Behavior Assessments for UO_2-BeO Enhanced Conductivity Fuels

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Many people have criticized beryllium because they believe it is toxic. While this is a common misperception, it is still a misperception. People believe this because it is repeated so many times. The reality is beryllium oxide, the form proposed as an additive to nuclear fuel, requires no modifications to a facility already processing uranium dioxide. Conducting certain processes in glove boxes, as done with uranium dioxide, offers the requisite protection required by the US OSHA.

Susceptibility to berylliosis can be determined using a simple blood test. Statistics reported by the Agency for Toxic Substances and Disease Registry estimate between 1 and 15% of people occupationally exposed to beryllium may develop berylliosis. The blood test is a leading indicator of susceptibility. IBC Advanced Alloys processes beryllium metal on a daily basis and has protected its workers for more than 30 years. For a nuclear fuel application, prudent process control such as that employed for handling uranium dioxide provides the desired degree of worker protection and safety. The benefits of beryllium can be obtained without increasing the risk of damage to workers' health and well being.

Improved thermal conductivity in uranium dioxide fuel through the addition of high conductivity additives has been under investigation for decades. The use of beryllium oxide as the preferred conductivity enhancing additive is the focus of the work described herein. This approach has historically introduced two challenges. First, the additive material occupies volume in the fuel that would normally be occupied by fuel atoms and second, most additives have thermochemical interactions with UO_2 at elevated temperatures.

The first challenge tends to require the use of enriched uranium to overcome the loss of fuel volume. The second has the potential to lower the maximum allowed centerline temperature of the fuel, thus limiting the benefit from the lower centerline temperature due to the additive. However, decreasing the fuel centerline temperature still enables other potential benefits such as reducing fuel swelling, restructuring, and fission product migration.

A sequence of analyses in a typical Pressurized Water Reactor environment have been completed. The analyses began with pellet heat conduction studies at various linear heat generation rates (LHGR).

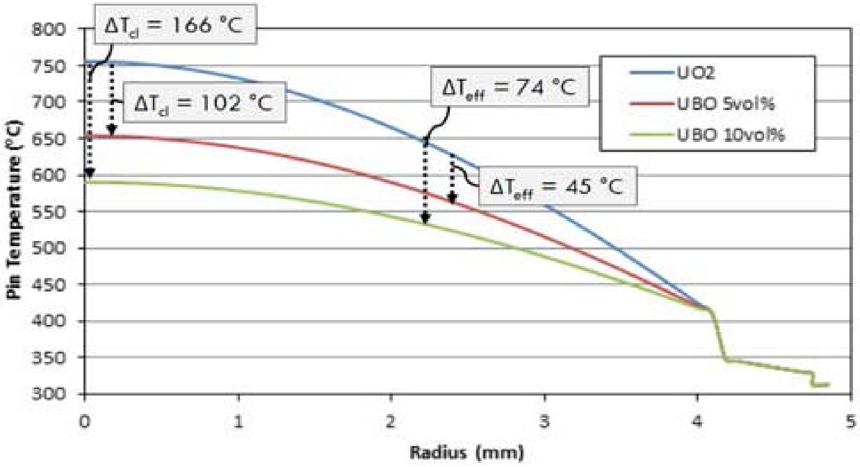

Fig. 1. Estimated temperature profiles showing reduced centerline (ΔTcl) and effective (ΔTeff) temperatures.

As a brief summary of the results, at an average LHGR of 163.4 W/cm, UO_2-10 vol% BeO was estimated to decrease the effective and centerline temperatures by 74°C and 166°C, respectively, as shown in Fig. 1. Similarly, at peak LHGR of 590 W/cm, UO_2-10 vol% BeO was estimated to decrease these temperatures by 219 and 493 °C, respectively. Simulations to compare fuel types were performed using 2D infinite lattice and 3D equilibrium core neutronic methods.

The 2D lattice analysis showed that an increased UBO fuel enrichment is necessary to maintain an equivalent cycle length as UO_2 fuel. Using a mass equivalent 235U basis and the linear reactivity model for an 18-month cycle, UO_2-5 vol% BeO and UO_2-10 vol% BeO fuel showed modest cycle increases of 1.9 and 3.3 days, respectively. Similarly, the 3D core simulation showed a cycle increase of 2.2 and 3.3 days, respectively. However, the maximum 3D burnup was increased by 3707 and 7624 MWd/t, respectively. These burnup enhancements may indicate a strategy where BeO enhancement may provide significant value.

