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ASSESSMENT OF URANIUM DIOXIDE FUEL PERFORMANCE WITH THE ADDITION OF BERYLLIUM OXIDE

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ABSTRACT

The Fukushima Daiichi accident in 2011 pointed the problem related to the hydrogen generation under accident scenarios due to the oxidation of zirconium-based alloys widely used as fuel rod cladding in water-cooled reactors. This problem promoted research programs aiming the development of accident tolerant fuels (ATF) which are fuels that under accident conditions could keep longer its integrity enabling the mitigation of the accident effects. In the framework of the ATF program, different materials have been studied to be applied as cladding to replace zirconium-based alloy; also efforts have been made to improve the uranium dioxide thermal conductivity doping the fuel pellet. This paper evaluates the addition of beryllium oxide (BeO) to the uranium dioxide in order to enhance the thermal conductivity of the fuel pellet. Investigations performed in this area considering the addition of 10% in volume of BeO, resulting in the UO_2-BeO fuel, have shown good results with the improvement of the fuel thermal conductivity and the consequent reduction of the fuel temperatures under irradiation. In this paper, two models obtained from open literature for the thermal conductivity of UO_2-BeO fuel were implemented in the FRAPCON 3.5 code and the results obtained using the modified code versions were compared. The simulations were carried out using a case available in the code documentation related to a typical pressurized water reactor (PWR) fuel rod irradiated under steady state condition. The results show that the fuel centerline temperatures decrease with the addition of BeO, when compared to the conventional UO_2 pellet, independent of the model applied.

1. INTRODUCTION

After the Fukushima Daiichi accident, the problem related to the production of hydrogen due to the oxidation of zirconium-based alloys in accident conditions, brought the importance of using materials more resistant aiming the safety improvement under these conditions [1]. As a consequence of this accident, the US Congress directed the Accident Tolerant Fuel (ATF) development initiative to the Department of Nuclear Energy (NE) [2]. The ATF programm has an aggressive agenda for upgrading ATF candidates for light water reactors (LWR).

The objective of this program is to evaluate the performance of the ATF candidates carrying out tests using single fuel rods or fuel assemblies in the core of commercial power reactors until the year of 2022. Efforts have been made in order to evaluate different materials which could be applied as cladding presenting a better behavior in accident conditions. In this sense, different iron-based alloys and ceramic materials as well as coated zirconium-based alloys are currently being studied as an option for the substitution of conventional zirconium-based alloys.

Another possibility in the framework of ATF development is the improvement of the fuel thermal conductivity by adding beryllium oxide (BeO) to the fuel pellet. Then, the new ATF could combine the changing of the cladding material and the increase in the fuel pellet thermal conductivity to exhibit a better performance under accident conditions.

Beryllium oxide presents higher thermal conductivity compared to that of uranium dioxide (UO_2). Studies in this field have shown that the addition of 10% by volume in the fuel pellet improves considerably the thermal conductivity of the fuel, decreasing the fuel centerline temperature and the energy stored in the fuel, enabling a better performance of the fuel.

The aim of this paper is compare the performance of the conventional uranium dioxide pellet to that of the fuel containing the addition of 10% in volume of BeO.

The adopted models to introduce the thermal conductivity of the UO_2-BeO in the fuel performance code FRAPCON 3.5 were obtained from the open literature [3][4].

2. METODOLOGY

2.1. Thermal Conductivity Models

Equations 1 and 2 present the two models used in this paper for the thermal conductivity of the UO_2-BeO fuel. Equation 1 was obtained in the paper of Chandramouli [3] and equation 2 from the experimental data carried out in Halden [4].

$$C_{Chandramouli}=\frac{1}{0.0375+0.0002165.TK-0.034248-0.000315.V.TK}+\frac{4750000000}{TK^2}.\exp^{\frac{-16361}{TK}}\left(\frac{W}{m.K}\right) \quad (1)$$

$$C_{Halden}=(1+K-BeO.FV_{BeO}).\frac{1}{0.1148+0.0040.Bu+2.475.10^{-4}.(1-0.00333.Bu).TC}+0.0132.\exp^{(0.00188.TC)}\left(\frac{W}{m.K}\right) \quad (2)$$

where:

V is the percentage in volume of BeO in the fuel pellet;
TK is the temperature in K;
K-BeO is the technological factor (0.03 for the additive and 0.05 for the matrix);
FV_{BeO} is the percentage in volume of BeO;
Bu is the burnup (MWd/kg); and
TC is the temperature in °C.

The comparison between these two models as function of temperature for the Beginning of Life (BOL) is presented in Fig. 1.

