STUDY OF MODELS FOR HIGH BURN BEHAVIOR OF URANIUM-7% GADOLINIUM FUEL RODS FOR PRESSURIZED LIGHT WATER REACTORS

M. E. MATTOS, A. T. E. SILVA, I. C. MARTINS, E. F. URANO DE CARVALHO

Nuclear and Energy Research Institute – IPEN/CNEN-SP, São Paulo – Brazil

ABSTRACT

The objective of this work is to verify the validity of the results provided by the FRAPCON-3.5 software in the simulation of the behavior of the fuel UO_2 - 7% by weight of Gd_2O_3, in order to evaluate the different models that are being proposed in codes of performance of fuels, in view of the behavior of fuel rods from PWR (Pressurized Water Reactor) under high burning conditions. To perform the analysis of the models that simulate the behavior of fuel pellets, the formation of the microstructure of (UO_2-7% Gd_2O_3), fuel restructuring, temperature in the center of the fuel, comparison of the thermal conductivity between UO_2 and the concentration of gadolinium as burnable venom, porosity in the restructured material, release of athermanous fission gases into the restructured material, release of thermally activated fission gases, including gas release models that occur due to grain growth. The results obtained in the computational simulations with the FRAPCON-3.5 program and its comparison with UO_2 and UO_2-7% Gd_2O_3, it will be possible to verify that the program has good capacity to predict the operational behavior of PWR fuel rods in permanent regime at high burns under transient condition initialized by reactivity.

1. Introduction

Nuclear energy has been widely used around the world. Some countries still depend heavily on nuclear energy, and lowering the operating costs of nuclear power plants has become an important issue that has been sought by countries and governments around the world. Straining to reduce the operational costs of installed nuclear plants, there is a movement of governments and companies that seek by means of innovative technologies to maximize the use of nuclear fuels while maintaining the nuclear fuel elements in use in the nucleus of the nuclear reactor. As a consequence, it became necessary to develop an understanding of fuel performance and to incorporate this knowledge into computational codes to provide the best estimate of predictions of fuel behavior.

The objective of this paper is to verify the validity of the results provided by the software FRAPCON-3.5, in the simulation process of the fuel behavior UO2 - 7% by weight of Gd2O3, in order to evaluate the different models that are being proposed in codes of fuel performance for in view of the behavior of fuel rods from PWR (Pressurized Water Reactor) fuel rods in steady state at high burnup under condition of transient initialized by reactivity [1,2].

2. Review of some FRAPCON-3.5 models

2.1. Fuel Thermal Conductivity (FTHCON)

The FTHCON subprogram is used to calculate the thermal conductivity of the fuel, as the behavior of the fuel rod depends heavily on temperature, however, the calculation of the thermal conductivity of the fuel evolved from the model originally proposed in MATPRO for the Nuclear Fuel Industries (NFI) modified and adopted by the Pacific Northwest National Laboratory (PNNL) and used in the codes FRAPCON-3.5 and FRAPTRAN-1.5 for UO_2, UO_2-Gd_2O_3 and MOX, respectively [3, 4].
The NFI model was further modified with a data correlation presented to include the gadolinium content is presented in equation 1.

$$K_{95} = \left[\frac{1}{A + a.\mathrm{gad} + BT + f(Bu) + (1 - 0.9^{-0.04Bu})g(Bu)h(T)}\right] + \left(\frac{E}{T^2}\right)^{-\frac{F}{T}} \qquad (1)$$

Where:
K = Thermal Conductivity, (W/mK)
T = Temperature, K
Bu = Burnup, GWd/MTU
f(Bu) = effect of fission products in crystal matrix (solution) = 0.00187 * Bu
g(Bu) = effect of irradiation defects = 0.038 * $Bu^{0.28}$
h(T) = temperature dependence of annealing on irradiation defects = $\frac{1}{1+396\exp(\frac{-Q}{T})}$
Q = temperature-dependent parameter (“Q/R”) = 6380K
A = 0.0452 m-K/W
B = 2.46 x 10^{-4} m-K/W/K
C = 5.47 x 10^{-9} W/m-K^3
D = 2.29 x 10^{14} W/m-K^5
E = 3.5 x 10^9 W-K/m
F = 16.361K

2.2. Fuel Thermal Expansion (FTHEXP)

The subroutine FTHEXP models dimensional changes in un-irradiated fuel pellets caused by thermal expansion. It can handle any combination of UO_2, UO_2-Gd_2O_3, or PuO_2 in solid, liquid, or solid-liquid states and includes expansion due to the solid-liquid phase change. Dimensional changes in the fuel affect the pellet-to-cladding gap size, which is a major factor in determining gap heat transfer and thus the stored energy, an important quantity for safety analysis [5].

