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Development of high thermal conductivity UO_2–Th heterogeneous fuel

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ABSTRACT

A novel design of heterogeneous UO_2–Th nuclear fuel for light water reactors (LWRs) is proposed. The main advantages of the design are higher thermal conductivity, reduced maximal temperature in the fuel, lower heat stored in the fuel system, or higher thermal breeding ratio. Thermal, neutronics and simple economics calculations were performed to determine the benefits of the new fuel concept. Moreover, an experimental setup utilizing flashing method for measuring of thermal characteristics was designed. It will serve to confirm theoretical assumptions and to precisely determine thermal conductivity and heat capacity of the proposed fuel design and to assess thermal resistance between UO_2 pellets and Th plates. The many substantial benefits of the proposed fuel design are reached with very competitive cost, which is also estimated.

1. Introduction

Thermal conductivity improvements for traditional oxide nuclear fuels increase both safety and efficiency of operating commercial LWRs. Hence, enhancement of thermal performance of nuclear fuel is one of the priorities of nuclear power research especially after the events at Fukushima-Daiichi power plant. Commercial reactors worldwide are fueled mainly by ceramic UO_2 slightly enriched with 235^{U} despite the potential availability of alternative types of nuclear fuels (MOX, metals, nitrides, silicides etc). There are several advantages of traditional UO_2 fuel including high melting temperature, good oxidation resistance and long-term experience with UO_2 behavior Baney (2012). However, its main disadvantage is the low thermal conductivity (λ) causing high center line temperature and steep temperature gradient during power operation which results in induction of undesirable phenomena such as non-uniform redistribution of pores, oxygen, grains, or fission products; thermal stresses resulting in cracking or plastic deformation of fuel pellet; or fission gas release. Researches aiming at improving the thermal conductivity of UO_2 have been mainly focusing on mixing UO_2 with additives (SiC, BeO, diamond etc. Tulenko and Subhash (2016); Yeo et al. (2013); Andrade and Ferreira (2007); Baney (2012)) or development of high-density concepts such as U_3Si_2, UN or UC Ross et al. (1988); Harp et al. (2015). Alternative approach of decreasing pellet temperature is design of annual fuel rods studied by Feng et al. (2007); Kazimi et al. (2003); Koo et al. (2013). There were also a few studies that proposed to use disks or different inserts (e.g. niobium plates, graphite disks, Mo) into fuel rods and thus increase its thermal conductivity Mariani et al. (2013); Hastings and Macdonald (1984); Chang Keun Jo et al., Jun. 2000; Lee et al. (2016); Boyle (1987).

One of the often considered additives to the UO_2 matrix is ThO_2 which due to its similar physical and chemical properties ensures compatibility of both components. In order to take advantage of thorium over uranium, such as better thermal breeding, higher λ, lower minor actinides creation, and higher availability of the substance, Th-U mixed fuel has to be mainly composed of Th. Fuels with very high ThO_2 content, often exceeding 80% of total volume are called thoria-based fuel Kutty et al. (2013). But even with such a high thoria content, the thermal conductivity enhancement is not very promising. Additionally, highly enriched uranium is needed making this concept rather expensive, alongside with other yet unresolved problems caused by the ThO_2 presence. When using a low volume of homogeneously distributed thorium, desired positive effects are negligible.

For these reasons, this paper proposes addition of heterogeneously distributed thorium metal (up to 20%) in order to make use of mainly one of advantages of thorium over uranium, which is its higher λ in a metal state. Similar approach was discussed in Mariani et al. (2013) where higher conductivity materials are proposed as a new components inside fuel rods. Th metal does not affect the neutron-physical performance of the fuel and thanks to higher breeding ratio these characteristics are even improved unlike with Nb disks which were proposed elsewhere. Because the heterogeneous distribution of thorium is suggested, the chemical compatibility of both materials is not an issue.

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Thin disks made of thorium metal are placed between UO_2 pellets to improve heat conduction, to reduce the temperature gradient in the fuel pellets as well as to reduce the maximal fuel temperature. In order to optimize λ of the proposed concept, different sets of a layout with different volumes of UO_2 pellet and Th metal disks were studied. The proposed composite pellets need to be experimentally characterized in detail to confirm theoretical calculations. In order to precisely determine a thermal diffusivity of different fuel designs and thermal resistance between different layers, measurement by the flashing method was proposed and designed. The facility can be utilized to confirm the benefits of proposed heterogeneous fuels as well as other concepts of nuclear fuel with enhanced thermal conductivity M. Sevecek and M. Valach (2016).

Moreover, basic calculations of neutron-physical and thermo-mechanical characteristics were performed. Mixed fuel burnup and thorium impact on multiplication coefficient of VVER-1000 reactor's infinite lattice were calculated for different concentrations of UO_2 and thorium metal using the Serpent Monte Carlo reactor physics burnup calculation code Leppänen (2013). Additionally, a new tool was written in Python to calculate the stationary thermal response of the heterogeneous fuel. Heat transfer inside the heterogeneous fuel pellet can be calculated for the fresh fuel during nominal steady-state operation with an emphasis on a variation of maximal temperature with different Th contents. Total heat stored within the traditional UO_2 fuel is compared to that of heterogeneous pellets which proves another benefit of the proposed fuel design. Finally, results of the basic economic evaluation are shown comparing additional cost of this enhanced fuel against accomplished benefits.

