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Current Development of Nuclear Thermal Propulsion Technologies at the Center for Space Nuclear Research

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Current development of Nuclear Thermal Propulsion technologies at the Center for Space Nuclear Research

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Abstract: The Center for Space Nuclear Research (CSNR) is pursuing a number of technologies, modeling and testing processes to further the development of safe, practical and affordable nuclear thermal propulsion systems. A summary of these activities is presented with respect to progress made.

Nomenclature

CSNR	=	Center for Space Nuclear Research
Cermet	=	Ceramic Metallic Matrix
INL	=	Idaho National Laboratory
NTP	=	Nuclear Thermal Propulsion
SPS	=	Spark Plasma Sintering
RSPS	=	Radiological Spark Plasma Sintering Facility

I. Introduction

Nuclear power and propulsion has been considered for space applications since the 1950s. Between 1955 and 1972 the US built and tested over twenty nuclear reactors / rocket engines in the Rover/NERVA programs[1]. The Aerojet Corporation was the prime contractor for the NERVA program. Modern changes in environmental laws present challenges for the redevelopment of the nuclear rocket. Recent advances in fuel fabrication and testing options indicate that a nuclear rocket with a fuel composition that is significantly different from those of the NERVA project can be engineered; this may be needed to ensure public support and compliance with safety requirements. The Center for Space Nuclear Research (CSNR) is pursuing a number of technologies, modeling and testing processes to further the development of safe, practical and affordable nuclear thermal propulsion systems.

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II. Challenges and Solutions

The recovery of Nuclear Thermal Propulsion (NTP) technology in the current socio-political environment is dependent on overcoming several issues. Simply expressed they are:

- System performance should sufficiently justify the "perceived" associated risks.
- Cost of development.
- Radioactivity emitted during operation and the release of fission products into the exhaust stream.
- Risk for "proliferation" on launch abort / re-entry of the Earth's Atmosphere.
- Sub-criticality on launch abort.

Issues three through five may all be addressed by using a tungsten-based fuel form. During the GE-710 program in the 1960s, the retention of fission products by the tungsten matrix was demonstrated using static irradiations. With respect to proliferation resistance, removal of the uranium from the tungsten matrix would be challenging and would require significant infrastructure in chemical processing. Conversely, a graphite based core could be fractured allowing the uranium to be extracted via pyrolisis. The other main advantage of the tungsten fuel form is on the scale of full-power, ground test facilities. If the fuel can be shown not to leak radioactivity into the exhaust, then a large, expensive containment facility to scrub out fission products would not be required. Use of a smaller test facility could dramatically reduce the program costs.

In collaboration with the Aerojet Corporation, the Center for Space Nuclear Research (CSNR) is pursuing a number of technologies and testing processes to further the development of safe, practical and affordable nuclear thermal propulsion systems. Some of these integrated activities include: *1)* The development of a complete tungsten-cermet fuel manufacturing and qualification process that can be applied and adjusted to a wide range of fuel element geometries, fuel-to-matrix volume fractions, and flow channel configurations. *2)* The assessment and development of low cost ground based borehole testing methods (SAFE) for NTP engines. *3)* Design, construction and commissioning of a Spark Plasma Sintering Facility for the processing of nuclear materials at the Idaho National Laboratory. *4)* The testing of cermet thermo-physical and mechanical properties made via the CSNR/Aerojet process in support of accurate computational analyses of NTP system designs. *5)* Computational modeling of heritage and concept NTP system designs (CFD and neutronics modeling). *6)* Safety analyses for launch abort and space flight accident conditions. A summary schematic of the CSNR's integrated activities is provided in Figure 1.

