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CERMET-FUELED REACTORS FOR ADVANCED SPACE APPLICATIONS

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INTRODUCTION

Cermet-fueled nuclear reactors are attractive candidates for high-performance advanced space power systems. The cermet consists of a hexagonal matrix of a refractory metal and a ceramic fuel, with multiple tubular flow channels. The high performance characteristics of the fuel matrix come from its high strength at elevated temperatures and its high thermal conductivity. The cermet fuel concept evolved in the 1960s with the objective of developing a reactor design that could be used for a wide range of mobile power generating systems, including both Brayton and Rankine power conversion cycles. High temperature thermal cycling tests for the cermet fuel were carried out by General Electric as part of the 710 Project (General Electric 1966), and by Argonne National Laboratory in the Direct Nuclear Rocket Program (1965). Development programs for cermet fuel are currently under way at Argonne National Laboratory and Pacific Northwest Laboratory.

The high temperature qualification tests from the 1960s have provided a base for the incorporation of cermet fuel in advanced space applications. The status of the cermet fuel development activities and descriptions of the key features of the cermet-fueled reactor design are summarized in this paper.

DESCRIPTION OF A CERMET FUEL ELEMENT

An illustration of a typical cermet fuel element is shown in Figure 1. The fuel is visualized as a continuous refractory metal structure surrounding the individual fuel particles (particle dimensions of between 40 and 75 microns) and providing fuel and fission product retention, high strength and good effective thermal conductivity to the fuel body. To

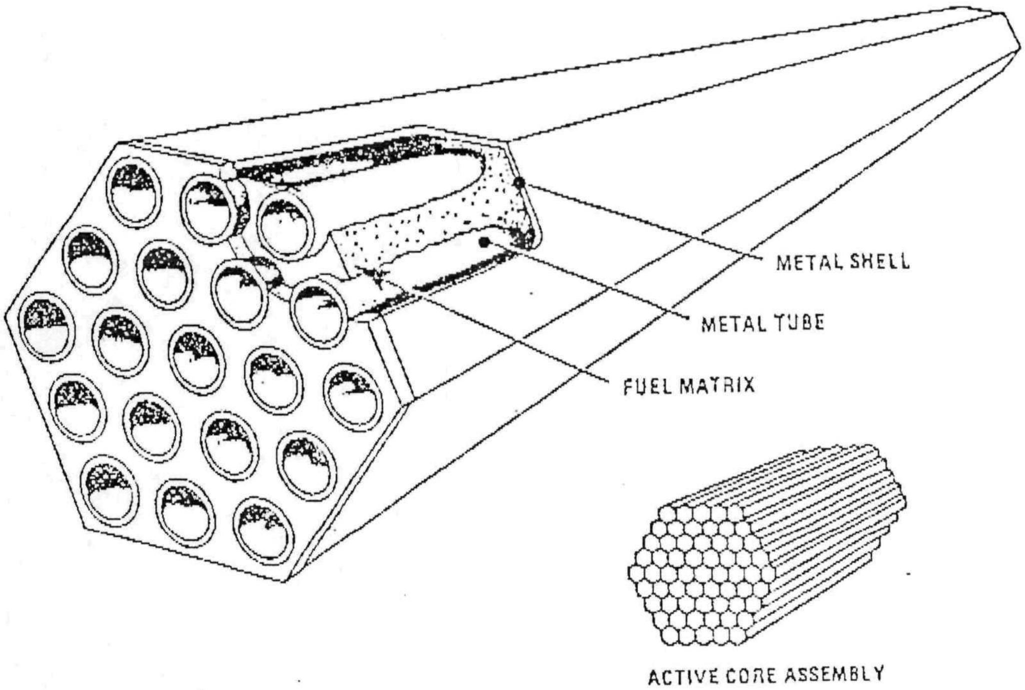

Figure 1. Illustration of a Cermet Matrix-Type Fuel Element

assure positive fission product and fuel retention for the overall fuel element, the cermet body is completely enclosed within a cladding to which it is bonded. A tubular fuel element concept is considered advantageous because tubes provide a flow channel independent of other structural elements, resist distortion and can be fabricated to close dimensional tolerances.

