Low-Enriched Very High Temperature Reactor Core Design

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ABSTRACT

The Very High Temperature Reactor (VHTR) is a leading Generation IV reactor concept capable of generating electricity, process heat, and hydrogen. This concept is a thermal reactor with an active core composed of an annular ring of prismatic graphite fuel blocks. The relatively low core power density and large graphite thermal mass ensures compliance with the fundamental goals of the Generation IV charter. However, modifications can be made to the current VHTR fuel and clad that can further improve the VHTR performance. Improvements that can: (1) lower the uranium enrichment, (2) achieve 18-month power cycles, and (3) increase the thermal safety margin under transient conditions.

The current fuel block design for the VHTR is the hexagonal Fort Saint Vrain reactor fuel block with 108 coolant channels, 210 fuel rods, and six burnable poison holes. The nuclear fuel is the well-known TRISO-coated particle fuel, which offers a strong high-integrity spherical pressure vessel for the containment of 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% particle packing fraction limitation in the fuel compacts, uranium loading in the TRISO fuel rods is inefficient and results in a strongly under-moderated core and a large reactivity and burnup penalty.

In order to remove this reactivity penalty, the new fuel design concept here 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 very thin rods. Although each of these different fuel forms may present some interesting and specific advantages, only the UO_2 fuel form will be discussed. The solid fuel form of the UO_2 offers the ability to efficiently load equivalent quantities of uranium in a much smaller volume relative to the TRISO-coated particle fuel. Plus, UO_2 is used worldwide in commercial light water reactors and has a strong experience base in terms of fuel fabrication and fuel performance relative to TRISO particle fuel.

The use of UO_2 in the form of thin rods (much thinner than the TRISO fuel rods) increases the neutron moderation by requiring less high-density graphite to be removed from the graphite fuel block 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 UO_2 fuel rod diameters would 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 small-diamter UO_2 fuel rods would be clad in a high-temperature material, such as zirconium carbide (ZrC), or other high-temperature carbide, nitride, or oxide material. These fuel rods (fuel and clad) would then be inserted into the drilled fuel holes in the prismatic graphite fuel block.

Neutronic results from MCNP/ORIGEN depletion calculations demonstrate comparable 18-month burnups between the new fuel/clad design with only 4-6 wt% enriched uranium and the current higher enriched 10-20 wt% TRISO fuel design. In addition, the new fuel/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 TRISO-coated particles have a 1600 ºC 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 ºC, respectively, and would provide a substantial thermal margin increase for the VHTR fuel and core under transient conditions.

Another advantage to using the high density UO_2 in small-diameter fuel rods is that there is sufficient space surrounding the fuel rods 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.