2.3. Fuel Swelling (FSWELL)

The subroutine FSWELL calculates fuel swelling, which is caused by the buildup of solid and gaseous fission products during irradiation. Fuel swelling (FSWELL) is combined with creep-induced elongation (FCREEP) and densification due to pressured sintering (FHOTPS) and irradiation (FUDENS) to calculate the overall dimensional changes in fuel.
The gaseous swelling correlation in FSWELL was not used in previous versions of FRAPCON-3 because it significantly over predicts swelling. However, a new gaseous swelling model was devised for FRAPCON-3.5 after ramp tests suggested gaseous swelling may contribute to permanent cladding deformation in high burnup rods. As for solid swelling, a modified version of the solid swelling correlation presented in the MATPRO FSWELL subroutine was adopted for FRAPCON-3. Although this solid swelling model is still used in FRAPCON-3.5, an additional model and recommendations for modeling solid swelling in gadolinium doped fuels is also provided [6.]

2.4. Cladding Thermal Conductivity (CTHCON)

The subroutine CTHCON is used to calculate cladding thermal conductivity, which is required for accurate predictions of fuel temperature. The thermal conductivity of the cladding is primarily a function of temperature. Other characteristics, such as residual stress levels, crystal orientation, and minor composition differences, may have secondary effects on thermal conductivity [7].

2.5. Gas Conductivity (GTHCON)

The subroutine GTHCON calculates the gas thermal conductivity as a function of temperature and gas fraction for seven gases: helium (He), argon (Ar), krypton (Kr), xenon (Xe), hydrogen (H), nitrogen (N), and water vapor (steam). The MATPRO, FRAPCON-3.5, and FRAPTRAN-1.5 codes use similar correlations to determine the gas thermal conductivity. However, FRAPCON-3.5 and FRAPTRAN-1.5 use updated fitting parameters to better estimate gas thermal conductivity at higher temperatures [9].

3. Methodology

The material of interest in this paper consists of UO_2-7% Gd_2O_3 pellets, being part of the study of models for high burnup behavior of fuel rods for pressurized light water reactors. The simulation performed and its results presented by the FRAPCON-3.5 program is a 16x16 fuel rod of a pressurized light water reactor - standard PWR, zircaloy coating and IPENCNEN / SSP version, with UO_2 pellets. The simulation takes place to make the comparisons with the percentage fractions of gadolinium of 2% to 7% in regime of high burning of up to 60 MWd/kgU.

The fuel rod used in the simulations was a PWR 16x16 reactor, filled with UO_2 and UO_2-2%Gd_2O_3 pellets to the UO_2-7%Gd_2O_3, filled with helium and whose technical specifications are detailed in table 1and table 2.

TABLE 1: HYDRAULIC REACTOR PARAMETERS

DESCRIPTION THE PARAMETERS	PARAMETERS
Total thermal power	2850 MWt
Coolant pressure	15,51 Mpa
Cooling inlet temperature	287,7°C
Average linear power of the rod	20,17 kW/m
Coolant mass flow	5.900 kg/s.m^2
Average coolant speed	4,98 m/s

TABLE 2: TECHNICAL FEATURES OF THE FUEL ROD TSQ002-D040

DESCRIPTION FEATURES	PARAMETERS
Tablet Height	9,91 mm
Outer diameter of insert	8,255 mm
Chamfer and dish	Sim
Table top height	3810 mm
Enrichment ^{235}U (%)	3,48
Outer Diameter of Coating	9,70 mm
Inside lining diameter	8,43 mm
Coating thickness	0,5715 mm
Filling gas pressure	2,62 Mpa
Filling gas	He
Average rod burning	60 MWd/kgU
Density	95,0 %Dt
Initial free volume	25,42 ml
Free end-of-life volume	17,8 ml
Number of axial nodes	12
Diametral gap	0,0825 mm
Δ free volume	-7,62 ml
Δ gás volume (EOL-BOL)	5,7%

4. Results and Discussion

The computational simulation made with code aimed to compare the results presented by each of the gadolinium portions in the following items:

- Fuel centerline temperature;
- Release of fission gases;
- Free volume inside the fuel rod;
- Internal pressure on the rod;
- Average coating temperature.