2. Fuel design

Two forms of thorium suitable for the nuclear fuel design were initially investigated: ThO_2 and pure thorium metal. ThO_2 similarly to UO_2 excels in a very high melting temperature (≈ 3650 K) Ronchi and Hiernaut (1996), but its thermal conductivity is higher only by tens of percent, especially at operating temperatures, as can be seen in Fig. 1 Cozzo et al. (2011); Yang et al. (2004); Saoudi et al. (2018); Bakker et al. (1997). Metal thorium, on the contrary, has lower melting temperature (≈ 1750 °C), but its λ is approximately twenty times higher at operating temperatures Benedict et al. (1981); International Atomic Energy Agency (2006) as shown in Fig. 1. Thermal conductivity generally highly depends on porosity of a material which should not be, especially for ceramic materials, neglected. Since values of thermal conductivity of Th metal are available only for zero porosity, the plots for UO_2 and ThO_2 were adjusted for 100% theoretical density.

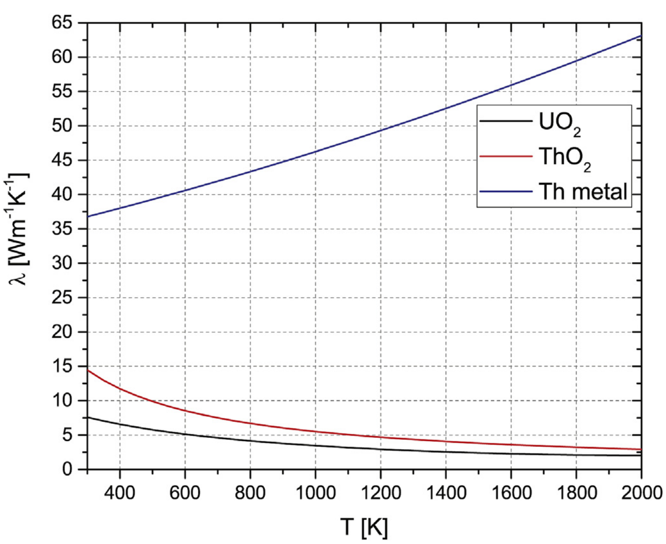

Fig. 1. Comparison of UO_2, ThO_2 and Th metal thermal conductivities Benedict et al. (1981); Ronchi et al. (1999); Bakker et al. (1997).

Fig. 2. Schematics of thin thorium plates placed between short UO_2 pellets.

2.1. Fuel thermal conductivity

The thermal conductivity of UO_2 is highly dependent, except for temperature, on burnup and dopants (e.g. Gd, Cr_2O_3) which might affect also λ of ThO_2 and Th metal. Thermal conductivity of ThO_2 and pure Th metal should be further investigated due to lack of experimental data.

UO_2 has a poor thermal conductivity between 2 and 6 $W\,m^{-1}.K^{-1}$ dependent on temperature and burnup Ronchi et al. (1999); Fink (2000). Conductive heat transfer in the ceramic UO_2 matrix same as in ThO_2 occurs by phonons, and by energy of electrons predominantly at higher temperature.

2.2. Heterogeneous fuel

Both of the proposed thorium-based materials (Th metal, ThO_2) are possible to use in the suggested novel fuel design since heterogeneous distribution does not require the two materials to be mixable, as one can be simply placed on the other, as can be seen in Fig. 2. If a material with suitable physical and material properties (elasticity, plasticity, resistance to cracking, thermal expansion, resistance to swelling etc.) is used, the plates placed between UO_2 pellets can have a larger diameter in comparison with uranium pellets, which decreases the size of the fuel-cladding gap and further enhances heat transfer. On the other hand, the expansion of the material in transient conditions can contact the cladding material and initiate its degradation. Since the thermal expansion of the Th metal is higher compared to that of UO_2, the design with wider Th plates represents the shape of the fuel during operation. However, in cold state the plates are actually not wider in comparison with UO_2 pellets as shown in Fig. 2. It should be noted that, swelling of the thorium disks will be limited thanks to both low fission rate in thorium and low swelling susceptibility of thorium metal Kutty et al. (2013) which restricts further growth of Th plates during operation. The swelling of base UO_2 can result at higher burnup in reverse of this effect. However, this phenomenon is rather complex and needs further experimental examination (see Fig. 3).

3. Neutron-physical calculations

Depletion calculations were performed using the Serpent continuous energy Monte Carlo reactor physics burnup calculation code Leppänen (2013). For the purpose of basic evaluation of proposed concept, infinite lattice with parameters of the VVER-1000 reactor core were