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Dynamics aspects of plutonium burning in an inert matrix

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Abstract

Burnup calculations have been performed on a mini fuel assembly containing 21 fuel rods and four water holes at the corners. The fuel rod positions were filled with 4% enriched UO_2 fuel and with either reactor grade or weapons grade plutonium mixed in an inert matrix. The ratio between the UO_2 and the IMF rods was varied to investigate the influence of the UO_2 fuel on the dynamics of the assembly. From a simple reactor model with one delayed neutron group and first-order fuel and temperature feedback mechanisms, the linear transfer function from reactivity to reactor power was calculated that was subsequently used in a root-locus analysis. From this, it is concluded that only 20% of the fuel rods need to be made of UO_2 to have a fuel that is linearly stable up to 1000 days of irradiation. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: transmutation, plutonium, inert matrix fuel

1. Introduction

To enhance the net plutonium consumption in thermal reactors, inert matrix fuels (IMF) are studied as an alternative to standard (Pu,U) MOX fuels. In many cases, UO_2 rods are added to the IMF to improve the dynamic characteristics of the fuel. For example, Puill and Bergeron [1] describe the nuclear and thermal-hydraulic design of a fuel assembly containing 36 annular fuel rods loaded with PuO_2 mixed in CeO_2 and 120 standard UO_2 rods. Obviously, in such an assembly, one would like to reduce the fraction of UO_2 fuel as much as possible to maximize the plutonium consumption. However, the smaller the fraction of UO_2 fuel, the lower the plutonium production rate and the larger the change of reactor physics parameters during burnup.

This article studies and quantifies the influence of UO_2 fuel on the dynamics of IMF. To this end, burn-up calculations have been performed on a 5x5 mini fuel assembly containing water rods at the four corners. The other positions are occupied by fuel rods with an IMF/UO_2 ratio of approximately 100/0, 80/20/, 60/40, 40/60 and 0/100% (this last fuel actually contained one IMF rod, so the real percentages are 5/95). The plutonium density in the IMF rods was 0.5 g cm^{-3} at beginning of

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irradiation, while the initial uranium enrichment in the UO_2 rods was 4%. Two grades of plutonium were used: one weapons grade (WG) with atomic composition of 93.0/6.0/0.08/0.02% for the isotopes $^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$, and one reactor grade (RG) with atomic composition of 58.1/24.0/12.9/5.0% for the same isotopes. As an inert matrix, Al_2O_3-ZrO_2-MgO was used with heat capacity of 100 J mol^{-1} K^{-1} ($\approx$ 4.2 J cm^{-3} K^{-1}). The boron concentration in the moderator was assumed to be constant and equal to 500 ppm.

The burnup calculations have been performed with the WIMS-7 code package, assuming a constant linear power of 3864 W cm^{-1} for the whole assembly. A special nuclear data library based on JEF2.2 was used to shield properly the nuclear resonances of the higher plutonium isotopes. The irradiation time was 1200 days. During the irradiation, at time intervals of 50 days, the fuel temperature coefficient (α_f), the moderator temperature coefficient (α_m), the mean neutron generation time (Λ), the delayed neutron fraction (β), and the precursor decay constant (λ) have been calculated. These data are subsequently used in the reactor model described in the next section.

2. Reactor Model

In this section, a simple reactor model is described with fuel and moderator temperature feedback mechanisms. The time-dependent reactor power is described with a point-kinetics model with one delayed neutron group:

$$\frac{dP(t)}{dt} = \frac{\rho(t)-\beta}{\Lambda} P(t) + \lambda \cdot D(t), \quad \text{and} \quad \frac{dD(t)}{dt} = \frac{\beta}{\Lambda} P(t) - \lambda \cdot D(t). \tag{1}$$

In these equations, the precursor density $D(t)$ is expressed as latent heat. All the other symbols have a meaning according to usual notation [2]. The equations for the lumped fuel and moderator temperatures read:

$$C_f \frac{dT_f(t)}{dt} = (1-\gamma) \cdot P(t) - h_s \cdot A_f \cdot (T_f - T_m), \quad \text{and} \tag{2}$$

$$C_m \frac{dT_m(t)}{dt} = \gamma \cdot P(t) + h_s \cdot A_f \cdot (T_f - T_m) - C_m \cdot h_m \cdot (T_{out} - T_{in}).$$

Here, C_f and C_m are the heat capacities of the fuel and moderator, respectively, T_f and T_m the temperatures, T_{in} and T_{out} the coolant inlet and outlet temperatures, respectively, A_f the heat transfer area of the fuel pin, h_s the heat transfer coefficient from fuel to coolant, and h_m the heat removal coefficient due to coolant flow. The parameter γ is the fraction of power deposited in the moderator. The feedback is given by $\rho(t) = \rho_{ext} + \alpha_f \cdot \delta T_f(t) + \alpha_m \cdot \delta T_m(t)$, where α_f and α_m are the fuel and moderator temperature reactivity coefficients shown as a function of time in Figs. 1 and 2. For IMF, the α_f and α_m as well as β, λ and Λ strongly vary with the irradiation time.