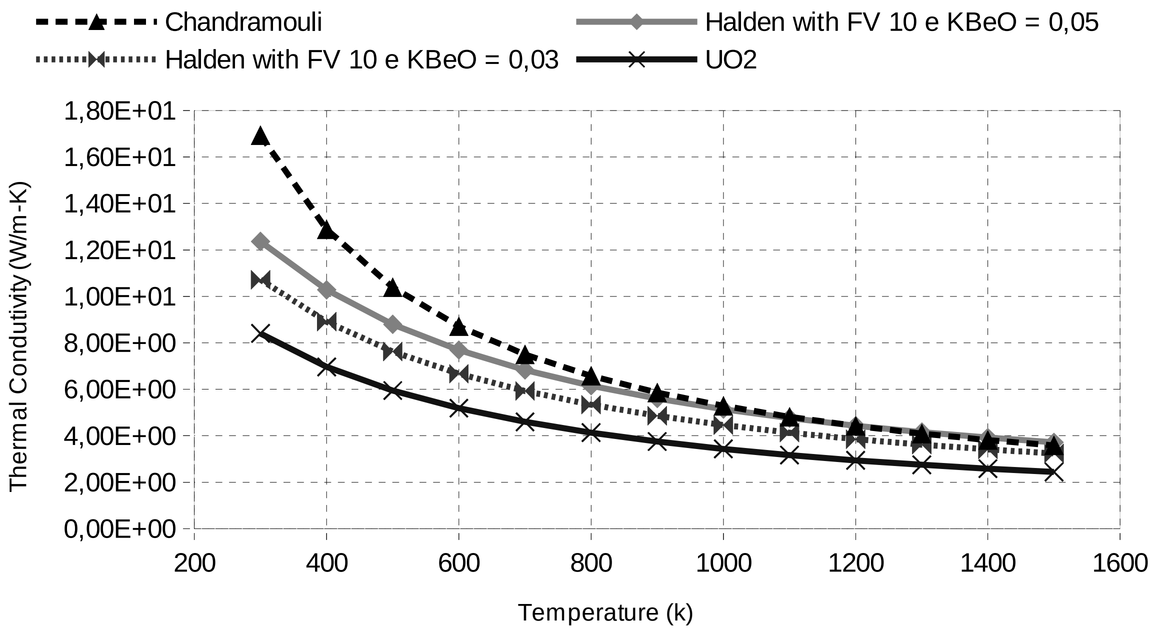

Figure 1: Models comparison for the UO_2-BeO thermal conductivity.

Fig. 1 shows that applying the Chandramouli model is obtained a higher thermal conductivity compared to the Halden model at low temperatures and both models show that UO_2-BeO presents higher conductivity than the UO_2 conventional fuel. With the increase of the temperature, the difference between the models decreases and at high temperatures no significant difference is observed.

2.2. Fuel Performance Code Modification

The code used to evaluate the fuel performance was the FRAPCON version 3.5 [5]. This is one of the reference codes in the area of nuclear fuel performance, used when steady-state conditions can be applied, ie, it can be applied to assess the performance of a single fuel rod during the reactor operation without consider power transients.

The original version of FRAPCON code contains a collection of subroutines written in fortran language which enables to assess the behavior of fuel rods manufactured using zirconium-based alloys as cladding and UO_2 as fuel. These subroutines can be modified in order to introduce properties of different materials, allowing the evaluation of the fuel performance of fuel rods with different claddings and fuels. The modified versions of the FRAPCON code used in this paper were obtained introducing separately in the fthcon subroutine, which calculates the thermal conductivity of the fuel pellet, the models concerning to the UO_2-BeO fuel. All the other subroutines were kept the same of the original code version.

2.3. Test Case

The input related to the experiment TSQ002.in contained in the FRAPCON documentation [6] was applied as test case in this paper.

The experiment identified as TSQ002 in the FRAPCON documentation corresponds to a fuel rod containing UO_2 pellets obtained from a fuel assembly with standard 16x16 design irradiated in a PWR environment. The accumulated burnup of the TSQ002 fuel rod at end-of-life was 56.1 GWd/MTU. The rod-average linear heat generation rate (LHGR) varied from 2.75to 6.95 kW/ft with the higher values near BOL [6].

3. RESULTS AND DISCUSION

The simulations considering the conventional UO_2 fuel pellet were carried out using the original version of the FRAPCON code. Two modified code versions were used to evaluate the UO_2-BeO fuel performance using both thermal conductivity models obtained from the literature.

The evolution of the fuel centerline temperature as function of time for the conventional UO_2 fuel pellet and the UO_2-BeO using different thermal conductivity models are presented in Fig. 2.