The cermet fuel element may be utilized with either a liquid metal or a gas coolant. In the investigations which have been carried out at GE the emphasis has been placed on the gas-cooled concept with a Brayton power conversion cycle. This is primarily to provide a source for direct burst power operation. However, it is recognized that the choice of coolant, as well as the fuel matrix materials, are dependent upon specific mission requirements in which temperature, burnup and mass limitations are key design criteria.

A 60 UO_2-40W (volume%) cermet fuel matrix was selected for the gas-cooled designs. In general, the choice of fuel material was limited to UO_2 or UN (primarily because of melting point considerations). There were found to be a number of advantages which favored the UN cermet including a higher density (potential for smaller core size) and slightly higher effective thermal conductivity. However, the nitride will dissociate at lower temperatures than the oxide, and there are less experimental data for the nitride. For these reasons, the oxide cermet was selected to enhance the high temperature performance capability.

The tungsten matrix material for the cermet was selected because of its high creep strength. This was deemed particularly important because of the requirements for high fuel performance (fission product swelling response) at moderate fuel burnups. Another recently identified possible

The high-temperature cermet fuel qualification tests were a major accomplishment of the 710 Program. In addition, fuel fabrication methods including drilling, grinding, machining, welding, bonding, sintering, fuel agglomeration and compact processing were refined and perfected. It was concluded that the fuel element fabrication process was developed to a point where a high-quality reproducible product can be assured.

FUEL SWELLING BEHAVIOR

Irradiation test data reported by Keller and Chubb (1967) and Keller (1972) have indicated that fuel swelling can be significant above about one atom percent burnup. However, the test data also indicate that the swelling is substantially reduced when a gross porosity is introduced into the fuel. Based upon these results a gross porosity of approximately 20% is incorporated in the UO_2 fuel to partially accommodate the buildup of fission gas pressure in those space applications where the burnup level is intended to exceed one atom percent.

KEY FEATURES OF CERMET-FUELED REACTORS

The key features of the cermet-fueled, nuclear design include coolant temperatures which exceed 2400K and power densities which exceed 2400 W/cm^3. In addition, because of the very high thermal conductivity of the tungsten in the fuel matrix, there is a potential for the rapid dissipation of heat so that thermal stresses and thermal shock in the fuel are tolerable during the rapid transition from steady-state to burst power operation. While it is acknowledged that the rapid rise to power will be a challenging requirement for any reactor concept, the cermet reactor appears to have a major advantage in this regard.

The simplicity of the cermet-fueled design is characterized by the presence of only fuel, cladding, and coolant in a fast-spectrum core. Because of the low neutron capture cross sections of the refractory alloys and fission products, it is possible to achieve small core sizes, particularly for extended operations above 3 to 10 megawatts. The neutronic insensitivities to fission products also means that there is a potential for minimizing the system control requirements. The simplicity of the reactor concept can be enhanced by the use of an integrated front support and reflector elements, and integrated fuel elements and rear reflectors (if necessary).

The fundamental features of the cermet-fueled reactor design include several key safety features which are attributed to the properties of tungsten and rhenium refractory metals. Because of the resonance absorption neutronic properties of tungsten and rhenium the reactor will remain substantially subcritical under conditions of water immersion. In addition, the high strength of the refractory metals provide resistance against compression forces leading to compaction and/or reconfiguration of the core geometry. Finally, the cermet fuel is characterized by a negative temperature coefficient due, in part, to the contribution to the negative Doppler coefficient from tungsten and rhenium. These features enhance the safety performance of the cermet-fueled design.

matrix is a precipitation-strengthened molybdenum alloy, probably in combination with a high porosity fuel particle. The development work for the 710 Reactor has established that UO_2 can be combined with tungsten to form a cermet material. In addition, the fuel element work has demonstrated consistency in obtaining a virtually continuous tungsten matrix encasing the fuel particles for a cermet with 40 volume percent tungsten. The fabrication development effort under the 710 Program has also proved that the cermet material could be machined and drilled to close dimensional tolerances.

