

Submersion criticality safety of tungsten-rhenium uranium cermet fuel for space propulsion and power applications



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HIGHLIGHTS

- Criticality safety studies consider a generic space nuclear reactor in reentry scenarios.
- Describes the submersion criticality behavior for a reactor fueled with a tungsten cermet fuel.
- Study considers effects of varying fuel content, geometry, and other conditions.

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ABSTRACT

Nuclear thermal rockets are the preferred propulsion technology for a manned mission to Mars, and tungsten–uranium oxide cermet fuels could provide significant performance and cost advantages for nuclear thermal rockets. A nuclear reactor intended for use in space must remain subcritical before and during launch, and must remain subcritical in launch abort scenarios where the reactor falls back to Earth and becomes submerged in terrestrial materials (including seawater, wet sand, or dry sand). Submersion increases reflection of neutrons and also thermalizes the neutron spectrum, which typically increases the reactivity of the core. This effect is typically very significant for compact, fast-spectrum reactors. This paper provides a submersion criticality safety analysis for a representative tungsten/uranium oxide fueled reactor with a range of fuel compositions. Each submersion case considers both the rhenium content in the matrix alloy and the uranium oxide volume fraction in the cermet. The inclusion of rhenium significantly improves the submersion criticality safety of the reactor. While increased uranium oxide content increases the reactivity of the core, it does not significantly affect the submersion behavior of the reactor. There is no significant difference in submersion behavior between reactors with rhenium distributed within the cermet matrix and reactors with a rhenium clad in the coolant channels. The combination of the flooding of the coolant channels in submersion scenarios and the presence of a significant amount of spectral shift absorbers (i.e. high rhenium concentration) further decreases reactivity for short reactor cores compared to longer cores.

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1. Introduction

Nuclear thermal rockets are the preferred propulsion technology for a manned mission to Mars (National Research Council, 2008), and tungsten–uranium oxide cermet fuels could provide significant performance and cost advantages for nuclear thermal rockets. A nuclear reactor intended for use in space should remain subcritical before and during launch and should not become critical

until it has reached orbit and is required by its mission (Marshall and Sawyer, 1992). Additionally, a properly designed space nuclear reactor will remain subcritical in any credible accident or launch abort scenarios where the reactor falls back to Earth and becomes submerged in terrestrial materials, including seawater, wet sand, and dry sand (Marshall and Sawyer, 1992). Submersion increases the reflection of neutrons and also decreases the average energy of the neutron energy spectrum and shifts it to a more thermal spectrum. This spectrum shift increases the effective fission cross-section, which typically increases the reactivity of the core and could possibly make the reactor supercritical (King and El-Genk, 2006). This effect is usually very significant for compact fast-spectrum reactors (Craft and King, 2011). High core length to

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diameter ratio (L/D), large reflector worth, low core void fraction, and resistance to compaction typically help to assure the reactor's subcriticality during a launch abort scenario (Poston, 2002).

This paper provides a submersion criticality safety analysis for a representative tungsten/uranium oxide fueled reactor with various fuel compositions. Submersion studies consider reactivity effects of the rhenium content within the cermet matrix, uranium oxide volume fraction in the fuel, and the core L/D ratio. Also, it is possible that the reactor's reflector may detach from the reactor during reentry prior to submersion. This paper examines the reactivity of the submerged reactor with and without its reflector. Some previous reactor designs, such as the SP-100 space reactor, proposed using a rhenium sleeve around the fuel pin (Demuth, 2003); this paper also compares the reactivity effects of submerged reactors with rhenium in the cermet matrix and with a rhenium layer on the outside of the reactor's coolant flow channels.

2. Tungsten-based cermet fuel

Nuclear power and propulsion have been considered for space applications since the 1950s. Between 1955 and 1972, the United States built and tested over twenty nuclear reactors and rocket engines in the Rover/NERVA programs, with the Aerojet Corporation as the prime contractor (Argonne National Laboratory, 1966; Finseth, 1991; Bennett et al., 1994; Howe and O'Brien, 2010). The Center for Space Nuclear Research (CSNR) is pursuing development of tungsten-cermet based fuels in collaboration with the Aerojet Corporation for use in Nuclear Thermal Propulsion (NTP) systems (Burkes et al., 2007). Additional efforts at Marshall Space Flight Center are also developing tungsten cermet fuels for nuclear thermal propulsion applications (Hickman et al., 2005, 2012). Recent advances in fuel fabrication and testing options indicate that a nuclear rocket with a fuel form that is significantly improved over the NERVA designs can be engineered, which may be necessary to ensure public support and compliance with anticipated safety requirements (O'Brien and Jerred, 2011).

