MOX@EON
EON Operational Experience

Fall 2011 Meeting of the
US Nuclear Waste Technical Review
Board
Wolfgang Faber, EON-Kernkraft
September 14, 2011
### Irradiation Record of EON-

<table>
<thead>
<tr>
<th>NPPs</th>
<th>HM U-FA (t)</th>
<th>Reproc. (t)</th>
<th>HM MOX (t)</th>
<th>Pu (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brokdorf</td>
<td>609</td>
<td>187</td>
<td>126</td>
<td>8</td>
</tr>
<tr>
<td>Unterweser</td>
<td>839</td>
<td>517</td>
<td>107</td>
<td>6</td>
</tr>
<tr>
<td>Grohnde</td>
<td>739</td>
<td>283</td>
<td>66</td>
<td>4</td>
</tr>
<tr>
<td>Grafenrheinfeld</td>
<td>793</td>
<td>376</td>
<td>81</td>
<td>5</td>
</tr>
<tr>
<td>Isar-2</td>
<td>603</td>
<td>181</td>
<td>81</td>
<td>5</td>
</tr>
<tr>
<td>Stade</td>
<td>496</td>
<td>496</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Würgassen</td>
<td>344</td>
<td>344</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Isar-1</td>
<td>733</td>
<td>337</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>5155</strong></td>
<td><strong>2721</strong></td>
<td><strong>461</strong></td>
<td><strong>28</strong></td>
</tr>
<tr>
<td><strong>Pu</strong></td>
<td><strong>57</strong></td>
<td><strong>Pu for EKK</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MOX still to be loaded: 88 PWR/47 t HM/3 t Pu

### Balance for EKK operated units (8)

- 5200 t HM in U-FA irradiated
- 2700 t HM reprocessed (50%)
- 60 t Pu created
- 30 t (50%) recycled as MOX
### MOX Licensing at EKK units (authorities of 3 different states)

<table>
<thead>
<tr>
<th></th>
<th>MOX / reload</th>
<th>MOX / core</th>
<th>Pu fiss/Putot</th>
<th>Pu fiss</th>
<th>U-235</th>
<th>remark</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>KBR</strong></td>
<td>1/3</td>
<td>64</td>
<td>equivalent to 4,0 w/o U-235</td>
<td>Unat Utails</td>
<td></td>
<td>no. enr-levels not restricted, wet storage</td>
</tr>
<tr>
<td><strong>KKU</strong></td>
<td>16/20/24</td>
<td>96</td>
<td>&lt;= 81,4</td>
<td>3,5</td>
<td>4,5</td>
<td>16x16-20-4; 3 enr.-levels; wet storage</td>
</tr>
<tr>
<td><strong>KWG</strong></td>
<td>16</td>
<td>64</td>
<td>3,2</td>
<td>Unat Utails</td>
<td></td>
<td>16x16-20-4; wet storage only</td>
</tr>
<tr>
<td><strong>KKG</strong></td>
<td>16</td>
<td>64</td>
<td>81,4</td>
<td>3,07</td>
<td>4,65</td>
<td>no. enr-levels not restricted, wet storage</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>58...71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>KKI-2</strong></td>
<td>24</td>
<td>96</td>
<td>71,2</td>
<td>3,8</td>
<td>Unat Utails</td>
<td>18x18-24-4, no. enr-levels not restricted, wet storage</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>equivalent to 4,4 w/o U-235</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>KKS</strong></td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td><strong>KWW</strong></td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td><strong>KKI-1</strong></td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td></td>
</tr>
</tbody>
</table>

1) $\text{Pu}_{\text{tot}} \leq 8,02 \text{ w/o}$  
2) $0,2...0,3 \text{ w/0 U-235}$
MOX - Handling Aspects