The cermet fuel is enclosed within a cladding to assure fission gas product containment. Heat transfer and mechanical considerations required that the cladding be bonded to the cermet. This is possible because the UO_2-40W cermet and the potential refractory metal cladding candidates have similar thermal expansion coefficients. The method developed for bonding was a high pressure, high temperature process. The resulting bonded element is a monolithic structure which derives its primary strength from the tungsten component of the cermet material. Testing of both a tantalum and W-Mo-Re alloy cladding was carried out under the 710 Program. In general the W-Mo-Re alloy was favored because of high resistance to oxygen permeation at elevated tempertures.

REVIEW OF THE 710 FUEL TEST PROGRAM

The 710 Program was undertaken in the early 1960s with the initial emphasis on the development of the design and fabrication technology for refractory metal fuel elements to be operated at temperatures greater than 2400K (3500°F). The initial program was to include the construction and operation of a $10MW_t$ reactor in a closed loop facility and subsequent open-loop tests with hydrogen as the coolant. The open-loop tests were to be operated at a power level of approximately 220 MW_t and a gas temperature of 2477K (4000°F). The original program proceeded to the point where a number of partial-length hexagonal fuel elements (and a few full length elements) were successfully fabricated; the fuel elements were approximately 2.3 cm across flats with 91 coolant channels per assembly and a channel hydraulic diameter somewhat greater than 0.09 cm.

In the mid 1960s the 710 Program was reoriented to the development of a reactor for a 200 kW_e Brayton cycle space power system, and an extensive fuel test program was initiated. Test temperatures for the new program were established as 1920K (3000°F) and the number of coolant channels per assembly were reduced to 19. A summary of the 710 fuel element tests is given in Table 1. All discharged specimens were found to be leaktight, well-bonded and showed excellent weight and dimensional stability. In addition, material interactions, gas stream impurities, fission product retention and the onset of cladding failure were not observed to be the limiting potential causes of failure under the test conditions imposed. It was concluded that the cermet fuel was qualified for gas temperatures of 1900K (2960°F) and for operating times approaching 10,000 hours. However, the peak burnups obtained for the in-reactor test specimens were all less than 1.0 atom percent. Thus, additional testing of the cermet fuel will be required to qualify the fuel to moderate burnup levels (i.e., 2 to 4 atom percent burnup).

Table 1. Summary of 710 Fuel Element Qualification Program Testing.[a,b]

Type of Specimen	No. of Specimens	Specimen Test Time (Hrs)
Non-Nuclear Static Tests (19-Channel, Partial-Length)		
W-Re-Mo-Clad	3	22,125
T-111-Clad	6	58,900
Mo-Re-Clad	2	17,660
	11	98,685
Non-Nuclear Static (Single-Channel, Partial-Length)		
W-Re-Mo-Clad	13	62,561
T-111-Clad	1	4,666
	14	67,227
Non-Nuclear Dynamic Tests (19-Channel, Full-Length)		
W-Re-Mo-Clad	1	2,000
T-111-Clad	2	13,669
	3	15,699
In-Reactor Static Tests (Single-Channel, Partial-Length)		
W-Re-Mo-Clad	20	116,066[c]
T-111-Clad	1	5,000
	21	121,066[c]

[a]Non-nuclear dynamic and static tests were performed at 1920K, whereas static in-reactor tests were performed at a maximum temperature of 1810K.
[b]Thermal cycle tests (10-40) were carried out from 500K to peak operating temperatures for all test specimens.
[c]Some tests were continued beyond the period indicated.

CONCLUSIONS

Cermet-fueled nuclear reactors can be utilized for advanced space power systems which require high coolant temperatures, high power densities, multiple restart capabilities, rapid transitions between operating modes and long operating lives. In general, the qualification test programs from the 1960s provide a significant data base for predicting the cermet fuel response. However, some additional qualification testing of the cermet fuel will be required to verify the thermal-mechanical behavior, with the focus transient and/or moderate burnup cycling performance. A balanced qualification test program is expected to establish a framework for the successful development of a cermet-fueled reactor for a broad range of advanced space applications.

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