis appears to show the tricarbides moving toward a solid solution. Solid solutions refer to an ideal mixture of the tricarbides as opposed to discreet clusters of compacted binary carbide powders. This is indicated by the shifting toward a single defined peak at an intermediate 2Θ values. This XRD data can be seen in Figure 3.

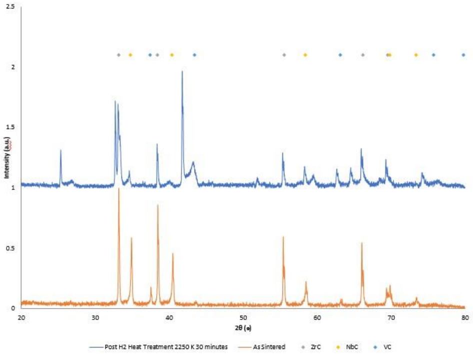

Figure 3. X-Ray spectroscopy analysis before and after testing in CFEET

Unidentified peaks do exist posttest. Further analysis is needed to verify if unidentified peaks are due to the formation of free carbon, NB2C, or other lower melting temperature compounds.

Additional CFEET tests were run on samples produced from milled powders. These samples were run at 2500 K and 2750 K for 45 minutes. Cracks seen prior to CFEET testing grew considerably and blister formation was observed. This can be seen in Figures 4 and 5.

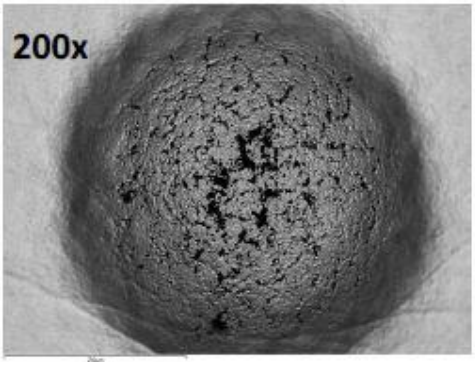

Figure 4. Blister formation post CFEET test in sample made from milled powders

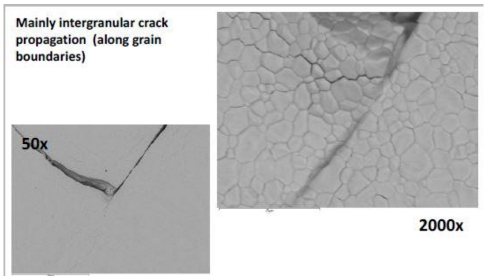

Figure 5. Crack formation in carbide samples following CFEET Test

XRD analysis of post CFEET samples showed spikes suggesting zirconium oxide (ZrO) formation. XRD analysis was conducted on powder before and after milling. Unmilled powder showed no signs of ZrO formation while milled powder showed ZrO and free carbon. It was determined that the milling process results in ZrC formation in which the carbon is freed. The blisters are found to be very carbon rich. It is determined that the milling process must be modified to avoid oxidation if it is to be incorporated into the fabrication of the carbide fuel elements. It is believed this can be accomplished in future work. The XRD results can be seen in Figures 6 and 7.

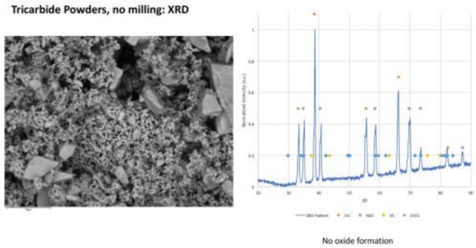

Figure 6. XRD analysis prior to milling carbide powder

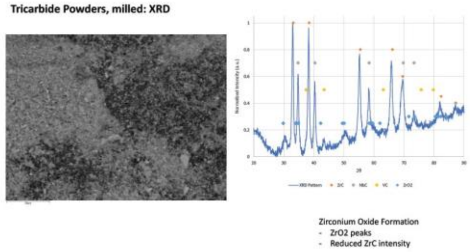

Figure 7. XRD analysis following carbide powder milling

V. Conclusions

This project set out to begin development of the fabrication process of carbide fuels for a grooved ring fuel element of a nuclear thermal rocket. The team ran the initial calculations and models to drive the carbide fuels experiments.

Direct current sintering experiments were shown to be quite effective at achieve high density carbide samples and reasonable material distribution. Testing of sintered carbides in a hot hydrogen environment also showed positive results. The tests showed the carbide samples moving toward a solid solution which is optimal for fuel design. They also showed the carbide could withstand the hot hydrogen environment when there was low oxide formation. Although unmilled sintered tricarbide samples performed well when exposed to hydrogen at high temperatures, oxidation of the carbide powders during the milling process resulted in severe cracking and blister formation in the hot hydrogen environment.

The next step in developing the fabrication process is to address the oxidation of the carbide powders during the milling process. This process is employed to improve material distribution throughout the sintered carbide mixture by reducing particle size. Oxidation must be prevented in order to develop carbide fuels that will maintain structural and chemical integrity in the hot hydrogen environment of a nuclear thermal rocket.

Additionally, experiments need to be run to determine a method for moving the carbide mixtures toward a solid solution. Heating in a graphite furnace under vacuum may achieve this and is planned for testing. Machining of the grooves and central passage to form the carbides into grooved rings for the construction of a full size element must also be addressed. Tests are planned for cutting the sintered carbides in a water jet. Finally, a full size prototype grooved ring fuel element needs to be built and tested in the Nuclear Thermal Rocket Element Environment Simulator (NTREES) for performance assessment.

The team believes the results of the work conducted in FY17 to be encouraging. The carbide fuels and the grooved ring fuel element are a promising fuel form and design geometry for future nuclear thermal rockets.

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