4.1. Thermal Conductivity of Fuel UO_2 and with fractions of 2 to 7% of gadolinium

The conductivity was performed for samples with Gd_2O_3 concentration, from 2 to 7% by mass, in a temperature range of 100K to 1800K. It is verified that the thermal conductivity of the solid solution depends on the microstructure and Gd content added to the fuel. Specifically, for additions between 2 and 7% by mass of Gd_2O_3, a large drop in the thermal conductivity values occurs. Considering the range between 2 and 7% addition, the curves have a strong stability, i.e. the conductivity values are virtually independent of the concentration, especially for higher temperatures as shown in fig.1 below.

4.2. Temperature in the center of the fuel rod

The central temperature of the fuel is a result of the models, which represent the thermal behavior of the rod. By comparing a UO_2 fuel rod with a rod with gadolinium fractions by weight, the central temperature of the fuel despite the modifications made in this set of models, it was observed that they remained the same at the beginning of the burn up to 10 MWd/kgU, with a slight temperature change between 10 and 43 MWd/kgU, as is evident in fig.2.

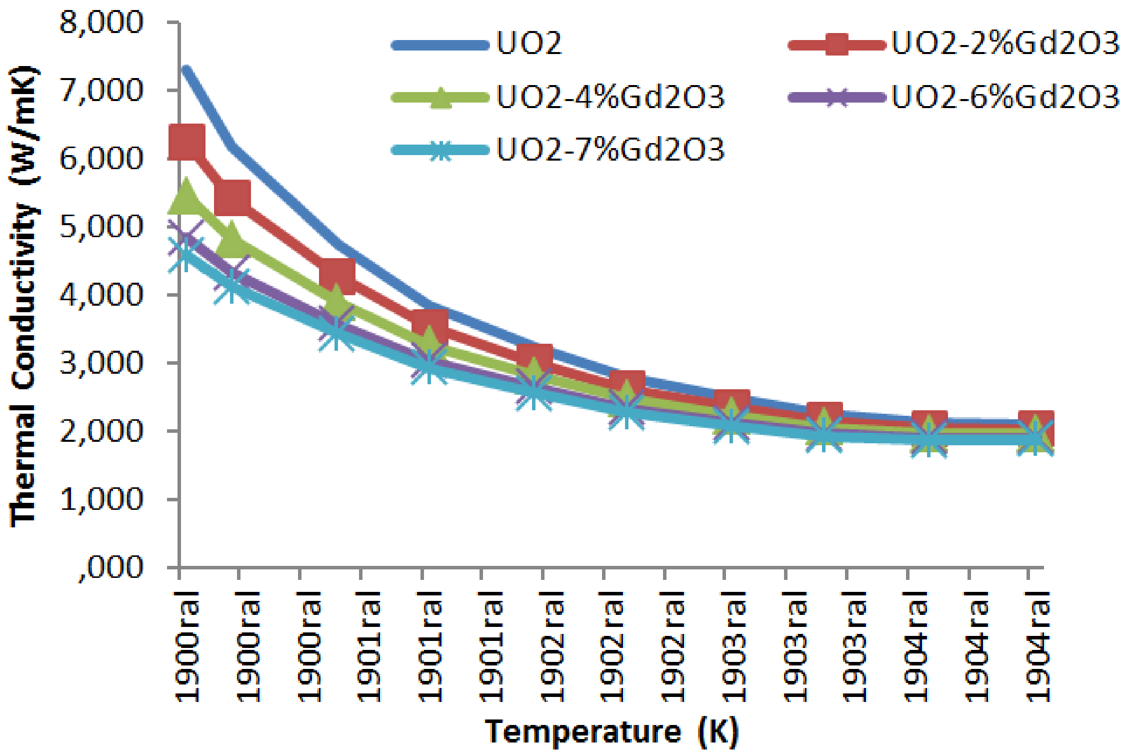

Figure 1. Thermal conductivity as a function of temperature for different concentrations of gadolinium.

