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Dissolution, Reactor, and Environmental Behavior of ZrO2-MgO Inert Fuel Matrix: Neutronic Evaluation of ZrO2-MgO Inert Fuels

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Dissolution, Reactor, and Environmental Behavior of ZrO_2-MgO Inert Fuel Matrix

Neutronic Evaluation of MgO-ZrO_2 Inert Fuels

3rd Progress Report

Prepared by Reactor Analysis Group

Department of Nuclear Engineering

Ben-Gurion University of the Negev

Beer-Sheva, Israel

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Task 3: Three Dimensional Coupled Neutronics-Thermal Hydraulics Calculations of Selected IMF Core Designs

SUMMARY

- The work is in progress on 3 dimensional full core neutronic modeling of MgO-ZrO_2 fertile free fuel with previously selected most promising burnable poison designs.
- In the initial stage of the full core modeling, the focus is to determine the Pu and BP loading such that would ensure the core reactivity control and desired fuel cycle length.
- As a part of 3-dimensional full core analysis, the main analysis tool – SILWER computer code – was modified to account properly for thermal conductivity of the fuel.
    - The original version of SILWER assumes UO_2 by default for all analyzed fuel types.
    - Thermal conductivity of FFF varies greatly with the matrix material composition and differs from UO_2. As a result, the calculated average fuel temperature subsequently used for Doppler feedback calculations is calculated inaccurately. Moreover, the original version of the SILWER code accepts only sold fuel pellet geometry, which in case of annular pellets also results in inaccurate fuel temperature calculation.
    - In updated version of SILWER, the following modifications were made in thermal-hydraulic feedback module of the code:
        - Thermal conductivity of the fuel as a function of temperature is specified by user as a set polynomial coefficients.
        - The temperature distribution of annular as well as solid fuel pellet geometries is calculated properly.

Modification of Thermal-Hydraulic Module in LWR Analysis SILWER Code

INTRODUCTION

Various fuel cycle concepts for plutonium incineration in existing PWR loaded with Inert Matrix Fuel (IMF), in which uranium is replaced by neutron-transparent inert matrix material, are currently under investigation at BGU. Some of the studied designs include ZrO_2-based IMF with annular fuel geometry and ZrO_2-MgO based IMF with the relative amount of MgO varied from 30v/o to 70v/o. These concepts are analyzed via detailed three-dimensional full core simulation of existing PWR including thermal-hydraulic feedback. The whole core simulations are carried out with the SILWER code. The SILWER code, which is a part of the ELCOS[1] system, performs three-dimensional neutronic calculations with thermal-hydraulic feedbacks of the full reactor core. Ability of the SILWER code to simulate the operation of a modern PWR loaded with all-UO2 fuel was demonstrated in the past[2]. However, two important limitations of the SILWER code with regards to the IMF analysis should be noted.

1. During fuel temperature calculations, SILWER thermal-hydraulic module employs the thermal conductivity of UO_2. These data cannot be applied to IMF because the thermal conductivity of IMF differ from UO2 and depends on inert matrix material composition (Fig. 1).

2. Thermal-hydraulic module performs fuel temperature calculations assuming solid fuel pellet geometry even for the annular fuel. Thus, in order to adapt the SILWER code for simulation of PWR core loaded with IMF several modifications to the SILWER code were made.

This section summarizes these modifications and presents the effect of the modifications on the accuracy of calculation.