Tungsten-cermet fuel is capable of maintaining structural integrity in the challenging conditions present in a nuclear thermal rocket and has excellent compatibility with high-temperature hydrogen gas (Bhattacharyya, 2001). Legacy experimental work in programs such as the Argonne National Laboratory and General Electric 710 programs demonstrated the durability of the fuel form (Bhattacharyya et al., 1988; General Electric Co, 1967). Tungsten-cermets exhibit good thermal conductivity and high melting points, and are resistant to creep deformation at elevated temperatures (Baker et al., 1966). Additionally, tungsten-cermet matrices offer radiation self-shielding properties that translate into reductions in external shielding requirements (Craft et al., 2011). Tungsten-cermets may be engineered to be resistant to physical changes induced by radiation, such as reduction of parasitic neutron absorption and reduction of swelling from irradiation and fission product production. The GE-710 program in the 1960s demonstrated the retention of fission products by the tungsten matrix in static irradiation tests (General Electric Co, 1967).

In 2008, the CSNR undertook a small pioneering project to investigate the ability to fabricate tungsten fuel elements using a relatively new Spark Plasma Sintering (SPS) powder sintering process (O'Brien et al., 2009). Using the SPS furnace at the Idaho National Laboratory, the CSNR produced several samples of tungsten-cermet elements. The samples were approximately 1.2 inches in length and had a hexagonal cross section with 0.75 inches flat-to-flat (the same general external profile geometry as the NERVA elements). The samples were fabricated with 40 vol% ceria (CeO_2) that served as a non-nuclear surrogate for UO_2 within the tungsten matrix (O'Brien et al., 2009).

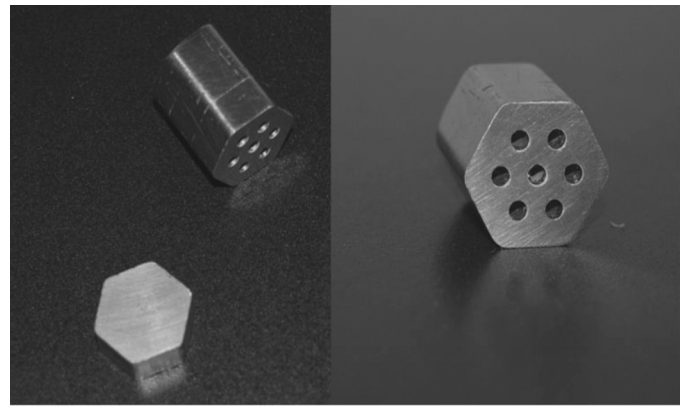


Fig. 1. Surrogate tungsten-cermet nuclear fuel elements loaded with 40 vol% ceria.

Fig. 1 shows three examples of the cermet fuel elements produced by the CSNR, which have a density in excess of 90% of their theoretical density (O'Brien et al., 2009). These specimens illustrate the capability to produce elements with multiple flow channels. The process can be adjusted to provide one, tens or hundreds of channels if required.

The CSNR has demonstrated the fabrication of tungsten-rhenium alloy cermet fuel element sections containing 19 flow channels. This fuel geometry is similar to the fuels developed under the Rover/NERVA program, and the resulting W-Re/ UO_2 cermets have a density in excess of 98% of theoretical (O'Brien and Jerred, 2011).

The recovery of NTP technology in the current socio-political environment is dependent on demonstrating performance related to several issues, including (1) risk analysis, (2) cost of development, (3) radioactivity emitted during operation and the release of fission products into the exhaust stream, (4) risk of proliferation after a launch abort or re-entry into the Earth's atmosphere, and (5) safety during launch abort scenarios. Issues three through five may all be addressed by a tungsten-based cermet fuel form, and the safety of a tungsten-cermet fueled nuclear thermal rocket during launch abort scenarios is the particular focus of this paper.

3. Neutronics model description

A space nuclear reactor model constructed using MCNP5 (X-5 Monte Carlo Team, 2005) version 1.6 provides insight into the reactivity effects of tungsten cermet fuel compositions. The modeled reactor geometry represents a generic and stereotypical space nuclear reactor. This removes extraneous factors, and allows the study to focus more precisely on the effects of the fuel composition. Thus, for the analyses in this work, the specific multiplication factors (k_{eff}) are not of significance, while the differential effects of each scenario on the reactivity of the reactor are very important.

Fig. 2a and b depicts axial and radial cross-sections, respectively, of the MCNP model analyzed in this study, and Fig. 2c shows a cross-sectional view of a single fuel element from the model. Table 1 lists the pertinent parameters regarding the reactor model.

The reactor core L/D ratio is 2.5, where the diameter refers to the outer diameter of the core not including the reflector (32 cm). The core consists of an array of hexagonal tungsten and uranium oxide cermet fuel elements with nineteen coolant channels arranged in a hexagonal array (Fig. 2c). While the manufactured fuel is a heterogeneous mix of UO_2 kernels within a metal matrix, the fuel is homogenized in the MCNP model. The fuel is 93% enriched in each case; however, the exact composition of the fuel and the fill material within the coolant channels vary for the different composition analyses and submersion scenarios in this study.

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