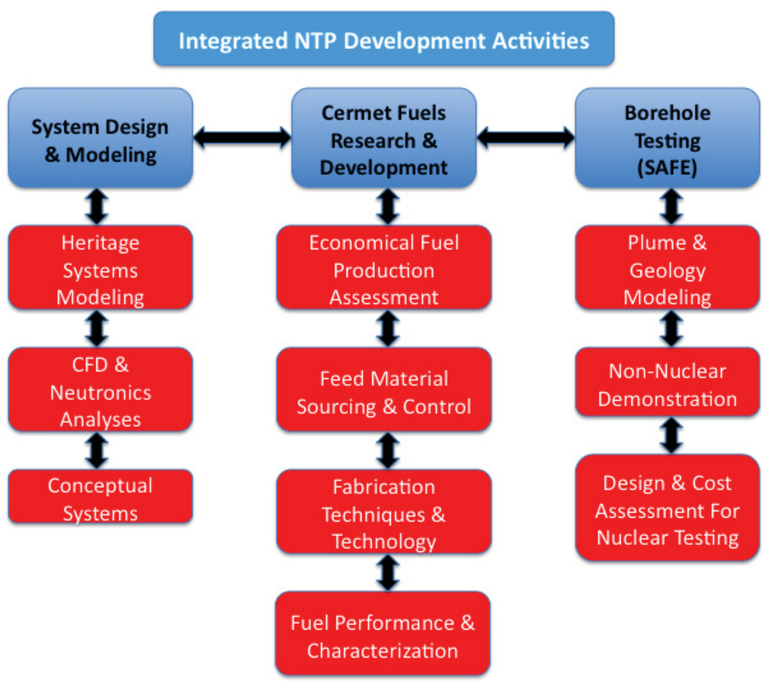

Figure 1: Integrated NTP development activities summary.

III. Affordable, High Performance Fuel Development

Tungsten-cermet fuel is a potentially high-endurance fuel form and has excellent compatibility with high-temperature hydrogen gas. Heritage experimental work in programs such as the ANL and GE 710 programs[2] demonstrated the durability of the fuels. Tungsten-cermets exhibit good thermal conductivity, a high melting point, and are resistant to creep deformation[3] and hydrogen embrittlement at elevated temperatures. Tungsten-cermet matrices offer radiation self-shielding properties that translate into reductions in external shielding requirements[4, 5]. Tungsten-cermets may be engineered to be resistant to physical changes induced by radiation, such as neutron absorption and swelling due to irradiation and fission product production. Additionally, the use of tungsten cermet fuels in NTP systems present significant safety enhancements over graphite in accident conditions associated with launch abort, failure to achieve orbit and flight termination. Specifically, recent studies performed at the CSNR have indicated that NTP reactor core configurations composed of tungsten cermet fuels remain subcritical in the event of submersion in sea water and wet sand[4, 6]. Overall, the development of an economical production process for high performance cermet fuels is essential for the recovery of NTP and is central to the current research programs at the CSNR.

In 2008, the CSNR undertook a pioneering project to investigate the ability to fabricate tungsten fuel elements via the relatively new Spark Plasma Sintering (SPS) powder sintering process[7 8]. By using the SPS furnace at the Idaho National Laboratory, several samples of tungsten-cermet elements were produced. SPS is a rapid processing technique that is performed at temperatures that are significantly lower than traditional sintering techniques[8] and thus is able to consolidate nuclear materials such as UO_2 to nearly 100% of their theoretical density without their volatilization or production of free metallic uranium[8]. The initial sample sections were approximately 1.2 inches in length, had a hexagonal cross section width of 0.75 inches across the flats (same external profile geometry as the NERVA fuel elements). The samples were fabricated in segments with a 40% by volume blend of CeO_2 that served as a non-nuclear surrogate for UO_2 within the tungsten matrix. These segments were then diffusion bonded by further processing via SPS. The results are shown in Figure 2. The initial element sections illustrated had a density in excess of 90% of their theoretical density.

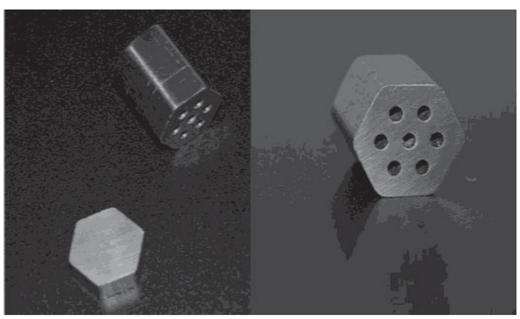

Figure 2: Early Tungsten-cermet nuclear thermal rocket fuel element sections loaded with CeO_2. CeO_2 (40% vol.), acted as a UO_2 simulant. The samples were fabricated in 2008 using a Spark Plasma Sintering furnace. This particular example illustrates the capability to produce elements with multiple flow channels.