The addition of BeO was selected over SiC, in part, because of its higher stability with UO_2 at elevated temperatures as compared to SiC. Lab-scale processing methods were established to create a novel microstructure with exceptional thermal behavior and a thermal model was created to predict the conductivity of this novel material. It has been known for some time that the addition of BeO to UO_2 improves the ceramic’s thermal conductivity.

The uniqueness of this concept arises from the tailored composite microstructure that enhances thermal conductivity. Figure 2 shows a schematic “cartoon” of the UO_2-BeO structures. The structure consists of primary UO_2 microspheres (50 to 500 μm) embedded in a mixed oxide matrix containing a continuous fine-grained BeO-rich matrix containing fine UO_2 particles liberated during processing.

PELLET FABRICATION

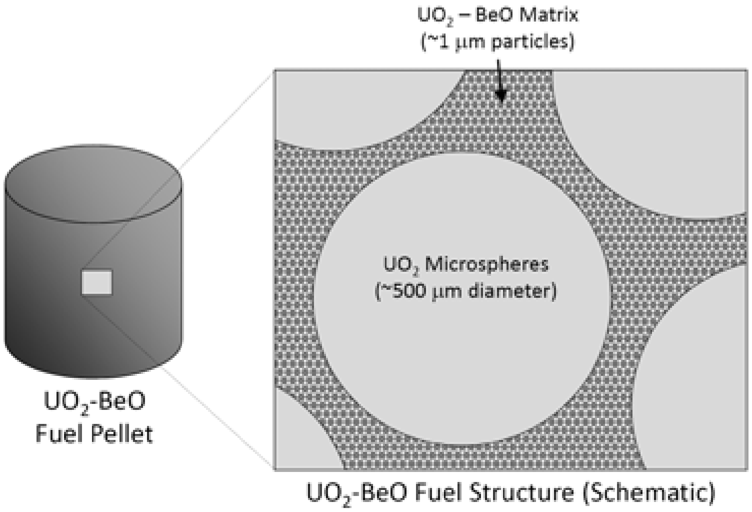

Fig. 2. Schematic of the UO_2-BeO fuel concept showing the dispersion of large UO_2 microspheres in a fine-grained BeO-rich matrix.

Pellet Fabrication Process

A bench-scale fabrication process was demonstrated previously[1]. The developments reported here were performed to reproduce that process with subsequent modifications to improve the properties of the lab-scale pellets. Fabrication used powder methods similar to commercial fuel fabrication methods and improvements to the lab-scale process are under evaluation. Figure 3 shows the current UO_2-BeO pellet fabrication process. There are a few steps that have been slightly modified from (Refs. 1, 2) as equipment improvements and optimization experiments have warranted changes.

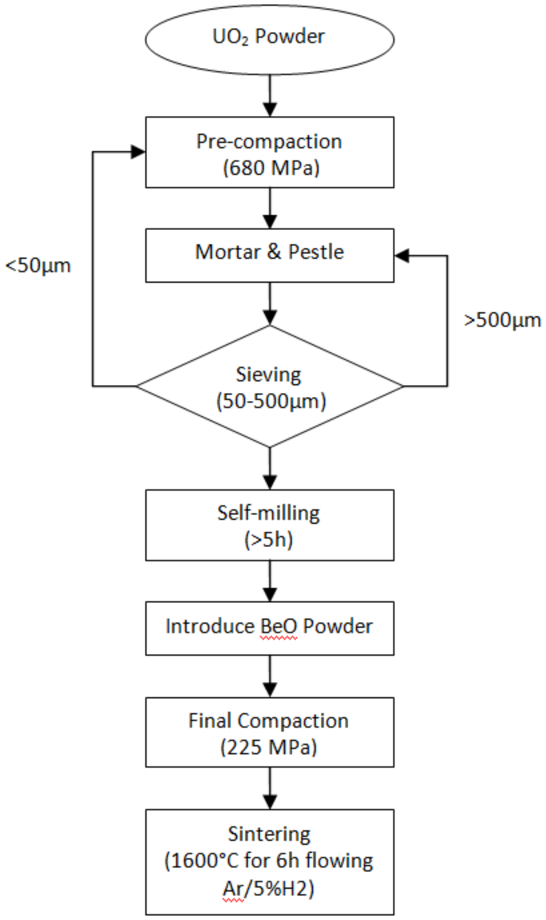

Fig. 3. UO_2-BeO pellet fabrication process flowchart.