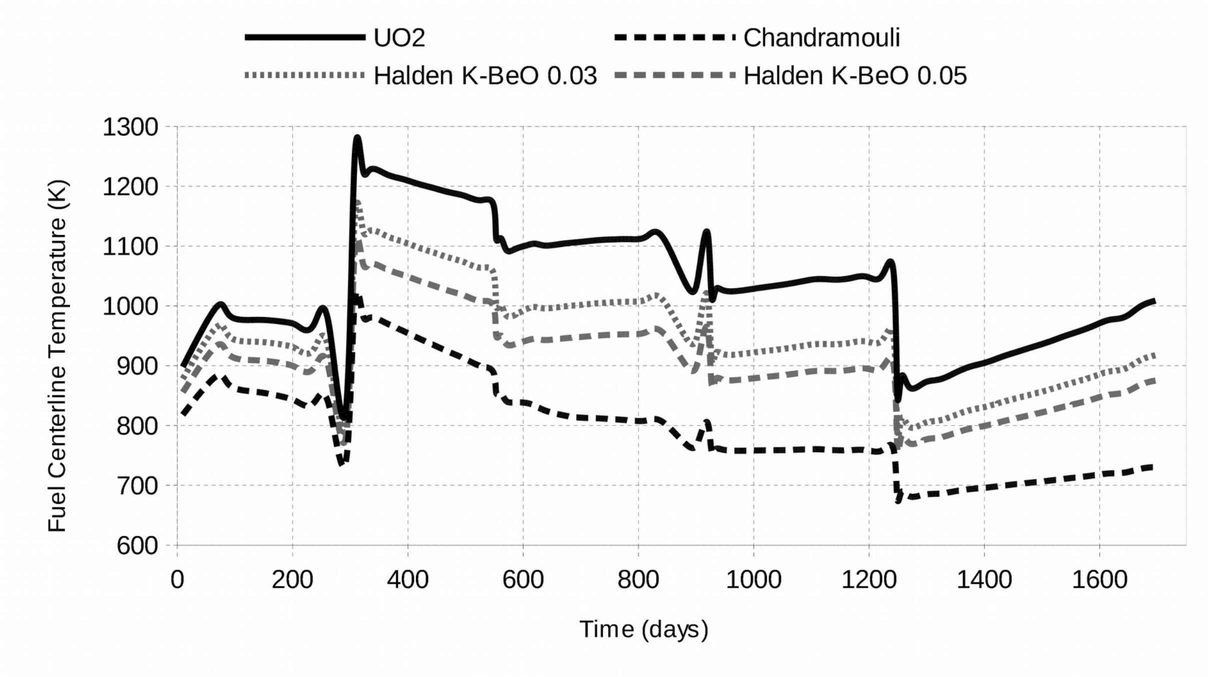

Figure 2: Evolution of fuel centerline temperature as function of time for UO_2 fuel and UO_2-BeO using different thermal conductivity models for the TSQ002 test case.

Fig. 2 shows that the fuel centerline temperature, independent of the thermal conductivity model applied, is lower for the UO_2-BeO fuel than to the conventional UO_2 fuel.

Comparing the obtained temperatures for UO_2 to the studied models to UO_2-BeO, the highest difference observed is 114 and 169.9 K after 548.7 irradiation days for the Halden model for technological factor 0.03 and 0.05, respectively; and 317.7 K after 919.8 irradiation days for the Chandramouli model.

The fuel centerline temperatures experienced using the Halden model are higher than those observed with the Chandramouli model, what was expected according to the data presented in Fig. 1 showing that the thermal conductivity of the UO_2-BeO in the Chandramouli model is higher than the Haldel model for all the temperature range.

The average difference, in each technological factor (K-BeO 0.03 and 0.05) in the Halden model, was of 43,05 K, the technological factor 0.05 (matrix) shows the best thermal conductivity that technological factor 0.03 (additive).

The analysis of the results obtained in the simulations carried out shows that the lowest temperature observed during all the irradiation period is obtained using the Chandramouli model. This is good in terms of fuel performance, but it is import to take into account that this model does not consider the degradation of the termal conductivity due to the burnup, what is considered in the Halden model (Bu term in equation 2).

4. CONCLUSIONS

The modification of the FRAPCON 3.5 code with the implementation of different models to evaluate the effects on the fuel performance of the BeO addition enabled to compare the evolution of the fuel centerline temperature during the irradiation.

The evaluation of the fuel performance of the UO_2-BeO fuel using the two thermal conductivity models compared to that of the conventional UO_2 fuel under the same power history confirmed that the fuel centerline temperatures are lower to the fuel containing BeO as additive due to the improvement in the thermal conductivity. As the temperature increases, the difference observed between the models decreases and at high temperatures no significant difference is observed.

Although the Chamdramouli model indicates lower temperatures, this model does not take into account the degradation of the thermal conductivity due to the fuel burnup. Thus, the results obtained using the Halden model can be considered more realistic.

This paper considered only the effect of the thermal conductivity changes due to the BeO addition, but other aspects shall be considered such as the necessity to improve the enrichment degree of the fuel pellet in order to reach the same irradiation conditions with the BeO addition.

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