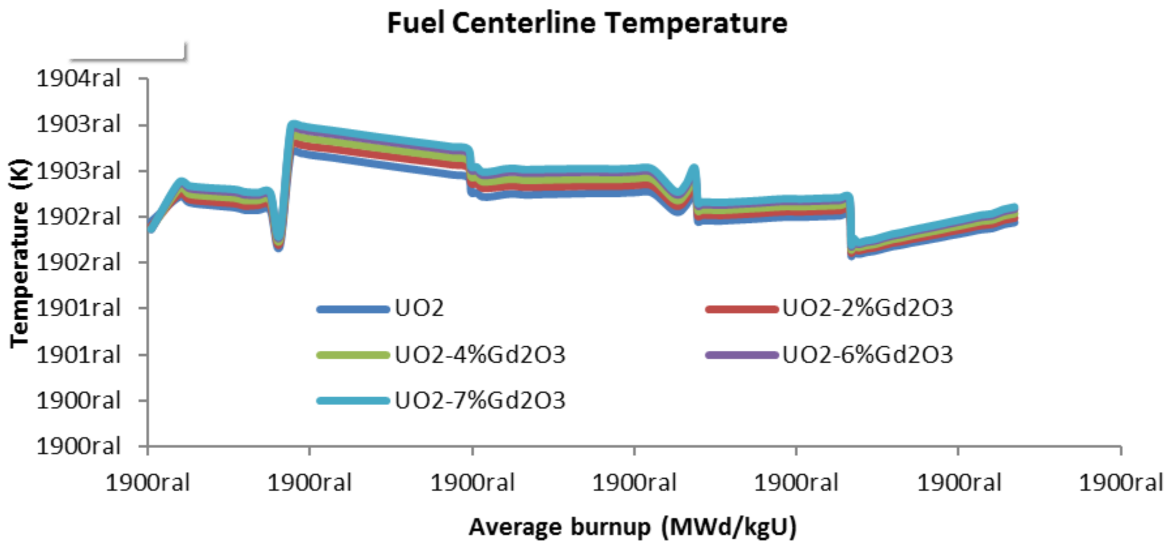

Figure 2. Fuel Centerline Temperature – UO_2 and the fraction of 2 a 7% of Gadolinium by weight.

4.3. Fission Gas Release

An appreciable amount of the fission products are constituted by noble gases Xe (xenon) and Kr (krypton), which have an extremely low solubility in the fuel matrix. The gas release model used by FRAPCON-3.5 showed no changes compared to UO_2 and among the gadolinium fractions as in fig. 3.

