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A novel research reactor concept based on coated particle fuel

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ABSTRACT

This work presents a preliminary study of a novel plate-type fuel concept for a high-performance and ultra-safe research reactor. This new fuel type consists of coated particle fuel (CPF) randomly dispersed in an aluminum matrix with a certain packing fraction that can be adjusted depending on the reactor design requirements. The CPF can also be varied in the fuel kernel material between UC and UO_2. For the purpose of this study, UO_2 was used as the reference fuel type. Using this novel fuel type, a 20 MWth pool-type research reactor was investigated to determine the preliminary performance and safety characteristics of the new fuel. The core thermal analysis was done using the MATRA-P code. The neutronics analysis was done using the Monte Carlo Serpent code for an equilibrium cycle resulting from a multi-batch fuel management. In this analysis, it was found that the Doppler effect is significantly enhanced through the implementation of CPF, in turn improving the inherent safety of the reactor. In addition to the notable improvement in safety, the new fuel type also promises to be able to achieve a high thermal neutron flux, improving the performance and utility of the reactor. It is concluded that the CPF-based fuel concept presented in this paper can enable new high-flux reactor designs using simple plate-type fuels with improved safety.

1. Introduction

Research reactors are mainly used to produce neutrons to be utilized in neutron-based scientific and engineering experiments and applications. Research reactors can support various kinds of researches and applications in physics, radiation material science, neutron activation analysis, neutron radiography, silicon doping, and the production of medical and industrial isotopes. The neutron flux level, neutron spectrum, and availability of irradiation facilities determine the potential applications, and therefore the competitiveness of a research reactor. For many applications, a high neutron flux is essential, resulting in research reactors being designed to provide a high neutron flux. Nowadays, research reactors can be considered not only as an essential tool to perform fundamental scientific research, but also as assets that satisfy industry irradiation needs (Tretiyakov et al., 2013).

An unparalleled level of safety is required for research reactors since they are usually located in residential areas with researchers working near the reactor itself. As a consequence, the thermal output of research reactors is small and they are typically fully submerged in a large water pool for both radiation shielding and dealing with the decay heat in case of an accident. In addition to the apparent safety characteristics of small size research reactors, it is also required that research reactors should have inherent safety characteristics in view of the reactor physics. For a stable and self-regulating reactor, the power coefficient of reactivity (PCR) needs to be negative. The PCR is a combined effect of the fuel temperature coefficient (FTC or Doppler effect) and the coolant temperature coefficient (CTC) in typical water-cooled research reactors.

The safety characteristics of research reactors are largely governed by the fuel type used. Nowadays, most research reactors use a U_3Si_2-Al dispersion fuel in which U_3Si_2 fuel particles are dispersed in an Al matrix (http://www.rertr.anl.gov/QualFuel.html) where low-enriched uranium (LEU) is typically adopted due to the proliferation concerns of using traditional high-enriched uranium (HEU) fuel. In modern LEU-based fuels, it is important to maximize the U loading in the fuel region for a high-performance research reactor. The U_3Si_2-Al dispersion fuel is known to be qualified with a uranium density of up to 4.8 g/cm^3. The U_3Si_2 fuel is presently considered the best qualified fuel in terms of uranium loading and performance. Recently, in order to increase the U inventory in the fuel, UMo-Al dispersion fuels are also actively under development (Guidez et al., 2002; Hayes et al., 2002). Regardless of the fuel materials, plate-type fuels are popularly used in many kinds of research reactors due to their simple design and proven performances. In the U_3Si_2 and UMo fuels, the fuel

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temperature should be kept rather low in order to achieve both a high fuel burnup and high power density. Therefore, the fuel plate thickness should be rather thin, usually less than 1 mm. Due to the low fuel temperature requirement, the FTC value is usually quite small in research reactors. Meanwhile, the coolant speed should be quite high in order to maintain a relatively low fuel temperature in high-performance research reactors. A high coolant speed may raise concerns regarding the mechanical integrity of the thin fuel plates. Consequently, the size of the plate fuel is also rather small.

Most research reactors are open pool type and the coolant temperature should be substantially lower than 100 °C in order to avoid coolant boiling. As a result, the coolant temperature rise from the inlet temperature is quite small. Also, the coolant volume fraction in typical research reactors is relatively high and neutron spectrum is very soft. Subsequently, the CTC turns out to be rather small in regular research reactors. Therefore, the PCR value of typical research reactors is usually close to zero or just slightly negative. Because of this, inherent safety characteristics of research reactors are not considered to be strong in comparison with power reactors such as LWRs (Light Water Reactors).

In this study, we have tried to devise a new fuel concept for research reactors to enhance the inherent reactor safety without compromising the performance of the reactor and the fuel. As a new fuel concept for a high-performance research reactor, a plate fuel based on a simple coated particle fuel (CPF) has been proposed with several motivations (Hidayatullah and Kim, 2013a,b; Hidayatullah, 2014). The main motivations of the CPF-based plate fuel are to achieve a much higher allowable fuel temperature for an improved FTC and to improve the mechanical integrity of the simple box-type fuel. In this paper, the new plate-type fuel has been characterized in comparison with the conventional fuels and has been applied to a research reactor design to demonstrate its potential as an advanced fuel.