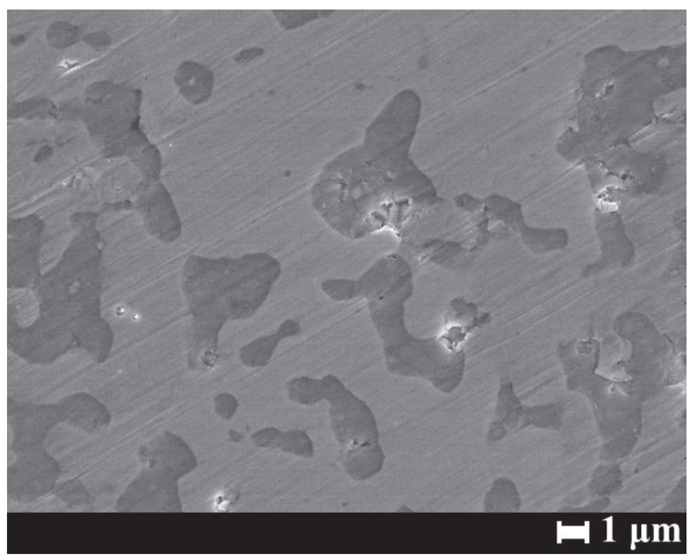

Figure 3: SEM image of first known UO_2-cermet fabricated by SPS[9]. Angular UO_2 particles (dark grey) are encapsulated within a continuous metal matrix (light grey).

In collaboration with the Aerojet Corporation, the CSNR has further developed its feed material mixing, control and SPS processing techniques, to allow for the affordable fabrication of high performance cermet fuels. These processes have been developed for production of cermets composed of a continuous, dilute W-Re alloy metallic matrix that encapsulates a dispersion of mono-sized UO_2 fuel particles. While initial cermet samples composed of

50% by volume depleted UO_2 powder dispersed in a W-Re matrix have been fabricated via SPS by the CSNR that were in excess of 98% of their theoretical density[9] (*see Figure 3*), the CSNR has established Alginate (*see Figure 4, Left*) and Internal Gelation processes for the production of Gd_2O_3 and Y_2O_3 stabilized UO_2 microspheres for use in cermet production. The use of microspheres in place of angular powders improves the uniformity of the fuel dispersion throughout the cermet matrix and eliminates inter-granular void formation that occurs at sites of agglomeration of angular fuel particles during cermet powder mixing processes. Internal void space is created within the UO_2 microspheres via heat treatments. This allows for the accommodation of gaseous fission products, fuel swelling and the coefficients of thermal expansion mismatch between the metallic matrix and ceramic components of the cermet. The dilute W-Re alloy metallic matrix is generated during the SPS sintering process from component powders. Un-alloyed blends of tungsten and rhenium feedstock powders are mixed together and combined with the ceramic UO_2 microsphere content. The tungsten and rhenium powders are carefully sized to be approximately 2 and 1 orders of magnitude less than the UO_2 microspheres respectively. During the mixing process performed in a 2-axis turbulent mixer, the metallic powders are blended and intermix around individual UO_2 microspheres. Prevention of electrostatic charge buildup within the mixture is essential to prevent agglomeration of the ceramic components and is facilitated by the electrical grounding of the aluminum mixing vessel. Once mixed, the cermet mixtures are loaded into a graphite die that is sized to produce net shaped cermet fuel segments during SPS processing. By innovative die design, the CSNR has developed the capability to produce multiple propellant flow channel features during the sintering of cermet segments. The process can be adjusted to provide single, tens or hundreds of channels if required by a specific element design. The elimination of drilling, chemical etching and electronic discharge machining methods for propellant flow channel production that were used in historical NTP programs has reduced the overall fuel production cost and time, in addition to activities that can result in fuel material waste and facility contamination.

A unique Radiological Spark Plasma Sintering (RSPS) facility was designed and developed by the CSNR in collaboration with Thermal Technology LLC of Santa Rosa, CA and Innovative Technology LLC of Amesbury MA in order to safely handle and fabricate nuclear material compacts from powdered feedstock materials. This first of its kind facility located at the Idaho National Laboratory's Center for Advanced Energy Studies features an integrated glovebox line, exhaust filtration system and internal powder handling and die loading/unloading equipment. A photograph of the RSPS facility is provided in Figure 4 (*Right*).