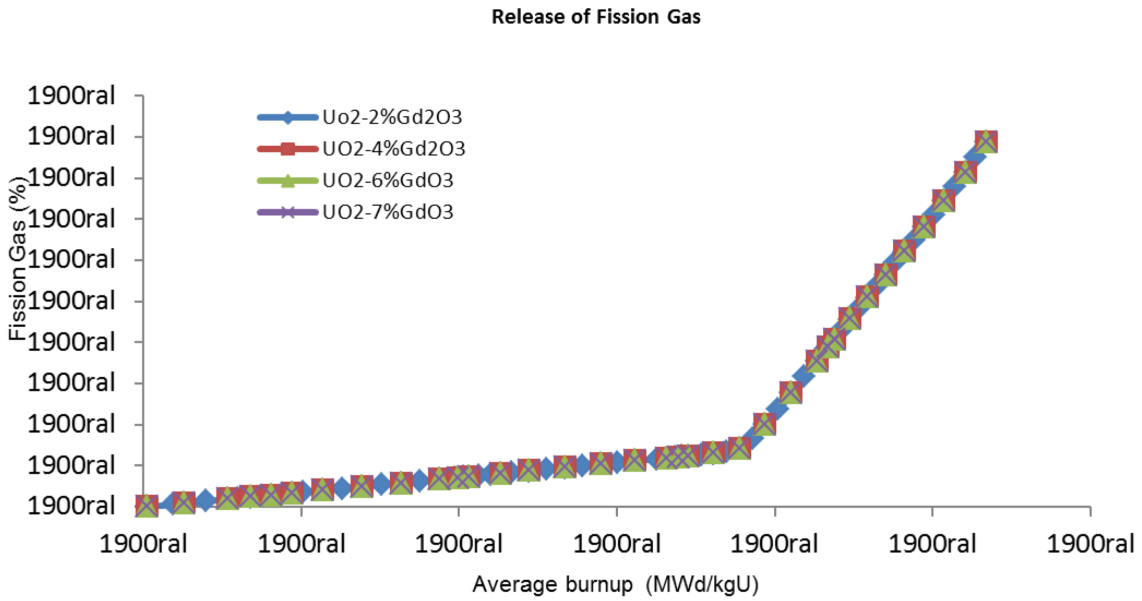

Figure 3. Release of fission gas - UO_2 and the fraction of 2 to 7% Gadolinium by weight.

4.4. Free volume inside the Fuel Rod

The free volume inside the fuel rod for calculation of the internal pressure is of fundamental importance. Fig. 4 illustrates containing only UO_2 was 23.5ml having a drop of 5.5ml up to 25 MWd/KgU and remaining at 17ml until the end of the burnup.

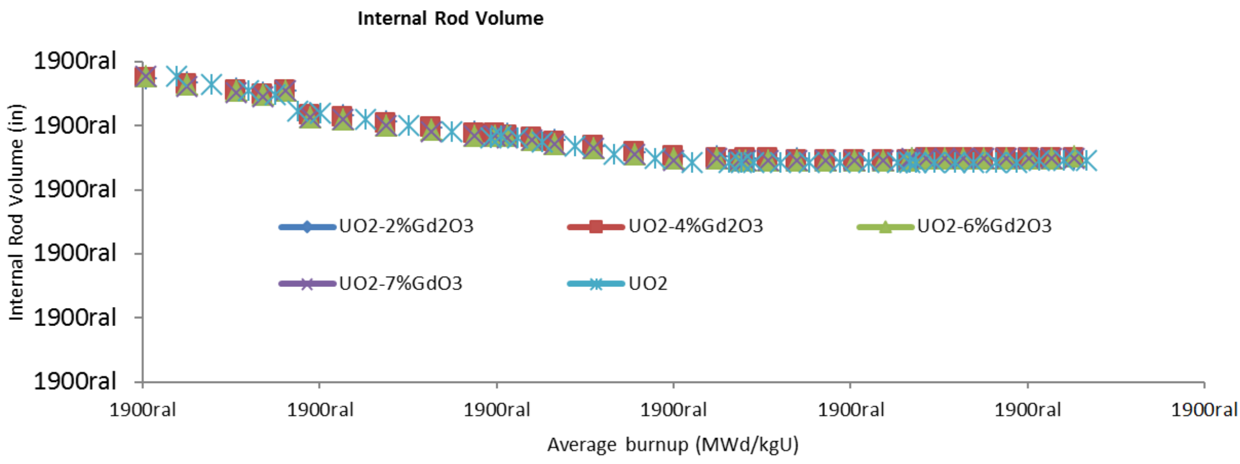

Figure 4. Free volume of the Fuel Rod - UO_2 and fractions of 2 to 7% of Gadolinium by weight.

4.5. Internal Pressure of the Fuel Rod

Fig. 5 illustrates the result obtained for the variation of internal pressure in the UO_2 fuel rod for the conditions employed in the experiment as expected when compared to the results provided with the gadolinium fractions employed in this analysis. The variations between the results provided are due to the variation in the amount of fission gas released.