After linearizing and Laplace transforming Eqs. (1) and (2), the system transfer function from reactivity fluctuations to power variations can be obtained [2]. This function writes as the ratio of a third-order and fourth-order polynomial in the Laplace variable $s = \sigma + j\omega$. The four poles (zeroes of the denominator) of this transfer function determine the time-dependent behaviour of the fuel after a small external reactivity introduction. Specifically, when the real part of a pole (σ) becomes positive, the system is linearly unstable and the reactor power increases with time after a positive reactivity insertion.

For UO_2 and "standard" (Pu,U) MOX fuels, the real part of each of the four poles is negative under a large range of operation conditions [3]. However, this is different for plutonium in an inert matrix. Various reactor physics parameters change considerably with burnup, due to the absence of uranium. This means that, when a specific parameter is varied, the loci of the poles of the transfer function can shift to undesirable regions of the complex s plane. In this paper, we focus on the sensitivity of the poles to the irradiation time.

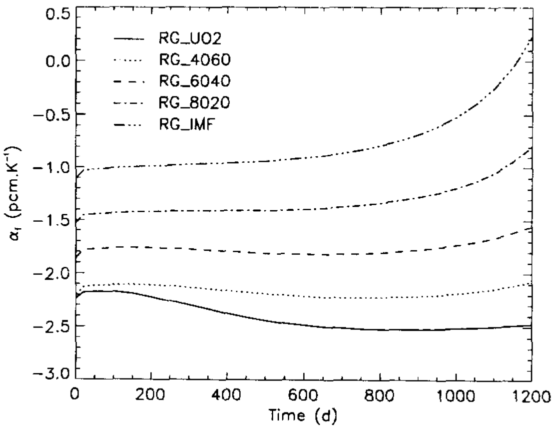

Fig. 1: The α_f of the assemblies as a function of irradiation time.

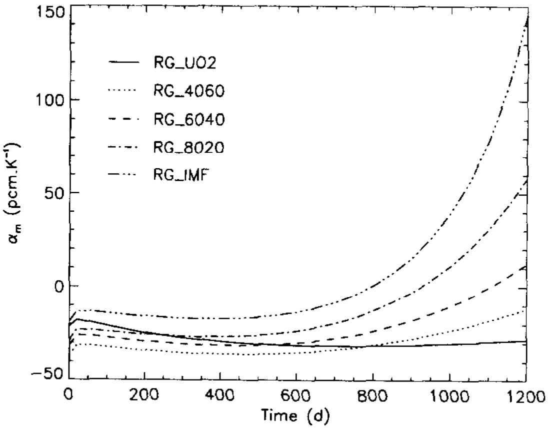

Fig. 2: The α_m of the assemblies as a function of irradiation time.

3. Results

As mentioned in the previous section, the transfer function from reactivity to power has four poles. Three of these have strongly negative real parts. One pole, however, the one located at the origin for a zero power reactor, is only weakly negative. The real part of this pole, in the remainder of this article called σ, is shown as a function of irradiation time in Fig. 3 for RG plutonium, and in Fig. 4 for WG plutonium.

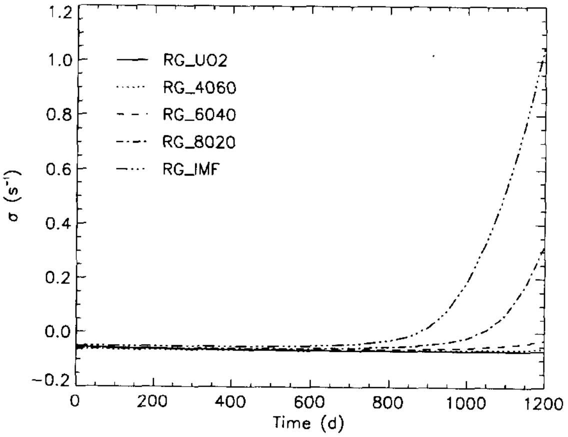

Fig. 3: Root-locus plot of the assemblies with reactor grade plutonium.