1. Manufacturing
2. Transport
3. Receiving inspection
4. On-site storage
5. Reactor-physics properties
6. Safeguards
7. Post-operation storage
8. Transport and intermediate storage

our area of expertise
MOX - Physical Properties (1): Pu-Balance

Uranium-FA

BOL 58721 MWd/t

TPu 0.04%

Pu 1.2%

Pu 6.7%

TPu 0.2%

MOX-FA

BOL 58613 MWd/t

Pu 4.1%
### MOX - Physical Properties (2): General Overview

<table>
<thead>
<tr>
<th></th>
<th>U 235</th>
<th>U 236</th>
<th>U 238</th>
<th>Pu 238</th>
<th>Pu 239</th>
<th>Pu 240</th>
<th>Pu 241</th>
<th>Pu 242</th>
<th>Am 241</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{f,\text{th}} ) (b)</td>
<td>583</td>
<td></td>
<td></td>
<td>743</td>
<td></td>
<td>1009</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \nu_{\text{th}} )</td>
<td>2,4</td>
<td></td>
<td></td>
<td>2,9</td>
<td></td>
<td>3,0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \beta_{\text{th}} )</td>
<td>0,0070</td>
<td></td>
<td>0,0023</td>
<td>0,0055</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E/fission (MeV)</td>
<td>201,7</td>
<td>205</td>
<td></td>
<td>210</td>
<td></td>
<td>212,4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( E_{n,\text{max}}, E_{\text{avg}} ) (MeV)</td>
<td>0,65/1,95</td>
<td></td>
<td></td>
<td>0,70/2,08</td>
<td></td>
<td>0,67/2,01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>heat (mW/g)</td>
<td>560</td>
<td>1,9</td>
<td>6,8</td>
<td>4,2</td>
<td>0,1</td>
<td></td>
<td></td>
<td></td>
<td>114</td>
</tr>
<tr>
<td>surface dose rate 1kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n-dose (mSv/h)</td>
<td>640</td>
<td>240</td>
<td>300,0</td>
<td>310,0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \gamma )-dose (mSv/h)</td>
<td>240</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>27000</td>
</tr>
</tbody>
</table>

\[ \chi_p(E) = \frac{2}{\sqrt{\pi}} \left( \frac{2}{3} E_{\text{avg}} \right)^{-3/2} \sqrt{E} e^{-E/\tau} \]
MOX - Physical Properties (3): PWR n-spectra (U and MOX-core)

transient reaction

Zry-properties
## MOX - Physical Properties (4): Consequences

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Affected Area</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-energy hardening</td>
<td>fast fluence in structural materials</td>
<td>irr.-</td>
</tr>
<tr>
<td></td>
<td>lower n-absorption</td>
<td>criticality, CRW</td>
</tr>
<tr>
<td></td>
<td>moderator-condition (density, void)</td>
<td>( \Gamma_T )</td>
</tr>
<tr>
<td>lower fraction delayed n (( \beta )) transients</td>
<td>faster transient response</td>
<td></td>
</tr>
<tr>
<td>higher fission energy</td>
<td>less fission-products</td>
<td></td>
</tr>
<tr>
<td>effectively none</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pu-241, Am-241 manufacturing</td>
<td>heating of unirradiated material</td>
<td></td>
</tr>
<tr>
<td></td>
<td>dose-rate</td>
<td>transport, inspection</td>
</tr>
<tr>
<td>ceramics</td>
<td>heat conductivity, inhomogeneous matrix</td>
<td></td>
</tr>
<tr>
<td>fuel rod design</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Practical Aspects of MOX - Handling (1): Delivery

on-site receiving inspection:
1) radiation dose for staff about 50-100μSv/MOX-FA
2) cooling in rack prior to wet-storage (about 1 hour per bundle)

on site storage of fresh MOX:
only wet-, not dry- storage (capacity)
Practical Aspects of MOX - Handling (1): Delivery

SIFA (truck) and MX4 (cask)

loading of cooling-rack

MX4 loaded with 4 MOX-FA

cooling-rack
Practical Aspects of MOX - Handling (2): Reactor Physics

Reactor-Physics Properties:

1. bundle design (enrichment-levels, water-rods)
2. reactivity versus burnup
3. power-distribution
4. measurement vs. prediction
5. transients and accidents

fuel rod design properties:

1. heat-conductivit
2. fuel temperature
3. fission-gas release
Practical Aspects of MOX - Handling (2): Bundle Design

MOX-FA

U-FA
Practical Aspects of MOX - Handling (2): MOX-Reactivity

reactivity-equivalence:

\[ \int_0^\infty k_\infty^{(U)}(e)de = \int_0^\infty k_\infty^{(MOX)}(e)de \]

alternative

\[ k_{ref} = k_\infty^{(U)}(e_0) = k_\infty^{(MOX)}(e_0) \]

or:
- OECD
- equilibrium-cycles (EKK-study)