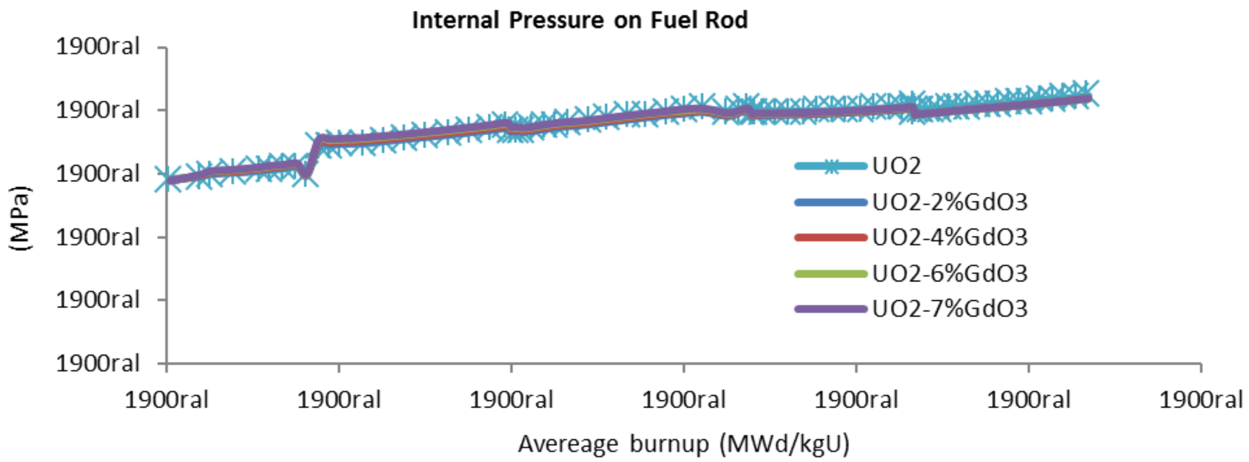

Figure 5. Variation of the internal pressure of the fuel rod as a function of the burning UO_2 and with the fractions of 2 to 7% of gadolinium.

4.6. Average Coating Temperatura

The average temperature of the fuel coating is an indirect result which depends on the size of the gap between the pellets and the coating and the temperature of the fuel. In all results obtained by the FRAPCON-3.5 program the average temperature of the coating remained the same at the beginning and at the end of the burn as shown in fig. 6.

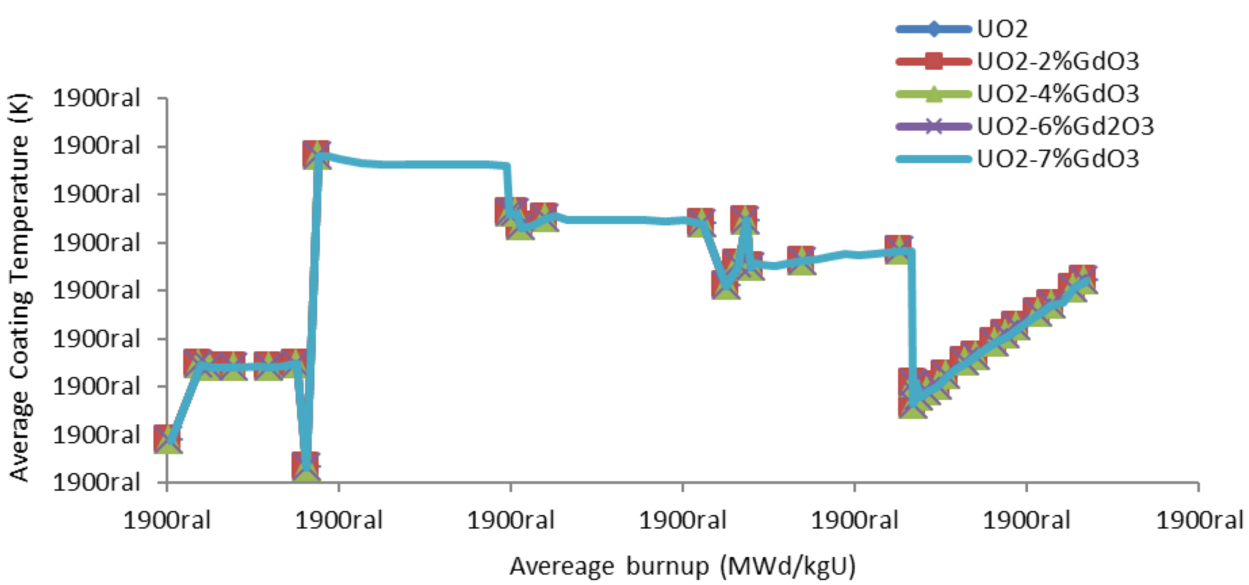

Figure 6. Mean Temperature in the Coating of UO_2 and the fractions of 2 to 7% of gadolinium by weight.

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