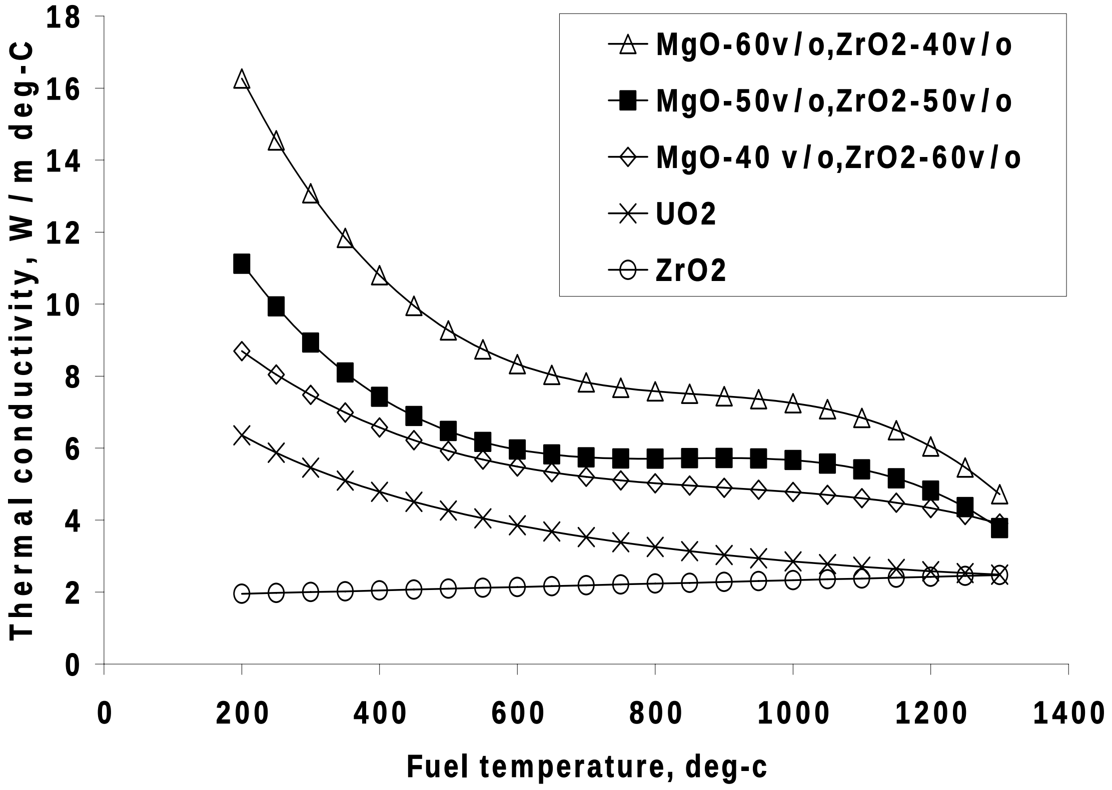

Fig.1: Thermal conductivity of various fuel matrices[3,4].

SUMMARY OF MODIFICATIONS

External data file

Actual thermal conductivity data and internal radius of the annular fuel pellet are provide to the SILWER via external ASCII file called THERMC.

Fuel thermal conductivity

In modified version of SILWER, the fuel thermal conductivity as a function of temperature is given in the form of the third order polynomial (1). The polynomial coefficients are read from THERMC file.

$$k(T) = aT^3 + bT^2 + cT + d \qquad (1)$$

where:

T - Fuel temperature, °C

k - Thermal conductivity of the fuel, W/m · °C

a,b,c,d - Coefficients

Temperature distribution in solid and annular fuel pellets

The temperature distribution in a solid and annular fuel pellets is given by (1) and (2) respectively[4]:

$$\int_{T}^{T_{max}} k dT = \frac{q''' r^2}{4} \quad (1) \qquad \int_{T}^{T_{max}} k dT = \frac{q''' r^2}{4}\left[1 - \frac{\ln(R_{fo}/R_V)^2}{(R_{fo}/R_V)^2 - 1}\right] \quad (2)$$

where:

T - Fuel temperature, °C

k - Thermal conductivity of the fuel, W/m · °C

q''' - Volumetric heat generation rate, w/m^3

r - Distance from the center of the pellet, m

R_{fo} - Outer radius of the fuel pellet, m

R_V - Internal cavity radius of the fuel pellet, m

The equation (1) is implemented in a previous version of SILWER code by dividing the fuel pellet into the four regions (Fig. 2) with equal volume while assuming the constant thermal conductivity in each region:

$$T_{m-1} = T_m + \frac{q''' R_{fo}^{\ 2}}{4 \cdot NF \cdot k_m}, \quad m = (NF + 1, NF, ..., 2, 1) \qquad (3)$$

where:

T_m - Fuel temperature, °C

k_m - Thermal conductivity of the m-th radial fuel region, W/m · °C

R_{fo} - Fuel pellet radius, m

NF - Number of radial fuel zones

For an annular fuel pellet, the expression for temperature distribution was added and is given by (4). SILWER automatically chooses the proper equation depends on the inner fuel pellet radius given in THERMC file.

$$T_{m-1} = T_m + \frac{q''' R_{fo}^{\ 2}}{4 \cdot NF \cdot k_m} \left[1 - \frac{\ln(R_{fo} / R_V)^2}{(R_{fo} / R_V)^2 - 1} \right] \qquad (4)$$

EFFECT OF MODIFICATIONS ON CORE PARAMETERS

In this section, we explore the sensitivity of the core parameters to a) variations in fuel thermal conductivity, and b) variations in fuel rod geometry. As a study case, we consider three-dimensional model of IMF PWR core proposed and evaluated at Paul Scherrer Institute (PSI) and reported in Ref 5. The selected core was calculated with varied fuel thermal conductivities and fuel pellet geometries. All calculations were performed with modified version of SILWER code. The list of calculated cases is presented in Table 1.

