INL/CON-05-00707
PREPRINT

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American Nuclear Society Annual Meeting

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November 2005

The INL is a
U.S. Department of Energy
National Laboratory
operated by
Battelle Energy Alliance

Idaho National Laboratory

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A High Temperature, non-TRISO Fuel and Clad Design with Commercial-grade Enrichment for the Prismatic Block Very High Temperature Reactor

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INTRODUCTION

The prismatic block Very High Temperature Reactor (VHTR) is a leading Generation IV reactor concept [1]. This reactor with its relatively low core power density and large graphite mass currently satisfies the fundamental goals of the Generation IV charter. However, modifications can be made to the fuel and clad design, such that (1) VHTR uranium enrichment can be lowered to near commercial-grade pressurized water reactor (PWR) enrichments, (2) fuel burnups are extended, and (3) the thermal safety margin under transient conditions is increased. This paper outlines a possible fuel and clad design concept for use in a VHTR prismatic block core which could lead to substantial improvements in overall VHTR economics and sustainability.

The results of depletion calculations here will demonstrate comparable burnup between the new fuel and clad design with only 4-6 wt% enriched uranium and the current higher enriched 10-20 wt% VHTR fuel design. In addition, the new fuel and clad design concept uses high-temperature ceramic fuel and clad materials that have the potential to significantly increase the thermal margin under VHTR transient conditions.

The current fuel block design for the VHTR is the hexagonal Fort Saint Vrain (FSV) fuel block with 108 coolant channels, 210 fuel rods, and six burnable poison holes drilled axially in the block. This basic FSV block is also part of the new design concept here. The basic hexagonal block dimensions remain fixed with only the fuel pellet and clad materials and radii changed. Further optimizations of the fuel block are in progress.

Currently, the proposed nuclear fuel for the prismatic VHTR is the well-known TRISO-coated particle fuel [2]. The TRISO-coated particle offers a nice spherical, high-integrity pressure vessel containment for the fission gases (SiC layer). However, due to the multiple particle coating layers, the fuel kernel represents only 9.4% of the total particle volume (350 μm kernel diameter particle) and together with the 35% packing fraction limitation in the fuel compacts, uranium loading in the fuel rods is not only very inefficient but, at VHTR uranium loadings, results in a strongly under-moderated condition in the core that translates into a large reactivity and burnup penalty.

FUEL/CLAD DESIGN CONCEPT

In order to remove the reactivity penalty, this fuel design concept replaces the TRISO-coated particle fuel with a high density solid solution fuel, for example, UO_2, UO_2-ZrO_2-CaO, UN, U_3Si, or UC_2 fuel forms made into thin rods. Although each of these fuel forms presents some interesting and specific advantages, only the UO_2 fuel form will be discussed further herein. The solid fuel form of the UO_2 offers the ability to load equivalent quantities of uranium in a much smaller volume relative to the TRISO-coated particle fuel and is currently used worldwide in commercial light water reactors. The fabrication and fuel performance of UO_2 are well-known and have a long experience base.

The use of UO_2 in the form of thin rods increases the neutron moderation by requiring less high-density graphite from the fuel block to be removed in order to accommodate the fuel rods. The overall block carbon-to-uranium ratio (C:U) increases from 300-400 for the TRISO-coated particle fuel to 1300-1500 (optimal C:U range) for the UO_2 fuel. Optimal fuel rod diameters would then be in the 2.0-4.0 mm range depending on the uranium enrichment. These diameters are much less than the current VHTR fuel rod diameter of 12.45 mm. It should be noted that fabrication of UO_2 fuel rods with these small diameters is feasible.

The thin fuel rods would be clad in a high-temperature material, such as zirconium carbide (ZrC), or other high-temperature carbides, nitrides, oxides, etc. These fuel rods (fuel and clad) would then be inserted into the drilled fuel holes in the prismatic fuel block. The fuel rods could be either the full length of the block or shorter length rods inserted in stacks.

New cladding technology would, however, have to be developed. Use of a ZrC clad, or other high temperature carbide clad material would require a new technology development program, but would have the SiC clad experience as a basis. Carbide clad would be more advantageous than an oxide or nitride based clad material, since the low-Z carbon atoms would provide better neutron moderation and reactivity.