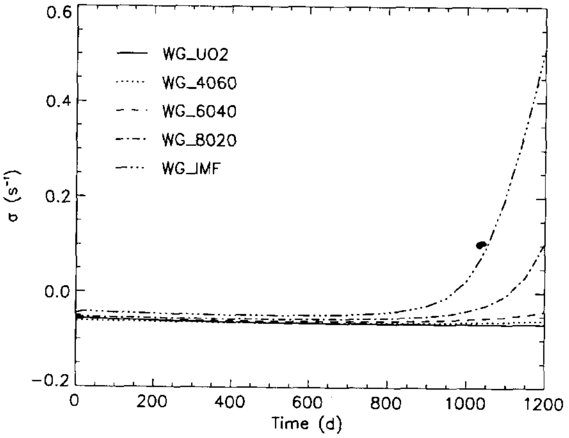

Fig. 4: Root-locus plot of the assemblies with weapons grade plutonium.

For an assembly containing IMF rods for 80% or more, σ shifts to positive values when the irradiation time exceeds 1000 days (Fig. 3) or 1100 days (Fig. 4). Then the system is linearly unstable. From this can be concluded that for an IMF/UO$_2$ assembly being stable up to 1000 irradiation days, only 20% of the rods need to be UO$_2$ fuel.

As mentioned before, the boron concentration, which dominates to a large extend the sign and magnitude of α_m, was equal to 500 ppm. To investigate the influence of this coefficient and that of α_f, two calculations were performed with varying α_f or α_m while all the other parameters were constant with values corresponding to an irradiation time of 1100 days. Figures 5 and 6 show the results. Clearly, reducing α_f or α_m shifts the real part of the pole (σ) to negative values.

Because several inert matrices might be used for IMF, the influence of the heat capacity of the matrix was investigated. Varying the heat capacity of the IMF from 0 to 20 J cm^{-3} K^{-1} (the nominal value of the IMF used equals about 4 J cm^{-3} K^{-1}) with all the other parameters having a value corresponding to an irradiation time of 1100 days, shifts σ to smaller positive or stronger negative values. This means that the IMF becomes more stable with increasing heat capacity.

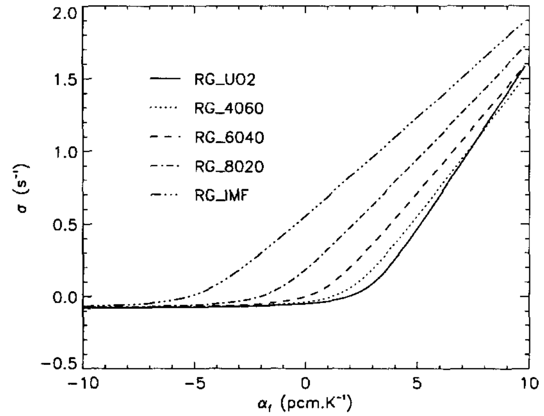

Fig. 5: Root-locus plot of the assemblies with RG plutonium. The α_f was varied, while all the other parameters had values corresponding to an irradiation time of 1100 days. The nominal value of α_f at that time step is -2.5 pcm K^{-1} for UO_2 and -0.26 pcm K^{-1} for IMF.

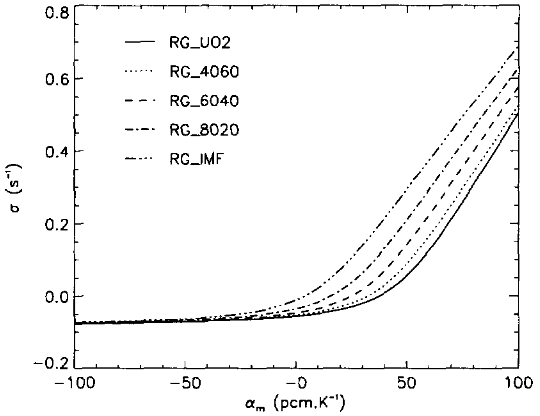

Fig. 6: Root-locus plot of the assemblies with RG plutonium. The α_m was varied, while all the other parameters had values corresponding to an irradiation time of 1100 days. The nominal value of α_m at that time step is -29 pcm K^{-1} for UO_2 and +78 pcm K^{-1} for IMF.

4. Conclusions

When an inert matrix is used to burn plutonium in a PWR, the reactivity coefficients of temperature and the kinetic parameters are very sensitive to the irradiation time due to burnup of the fissile isotopes in the fuel. The reactivity coefficients may become even positive, which might lead to the unacceptable situation that the system becomes linearly unstable.

It has been shown by root-locus analyses on a simple reactor model that a fraction of UO_2 rods in an IMF assembly as low as 20% is sufficient to improve the reactivity coefficients and kinetic parameters such that of all poles of the transfer function from reactivity to power have a negative real part for a long irradiation time up to 1000 days. But the longer the irradiation time, the larger the fraction of UO_2 fuel needs to be. From the stability point of view, differences between reactor grade plutonium and weapons grade plutonium are rather small.

Acknowledgements

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