INTRODUCTION

With the increasing interest to use plutonium as a fuel in PWRs, many papers have been published on mainly two subjects: compatibility of MOX fuel with UO₂, and the influence of multiple recycling of plutonium on spent fuel characteristics. Examples of the first focus on fuel assembly and core design, and on the reactivity and burnup potential of the MOX fuel. The trend is towards higher burnup and a larger MOX fuel fraction in the core [1]. The second category of papers focuses on the potential of PWRs to burn plutonium and on the spent fuel characteristics after each recycling [2]. More references can be found in recent GLOBAL and ENC proceedings.

The transient behaviour of MOX fuel is usually addressed by the authors, but not in great detail. Furthermore, a consistent approach is lacking, which makes it difficult to compare various studies. In this study, we investigate the influence of the moderator-to-fuel ratio on the transient behaviour of MOX fuel. Because the results are intended for comparative use only, a fairly simple point-kinetics model is adopted with Doppler and moderator temperature feedbacks. Various transients have been investigated: Reactivity Induced Accidents (RIA), Loss of Flow (LOF), Loss of Heat Sink (LOHS), Moderator Cooling Accidents (MCA), and Pump Over Speed (POS).

MODEL AND DATA USED

In this section, the reactor model is described with fuel and moderator temperature feedback mechanisms. In the model, all reactivity coefficients, kinetic parameters, heat capacities, and heat transfer coefficient are assumed constant and independent of the actual fuel and moderator temperatures. The equations for the thermal power density $P$, and the concentration of the delayed neutron precursors $D_i$ read:

$$\frac{dP}{dt} = \frac{p(t) - \beta}{\Lambda} P(t) + \sum_{i=1}^{6} \lambda_i D_i(t), \quad \text{and} \quad \frac{dD_i}{dt} = \frac{\beta_i}{\Lambda} P(t) - \lambda_i D_i(t) \quad \text{for} \quad i = 1...6. \quad (1)$$

Here $D_i$ are the delayed neutron precursor concentrations expressed in latent heat, while the other parameters follow conventional notation [3]. The fuel and moderator temperatures are described by two ‘lumped parameter’ balance equations using Newton’s law of cooling [3]:

$$\frac{dT_f}{dt} = \frac{1}{C_f} P(t) - \gamma_f(T_f - T_m), \quad \text{and} \quad \frac{dT_m}{dt} = \gamma_m(T_f - T_m) - h_m(T_{out} - T_m). \quad (2)$$

Here $\gamma_f$ and $\gamma_m$ are the inverse time constants of the fuel and moderator, respectively. All necessary data is available from burnup calculations [4,5] with the OCTOPUS burnup code system with JEF2.2 nuclear data.
The model is based on a French N4 PWR operated with 4% enriched UO$_2$ fuel in a five batch reloading scheme with discharge burnup of 47.5 GWd/tHM. After five years of interim storage, the spent UO$_2$ fuel is reprocessed and the separated plutonium is used to fabricate new MOX fuel. The plutonium density in the MOX suffices to obtain a discharge burnup of 47.5 GWd/tHM. The boron concentration is assumed to decrease linearly as a function of burnup during each fuel cycle with initial values obtained by forcing a flat reactivity curve during the third fuel cycle [4,5].

The MOX fuel has a moderator-to-fuel (MF) ratio of 2, 3 or 4, achieved by reducing the fuel pin diameter. The linear power, volumetric power and specific power read:

$$P_{lin} = \Phi_f 2\pi R_f$$ and $$P_{vol} = \frac{P_{lin}}{2\pi R_f}$$ and $$P_{spec} = \frac{P_{vol}}{\rho_{HM} R_f} = \frac{2\Phi_f}{R_f \rho_{HM}},$$

where $R_f$ is the fuel pin radius, $\Phi_f$ is the heat flux from fuel pin to coolant, and $\rho_{HM}$ is the Heavy Metal fuel density. To keep constant the heat flux, the linear power is reduced proportional to the fuel pin radius, which implies that the volumetric power increases proportional to the inverse of the radius. Also the specific power increases, which implies that the fuel reloading time reduces proportional to the pin radius. More information about this procedure is given in reference 5.

Table 1 summarizes the scenarios considered. The RIA is modelled by assuming that the reactivity increases instantaneously with 0.5$, the LOF by setting to zero the power removal inverse time constant $h_m$, the POS by increasing this inverse time constant by 50% at constant inlet temperature, the MCA by reducing the inlet temperature by 20 K, and the LOHS by assuming the inlet temperature equals the outlet temperature shifted $\tau$ seconds (in our case $\tau=20$).

Because the secondary circuit was not modelled, many (second-order) effects cannot be accounted for. However, it is believed that this model can assess many interesting effects connected to nuclear reactor safety [6] if the results are for comparative use only. Values of various parameters used are given in Table 2.