Table 1: List of Calculated Cases

Case	Thermal conductivity data	Fuel pellet geometry
1	ZrO2	Solid
2	UO2	Solid
3	MgO-40 v/o,ZrO2-60v/o	Solid
4	MgO-50v/o,ZrO2-50v/o	Solid
5	MgO-60v/o,ZrO2-40v/o	Solid
6	ZrO2	Annular

Table 2 reports the sensitivity of the core parameters to the thermal conductivity of different matrix compositions. The results presented in Table 2 demonstrate high sensitivity of the fuel temperature to variations in thermal conductivity. The difference in maximum fuel temperature for different matrix compositions can exceed 2000 °C. In addition, Table 2 demonstrates the effect of reduction of fuel cycle length with increasing of the fuel temperature. This effect is attributed to negative Doppler coefficient of the considered fuel. The difference in discharge burnup can reach 47 EFPD. Table 3 presents the sensitivity of core parameters to variations in fuel pellet geometry. Taking into account the annular fuel pellet geometry results in significantly lower fuel temperature. As a consequence, the core reactivity increases due to the negative Doppler coefficient and results in higher (more than 100 ppm) critical boron concentration for the same thermal conductivity data.

Figure 2 summarizes graphically the effect of the fuel matrix thermal conductivity and fuel pellet geometry on the radial temperature distribution within the fuel pellet. All cases presented in Figure 2 are plotted for identical linear power rating.

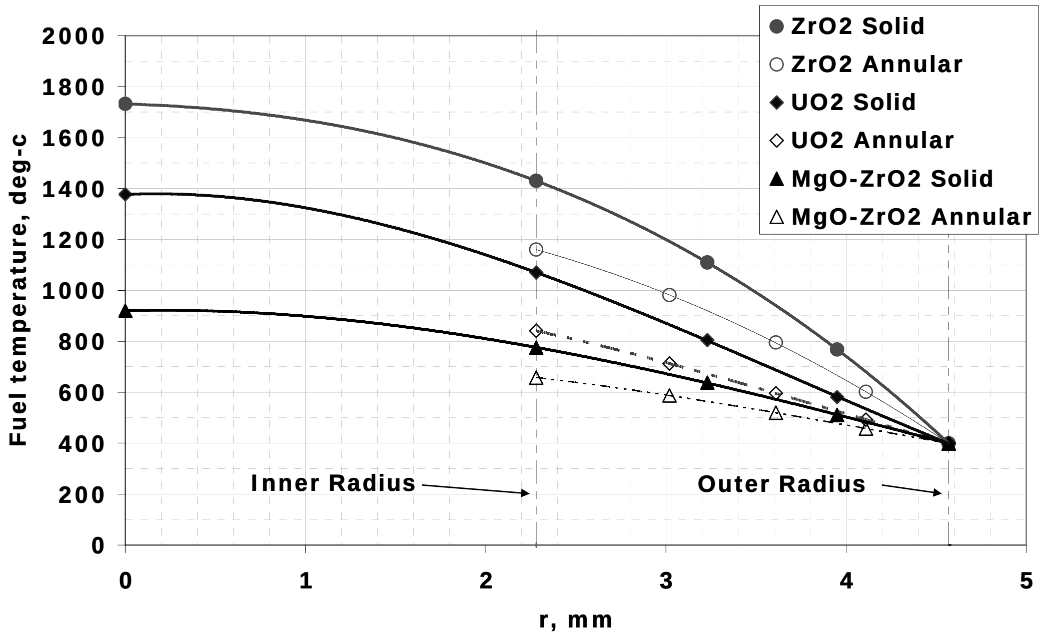

Fig.2: Radial fuel temperature distribution for different pellet geometries and fuel matrices

In summary, the results of calculations demonstrate the importance of using the actual thermal conductivity data and fuel pellet geometry. The use of thermal conductivity data of UO_2 for different inert matrix compositions and ignoring annular fuel pellet geometry introduces significant error into calculations.

Table 2: Sensitivity of core parameters to the thermal conductivity of matrix composition

Case	K ave BOC, W/m °C	T_{fuel} ave. BOC, °C	T_{fuel} max. BOC, °C	FC length, EFPD	Δ FC length,* EFPD
1	2.41	1147	3175	309	0
2	2.91	957	3089	325	16
3	5.05	767	2112	338	29
4	5.69	713	1946	342	33
5	8.53	525	1082	356	47

* Compared to ZrO_2 case

Table 3: Sensitivity of core parameters to variations in fuel pellet geometry

Case	Fuel pellet geometry	CBC, ppm	T_{fuel} Average, °C	T_{fuel} Max., °C	DC, pcm/°C
1	Solid	1147	1147	3175	-1.02
6	Annular	1272	895	2263	-1.39

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