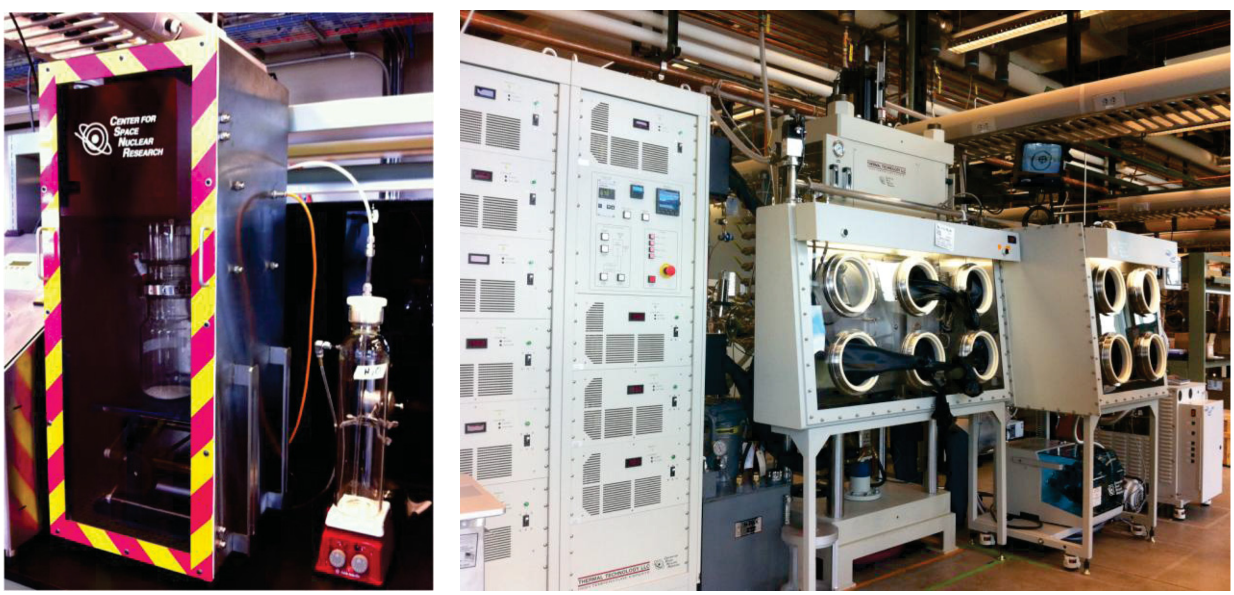

Figure 4: (*Left*) Photograph of the CSNR's Algination Microsphere Production Facility. (*Right*) Photograph of the Radiological Spark Plasma Sintering (RSPS) Facility developed by the CSNR at the INL's Center for Advanced Energy Studies. The Algination Microsphere production facility is used to produce uniform spherical stabilized UO_2 fuel particles with selectable diameters of 100 – 600 μm from UO_2 feedstock powders. The RSPS facility is used to sinter blended mixtures of UO_2 microspheres with tungsten and rhenium powders to produce cermet fuel segments and to diffusion bond element segments into fuel element sections.

Once fabricated, the fuel element segments are polished and cleaned in preparation for diffusion bonding together to form fuel element sections. The diffusion bonding of the segments is performed via SPS in a similar net-shaped graphite die used to orientate and align the flow channels and outer surfaces of the segments. In 2011, the CSNR successfully fabricated a hexagonal prismatic element section composed of 8 segments, each with a flat-to-flat length of 0.75" and with a 19-hole propellant flow channel configuration. A photograph of this element section is provided in Figure 5 (*Left*) in comparison to a graphite fuel element section from the NERVA program (*Right*). The full length fuel elements are assembled from several sections that feature ends that can be keyed together. An example 3-section fuel element assembly is illustrated in Figure 6. An overall summary of the CSNR's fuel element fabrication process is provided in Figure 7.

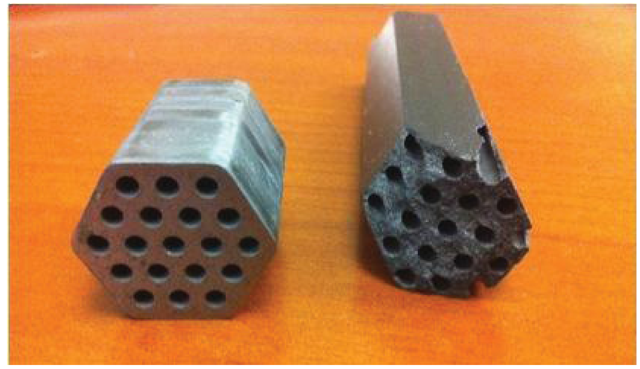

Figure 5: Photograph of 2011 CSNR cermet element section study result (*Left*) compared to a graphite element section form the NERVA program (*Right*). Both element sections have a flat-to-flat distance of 0.75" and a 19-hole propellant flow channel configurations.

Figure 6: Assembly of cermet fuel elements from sections. Here, a fuel element with a 19-hole propellant flow channel configuration is assembled from 3 sections with end features that are keyed together.