### Table 1: Overview of the modelling of the accident scenarios considered.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>External disturbance</th>
</tr>
</thead>
<tbody>
<tr>
<td>RIA</td>
<td>$\Delta \rho = 0.5$</td>
</tr>
<tr>
<td>LOF</td>
<td>$\dot{h}_m = 0$ (see Eq. (2))</td>
</tr>
<tr>
<td>POS</td>
<td>$\Delta \dot{h}_m = 0.5 \dot{h}_m$ (see Eq. (2))</td>
</tr>
<tr>
<td>MCA</td>
<td>$\Delta T_{in} = -20 K$</td>
</tr>
<tr>
<td>LOHS</td>
<td>$T_{in}(t) = T_{out}(t-\tau)$</td>
</tr>
</tbody>
</table>

### Table 2: Reactivity coefficients and kinetic parameters of the fuels considered [4].

<table>
<thead>
<tr>
<th>Fuel</th>
<th>MF ratio</th>
<th>CBC$^1$ (pcm)</th>
<th>FTC$^2$ (pcm/K)</th>
<th>MTC$^3$ (pcm/K)</th>
<th>$h_m$ (1/s)</th>
<th>$\beta_{eff}^4$ (%)</th>
<th>$\lambda^4$ (1/s)</th>
<th>$\Lambda^5$ (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UO$_2$</td>
<td>2</td>
<td>875</td>
<td>-2.9</td>
<td>-46</td>
<td>1.425</td>
<td>0.56</td>
<td>0.091</td>
<td>18</td>
</tr>
<tr>
<td>MOX</td>
<td>2</td>
<td>1190</td>
<td>-3.0</td>
<td>-54</td>
<td>1.425</td>
<td>0.39</td>
<td>0.087</td>
<td>5.3</td>
</tr>
<tr>
<td>MOX</td>
<td>3</td>
<td>720</td>
<td>-2.7</td>
<td>-54</td>
<td>1.075</td>
<td>0.39</td>
<td>0.085</td>
<td>14</td>
</tr>
<tr>
<td>MOX</td>
<td>4</td>
<td>625</td>
<td>-2.4</td>
<td>-32</td>
<td>0.897</td>
<td>0.39</td>
<td>0.084</td>
<td>21</td>
</tr>
</tbody>
</table>

$^1$ Critical Boron Concentration.  $^2$ Fuel Temperature Coefficient.  $^3$ Moderator Temperature Coefficient.  $^4$ Effective one-group values. In the model, six delayed neutron groups were used.  $^5$ Mean neutron generation time.
RESULTS

For the RIA, the power jumps instantaneously with a factor of two, which agrees of course with the prompt jump approximation, but stabilises after a few seconds to a level 10 to 20% above nominal. The fuel temperature increases only 35 K for MOX fuel with MF=2 and MF=3, about 45 K for MOX with MF=2 and 55 K for UO₂ fuel. The average coolant temperature increases only a few degrees. The temperatures of all the MOX fuels remain below that of UO₂.

The effects of the LOF scenario are rather moderate. Due to the increase of the coolant temperature, power levels off to zero. For each reactor, the fuel and coolant temperatures reach eventually the same value of 730 K for UO₂, 715 K for MOX fuel with MF=2, and about 695 K for MOX fuels with MF=3 and MF=4. Again the temperatures of all MOX fuels are lower than that of UO₂. In any case, temperatures are much lower than any limit imposed by cladding interactions (≈1475 K).

Within one second, the power in the POS scenario increases to a level of 25% above nominal for the MOX fuel with MF=4, and 65% above nominal for MOX with MF=2. Already after 3 seconds, power stabilises for all fuels at a level 15% above nominal. The fuel temperature increases 50 K for UO₂, 45 K for MOX with MF=4, and 55 K for MOX with MF=2. The average coolant temperature decreases 4 K for all fuels.

The most penalising scenario for the utilisation of MOX fuel in LWRs is the MCA or cold-water ingress scenario. For a 20 K inlet temperature reduction, results are shown in Figure 1. Both the MOX fuels with MF=2 and MF=3 become prompt supercritical, while the UO₂ fuel and the MOX with MF=4 remain sub-critical. For the two first-mentioned fuels, a large power spike is seen, as well as an instantaneous increase of fuel temperature. For UO₂ and for MOX with MF=4, fuel temperature increases only gradually. The increase of the average fuel temperature is between 150 and 200 K.

The LOHS scenario is modelled by assuming that the inlet temperature equals the outlet temperature shifted \( \tau \) seconds in time (in our case 20 seconds is assumed, but in reality this value is probably larger). Results are shown in figure 2. For all fuels, the fuel temperature decreases about 300 K, while the moderator temperature increases 40 K. The oscillatory behaviour is due to the circulation time of the coolant. The average moderator temperatures of the MOX fuels with MF=2 and MF=3 are slightly lower than that of the other two fuels.

CONCLUSIONS

Within the limits of the model applied, which restrict the interpretation of the results to comparative use only, no large differences can be observed between standard UO₂ fuel and MOX fuel with different MF ratios. For the RIA, LOF and LOHS scenarios the fuel and moderator temperatures for the MOX fuels are similar or lower to that of UO₂. For the POS and MCA scenarios, in which a reduction of the moderator temperature initiates the transient, the fuel temperature is higher than that of UO₂ for MOX fuels with MF=2 and MF=3, and lower for MOX fuel with MF=4. The MCA scenario seems the most penalising one in the sense that the average or ‘lumped’ fuel temperature is highest (>1100 K), but of course, this conclusion depends on the magnitude of the external disturbance initiating the transient. All scenarios have also been calculated for the case of increasing fuel rod pitch instead of decreasing fuel pin radius. This turned out to have only a modest impact. Spatial kinetics calculations should be performed to obtain accurate absolute results.
REFERENCES