Figure 4 shows the BeO structure resulting from the UO_2-BeO pellet fabrication process shown in Figure 3. The BeO structure is the primary contributor to the improvement in thermal conductivity which enables the reduction in pellet center line temperature at the same linear heat rate as the UO_2 fuel. The BeO structure also improves pellet integrity over the life of the pellet. The improved integrity results in less pellet cracking thereby reducing fission gas release from the pellet.

Figure 4. BeO structure after dissolution of uranium

Simulations to compare fuel types were performed using 2D infinite lattice and 3D equilibrium core neutronic methods. The 2D lattice analysis showed that an increased UBO fuel enrichment is necessary to maintain an equivalent cycle length as UO_2 fuel. Using a mass equivalent 235U basis and the linear reactivity model for an 18-month cycle, UO_2-5 vol% BeO and UO_2-10 vol% BeO fuel showed modest cycle increases of 1.9 and 3.3 days, respectively. Similarly, the 3D core simulation showed a cycle increase of 2.2 and 3.3 days, respectively. However the maximum 3D burnup was increased by 3707 and 7624 MWd/t, respectively. These burnup enhancements may indicate a strategy where BeO enhancement may provide significant value. It is also important to note the results with UO_2-5% BeO will allow for recovery of some of the uranium content penalty of the UO_2-10 vol% BeO fuel.

Thermal Diffusivity Measurements

The measured diffusivity data may be converted to a bulk thermal conductivity (*k*) by the following relationship:

$$k = \rho b \alpha c p \quad (1)$$

where ρb is the measured bulk density, α is the measured thermal diffusivity, and cp is the specific heat of the sample. The specific heat is approximated using the rule of mixing for known values for UO_2 and BeO:

$$Cp = \frac{\sum_{k=1}^{n}(Cp,k\ \rho k\ Vk)}{\sum_{=1}^{n}(\rho k\ Vk)} \quad (2)$$

where n is the number of elements in the mixture (2 in this case), ρk is the theoretical density of element k, vk is the volume fraction of element k, and cp,k is the specific heat of element k. Light Flash Analysis was used to measure diffusivities in three similar UO2-10vol.% BeO samples for temperatures from 25°C to 250°C and it is assumed that changes in the bulk density are negligible in this temperature range

Recognizing that this work is still being refined and all of the above assumptions appropriately qualify the nature of this data, the estimated values for the thermal conductivity of UO_2-10vol.% BeO are presented in Fig. 5 along with the calculated values based on the correlation.