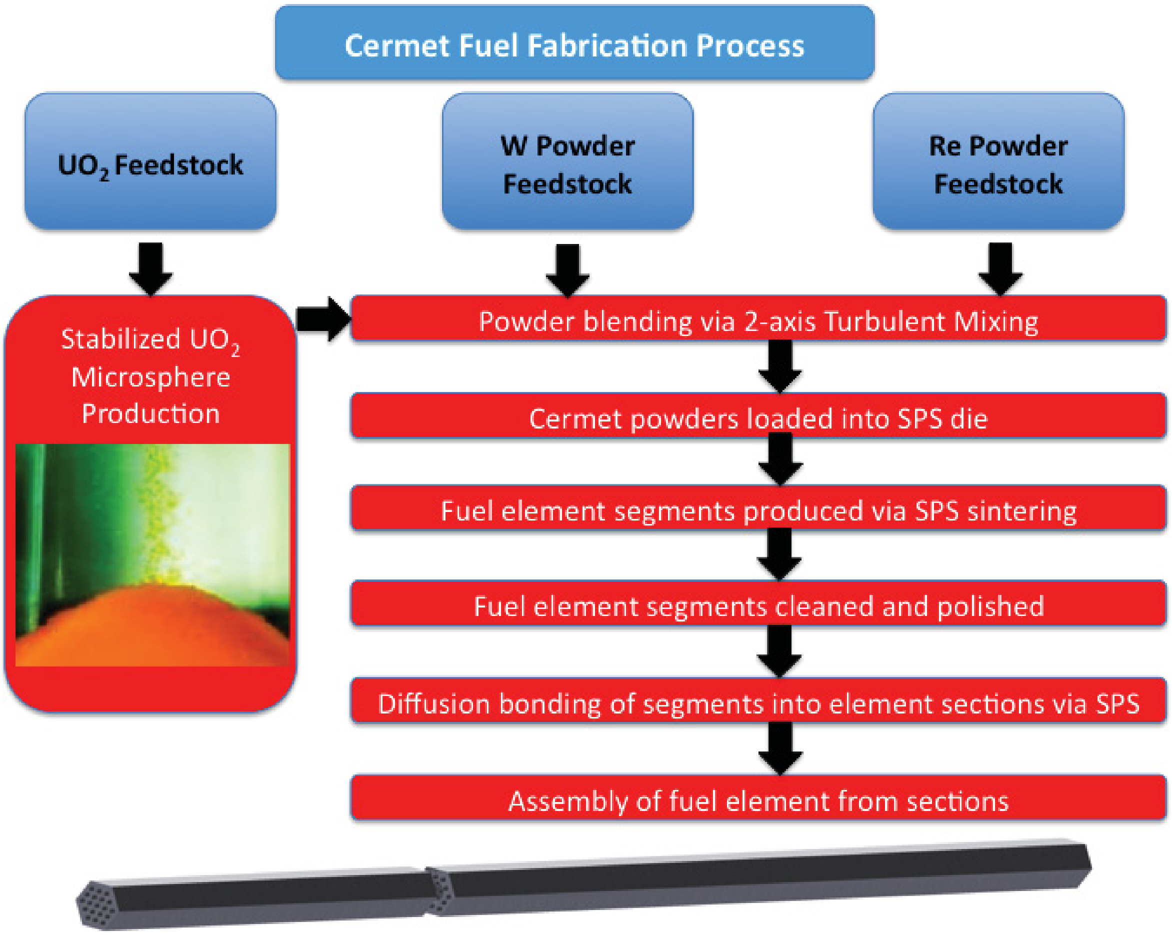

Figure 7: Summary of the cermet fuel fabrication process.

Cost effective methods for fuel qualification are currently being evaluated by the CSNR and will be the subject of future publications. The results from current thermo-physical properties analyses of cermet materials fabricated by the CSNR process are being used in modeling activities to ensure the accuracy of system performance prediction and will also be presented in future publications.

IV. Summary

Through the research and development activities discussed, the CSNR is currently completing an economical fuel production study. This study will allow the collaboration to accurately determine the necessary processes and associated costs for the scale-up of facilities and staffing should the need arise for the manufacture of cermet fuels for a NTP system over a one to two year period. Consequently, a more accurate understanding of the performance and overall costs associated with modern NTP system development and production will be made by the collaboration. This is essential for the determination of the near term feasibility of NTP to potential users such as NASA.

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