2. CPF-based plate-type fuel concept

In order to ensure a high level of safety and high performance in research reactors, a CPF-based plate-type fuel has been proposed. Although there are several plate-type fuels for research reactors, such as curved plate, a flat plate-type fuel is considered as the targeted design in this work since it is the most popular and is relatively cheap to fabricate. Additionally, the plate type fuel allows for an enhanced FTC by increasing the fuel temperature without compromising the fuel elements integrity. This is possible due to the application of dispersion fuels providing solution to this conflicting dual optimization. In this case, the fuel temperature can be increased by having a low thermal conductivity provided it is able to operate at elevated temperatures. In this regard, the fuel can be a ceramic one such as UO_2. Simultaneously, the temperature of the Al matrix needs to be sufficiently below its melting point (~660 °C), which is in turn ensured by the good heat transfer capabilities of both the matrix and the plate-type fuel.

Fig. 1 shows the basic concept of the newly proposed fuel plate where the CPF is randomly dispersed in an Al matrix. A single CPF is composed of a central fuel kernel coated by a carbon buffer layer and, if necessary, a thin metallic Zr layer. The role of the buffer layer is to accommodate the fuel swelling due to burnup and the Zr layer is used to prevent the release of fission products in the case of fuel failure. It should be noted that the Zr layer may be unnecessary if the CPF is safely contained in the Al matrix since the fission products will be hardly able to escape the Al matrix. In the simplified CPF with a single porous carbon buffer layer, the well-developed TRISO (Verfondern et al., 2007) fuel technology can be directly applied. Therefore, in this work the fuel kernel is assumed to be coated only by the buffer layer, which will be advantageous in terms of the U loading and the fabrication cost.

Taking into account the kernel requirements above, UO_2 and UC can be used as the kernel material in the CPF fuel. While UC fuel is a promising candidate for the fuel kernel due to its higher density, UO_2 is adopted as the reference fuel in this study due to its well-known performance in high temperature conditions and achievable burnup. It is worthwhile to note that a UN (U nitride) fuel can also be an attractive alternative kernel due to its high fuel density although it is not considered here. Since only LEU is considered, the U density of the fuel should be maximized as much as possible. In this regard, three main parameters need to be considered: kernel diameter, buffer thickness and packing fraction of the coated particle in the fuel meat. To maximize the U loading in the fuel, the kernel diameter and packing fraction should be maximized while the coating layer should be minimized. Based on the TRISO fuel technology, the fuel kernel diameter can be 700 μm or more. In regards to the packing fraction of CPFs, there is currently no available experimental data. Meanwhile, the typical fuel volume fraction in the U_3Si_2 fuel meat is limited to ~42% in order to achieve a high fuel burnup. Taking into account the robust configuration and design features of the new fuel plate, it is assumed that a packing fraction of 50% could be safely implemented for the fuel proposed in this work.

The necessary buffer thickness can be estimated by accounting for the swelling behavior of the conventional UO_2 fuel. The swelling behavior can be approximated by the following formula (Geelhood et al., 2006):

$$\frac{\Delta V}{V} = D \times (bu - 6) \times 8.0966 \times 10^{-4}, \tag{1}$$

where, $\Delta V/V$ = fractional volume change, bu = burnup (GWd/MTU), D = fraction of theoretical density (D = 0.95).

Eq. (1) indicates that when the burnup is smaller than 6 GWd/MTU, the UO_2 fuel actually shrinks with irradiation. In the case of an extremely high burnup of 200 GWd/MTU, the volume change is predicted to be about 15% or higher, corresponding to an increase in the radius of the kernel with a diameter of ~700 μm by about 16 μm. Therefore, it is assumed that the buffer thickness could be 20–30 μm in order to accommodate the kernel swelling resulting from a very high burnup.

The plate fuel integrity is also affected by the release of fission gas from the fuel kernel. For a high performance fuel, the fission gas release should be minimized. The relation between fission gas release as a function of burnup with temperatures lower than 400 °C can be approximately modeled as the following (Geelhood et al., 2006):

$$FGR = bu \times 7 \times 10^{-3}, \tag{2}$$

where FGR = fission gas release (%), bu = burnup (GWd/MTU).

For an extreme burnup of 200 GWd/MTU, the estimated fission gas release is only about 1.4%. Although the current estimation of fission gas release from the UO_2 kernel is quite uncertain, the fuel temperature in the CPF fuel is expected to be much lower than 400 °C, as shown later in this paper. Taking into account the Al melting temperature (660 °C), the maximum allowable fuel kernel temperature would be 400–500 °C. Therefore, the fission gas release from the UO_2 kernel will be quite small and limited in the new fuel design.

Table 1 shows the predicted uranium density in the fuel meat region of the new fuel concept for several configurations. It is clear that a larger kernel and a thinner coating thickness both provide a higher U density in the fuel meat. It is noted that the U density can be similar to that of the current U_3Si_2 fuel with a 700 μm kernel diameter. It is important to note that in the case of the UC kernel, the U density can be high and can be even higher than that of the current U_3Si_2 fuel.