Another advantage to using a high density solid solution fuel form, such as UO_2, and small diameter fuel rods is that there is increased space surrounding the fuel rod to accommodate a relatively thick clad. Clad thicknesses on the order of several millimeters would be possible. These thick claddings would act like super pressure vessel containers with many possible geometry configurations to optimize the fission containment and clad strength. For example, the relatively thick clad could be in duplex form, or dual cylindrical clad tubes containing the fuel pellets. The inner clad tube would act as a fission product barrier and the outer clad tube, a high-strength, high-integrity pressure vessel containment barrier. The inner clad might even have a low-density pyrolytic carbon sheath to act as buffer between the fuel and the inner clad wall in order to minimize fuel-clad interactions and improve fission product absorption and retention.

In addition, the TRISO-coated particles have a 1600 °C temperature limit at which decomposition of the SiC layer begins and particle integrity is compromised. The UO_2 fuel and ZrC clad have very high melting points of 2800 and 3540 °C, respectively, and would provide a substantial thermal margin increase for the VHTR fuel and core under transient conditions.

COMPUTER CODES/MODEL

The neutronic analyses were performed using the MCNP4C (Monte Carlo N-Particle) code version 4C [3]. The MCNP4C code is a general purpose, continuous energy, generalized geometry, coupled neutron-photon Monte Carlo transport code. The Evaluated Nuclear Data Files, ENDF-5 and ENDF-6, were used in the MCNP neutronic calculations.

The General Atomics Gas Turbine-Modular Helium Reactor or GT-MHR [4] was the reference basis for the MCNP4C model. A radially symmetric 1/12 full core MCNP4C geometry model was developed for the neutronic depletion studies.

The ORIGEN2.2 (Oak Ridge Isotope Generation) code version 2.2 [5] was used to calculate the time-dependent isotopic fuel rod inventory in the depletion calculations in conjunction with MCNP4C.

DEPLETION RESULTS

Depletion calculations were performed to compare and demonstrate the increased burnup capability of the proposed UO_2 thin rod fuel relative to the TRISO-coated fuel. The depletion calculations were performed using different enrichments and two fuel block loadings, 554 g (initial core) and 776 g U-235 per fuel block (two-batch reload). These loadings achieve an 18-month power cycle length and were assumed to be uniform across the core. In the UO_2 cores, the clad was assumed to be silicon carbide (SiC) with a thickness of 1.5-mm. A slight reactivity penalty would be observed for use of ZrC clad instead of the SiC clad used in these calculations.

In the first depletion calculation, the TRISO particle enrichment was 10.0 wt%, with a particle packing fraction (PF) of 0.24715, uranium oxy-carbide kernel diameter of 425µm, kernel density of 10.50 g/cc, and a fuel rod diameter of 12.45mm. For the UO_2 case, the enrichment was only 5.0 wt% with a fuel rod diameter of 3.06mm. The TRISO-coated particle fuel core goes subcritical at approximately 560 EFPD (Effective Full Power Days at 600 MW_{th} total core power) and the UO_2 core at 630 EFPD. Use of the UO_2 core, block, and fuel design achieves a substantial increase of 70 EFPDs (13% increase). The important point here is that the power cycle can be met and exceeded with very low-enriched uranium fuel and opens up the possibilities for either a much longer power cycle or perhaps a further reduction in uranium enrichment (e.g. 4 wt%) for the 18-month power cycle length.

The second burnup calculation used reload blocks uniformly distributed across the core, each block with 776 g U-235. For the TRISO-coated particle fuel, the enrichment was increased to 14.0 wt% U-235. For the UO_2 case, the enrichment was again only 5.0 wt% with a fuel rod diameter of 3.63 mm. The TRISO-coated particle fuel core went subcritical after 890 EFPDs. The UO_2 core with 5.0 wt% went subcritical after 815 EFPDs, or a decrease of 78 EFPDs relative to the high enrichment TRISO-coated particle core. Furthermore, by increasing the UO_2 enrichment from 5.0 to 6.0 wt% and reducing the fuel rod diameter slightly from 3.63 to 3.31 mm in order maintain the 776 g U-235 per fuel block, the UO_2 core then achieved a burnup of 915 EFPD or an increase of 100 EFPDs, longer now than the TRISO-coated particle fuel core by 25 EFPDs.

It is quite apparent that the UO_2 cores are comparable to the TRISO-coated particle fuel cores in terms of burnups (EFPD), but with much lower uranium enrichment.

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