Equivalence dependent on surrounding U-235 enr.:

Excess reactivity less pronounced – Pu-238, Pu-240, Pu-242
reactivity decline slower – in-situ breed&burn of Pu-241

4.55w/o Pu_{fiss}, \[ \text{Pu}_{fiss}/\text{Pu}_{tot} = 63.80\% \]
Practical Aspects of MOX - Handling (2): Power Distribution
Practical Aspects of MOX - Handling (2): Exp. vs Prediction
Accuracy of core-simulator prediction:

1. no influence of MOX loading on difference calculation – aeroball-measurement

2. apparent influence on prediction of critical boron-concentration, but code specific: only AREVAs CASCADE-simulator affected, not e.g. CMS (Studsvik-Scandpower)
Practical Aspects of MOX - Handling (2): Transients

Most pronounced examples:

1. ATWS: more negative $\Gamma_T$ helps voiding and reduces heat input at ATWS

2. LOCA: PCT higher in MOX - ECR not limiting in KWU-plants (2 min); core failure rates (German safety criterion) higher in mixed cores;

FIG. 5. Resulting distribution of rod internal pressures in the core of a German 16x16 PWR with 45370 FRs containing $\text{UO}_2$, $\text{UO}_2/\text{Gd}_2\text{O}_3$, and MOX fuel
Practical Aspects of MOX - Handling (2): Fuel-Rod-Design

- heat-conductivity lower
- Pufiss-distribution inhomogenous compared to U-235 nuclei in U-Matrix: >60% proportion of fissile nuclei in PuO microcrystal vs 5% proportion of fissile nuclei in UO2 microcrystal
- more reactivity and power at higher burnup (reflecting $k_{\text{inf}}(\text{burnup})$)
- higher fuel temperature
- more fission gas release
- KWU-plants: generally additional lower fuel-rod-plenum!
Practical Aspects of MOX - Handling (2): Fuel-Rod-Design

Stored energy in the rods of a UO2 core at BOC

Red symbols: Top 5%
Red and black symbols: all rods in the core

Stored energy in the rods of a MOX/UO2 core at BOC

Red symbols: Top 5%
Red and black symbols: all rods in the core
Practical Aspects of MOX - Handling (2): key parameters

- $k_{\text{inf}}$
- $p_i$
- $T_F$
- $\lambda$
- microstructure
- fission-nuclei/n-energy
Practical Aspects of MOX - Handling (3): Fast Fluence

- RPV-Fluence in U- and U/MOX-core: no practical impact of MOX - effect of different loading schemes dominant (in-out-loading vs. out-in)

![Graph showing fast fluence per FPD vs. operation period (cycles)]

- Fast flux: green, white highest

- Cycle 28 (40 MOX)
- Cycle 29 (0 MOX)
- No difference where it matters (outer row)
Practical Aspects of MOX - Handling (4): CR-worth

- no adaption necessary in KWU-plants
- IFM cold shutdown-criterion easy to meet
- KKU-example cycle 28 (U/MOX) vs. cycle 29 (U):
  148 ppm B/%$\Delta \rho$ (MOX) vs. 138 ppm B/%$\Delta \rho$
Practical Aspects of MOX - Handling (5): Safeguards

1. camera-surveillance system: additional cameras
2. IAEA inspections: monthly inspections
Practical Aspects of MOX - Handling (6): Back-End

transport and storage container:
• max 4 MOX-FA out of 19 FA per cask (expected 6 starting in 2012)
• burnup restricted to 55 MWd/kg (U: 65 MWd/kg)
• heat load restriction requires longer storage time: MOX-free cores

EOPL!!!
today:

<2.65 KW
<1.83 KW
Practical Aspects of MOX - Handling (6): Back-End

future (a little bit more fortunate):

<3.5 KW = h_{MOX}

depending on h_{MOX}

depending on h_{MOX}
Conclusions:

MOX are …

• …more expensive (at least German situation)
• …more difficult to fabricate
• …more complicated to handle on-site
• …more closely supervised by IAEA
• …more appreciated by IFM-people
• …in need of longer post-operating storage time
• …more difficult in intermediate storage period

…than Uranium FA.