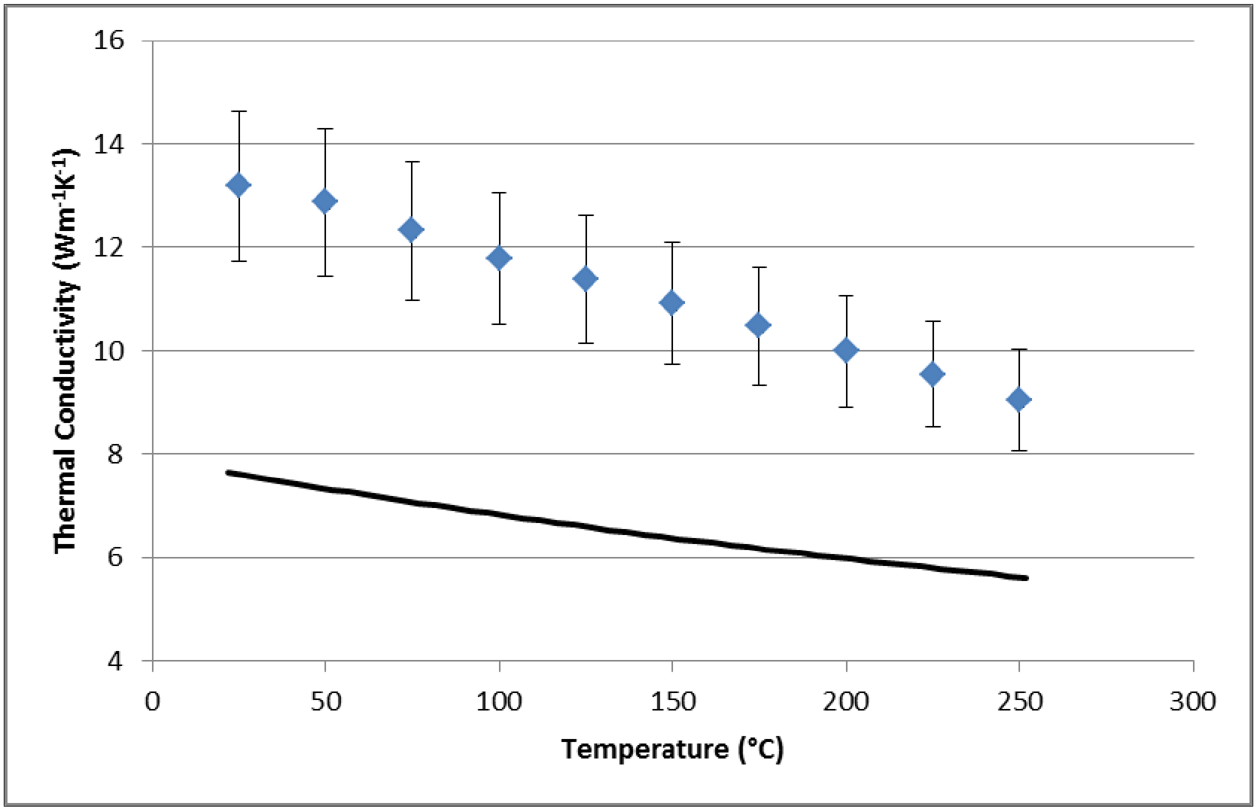

Figure 5 Estimated values for the thermal conductivity of UO_2-10vol.% BeO.

Three test samples were prepared by sectioning sintered pellets into 1-mm thick wafers with parallel faces; the faces were lightly carbon coated to guarantee maximum absorption of the heat flux into the sample. The thermal diffusivity of each pellet was measured at 10 different temperatures (25°C increments). At each interval, the LFA device measured seven independent values of the diffusivity. These data (7 points for 3 samples, or 21 data points per temperature) were then averaged to estimate the thermal conductivity of the UO2-10vol.% BeO pellets using Eqs. (1) and (2).

In order to compare the measured data to published values, a minor density correction must be made. The three samples ranged in density from ~90 to ~92%TD. The correlation by Ronchi6 used for comparison to UO_2 was recommended by J. Fink[3] and the International Atomic Energy Agency database[4] is for solid UO_2 at 95%TD. Therefore, the measured values for conductivity were adjusted to apparent 95%TD using the recommended porosity conversion equation, which may be manipulated and written as:

$$k_{95} = k_m \left[\frac{(1 - 0.05\varepsilon)}{1 - \varepsilon P} \right]$$

$$\varepsilon = 2.6 - 0.0005T$$

Where ε is porosity and P is the measured conductivity.

Benefits of BeO in PHWR Fuel

There are potential advantages related to addition of beryllium oxide to PHWR fuel. Studies conducted on PWRs indicate increased burnup and greater thermal conductivity. The increased thermal conductivity allows operation with a reduced fuel center line temperature while achieving the same surface heat flux. Improved thermal conductivity can be used to improve safety margins or increase power.

Increasing burnup in a PHWR means the fuel can traverse the reactor at a slower rate. Allowing fuel to remain in the reactor for a longer period reduces the duty on the refueling machines. Reduced duty may allow extension of the maintenance intervals for the refueling machines.

Reduced fission gas release is an additional benefit due to the addition of BeO to PHWR fuel. The lower operating temperature and the BeO structure combine to reduce the rate of fission gas release. Reducing the fission gas release benefits the fuel in case of a cladding breach because there is less fission gas in the fuel rod.

References

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