# MOX@EON
# EON Operational Experience

Fall 2011 Meeting of the
US Nuclear Waste Technical Review Board

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September 14, 2011

# Irradiation Record of EON-NPPs

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

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

<u>Balance for EKK operated units (8)</u>

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)

| | MOX / reload | MOX / core | Pufiss/Putot | Pufiss | U-235 | remark |
|---|---|---|---|---|---|---|
| **KBR** | 1/3 | 64 | equivalent to 4,0w/o U-235 | | Unat<br>Utails | no. enr-levels not restricted, wet storage |
| **KKU** | 16/20/24<br>(59/71/>71) | 96 | <= 81,4 | 3,5<br>4,5 | Unat<br>Utails | 16x16-20-4; 3 enr.-levels; wet storage |
| **KWG** | 16 | 64 | | 3,2 | Unat | 16x16-20-4; wet storage only |
| **KKG** | 16 | 64 | 81,4<br>58…71 [1)] | 3,07<br>4,65 | Unat<br>Utails [2)] | no. enr-levels not restricted, wet storage |
| **KKI-2** | 24 | 96 | 71,2<br>equivalent to 4,4 w/o U-235 | 3,8 | Unat<br>Utails | 18x18-24-4,<br>no. enr-levels not restricted, wet storage |
| **KKS** | n.a. | n.a. | n.a. | n.a. | n.a. | |
| **KWW** | n.a. | n.a. | n.a. | n.a. | n.a. | |
| **KKI-1** | n.a. | n.a. | n.a. | n.a. | n.a. | |

1) $Pu_{tot}$<=8,02 w/o

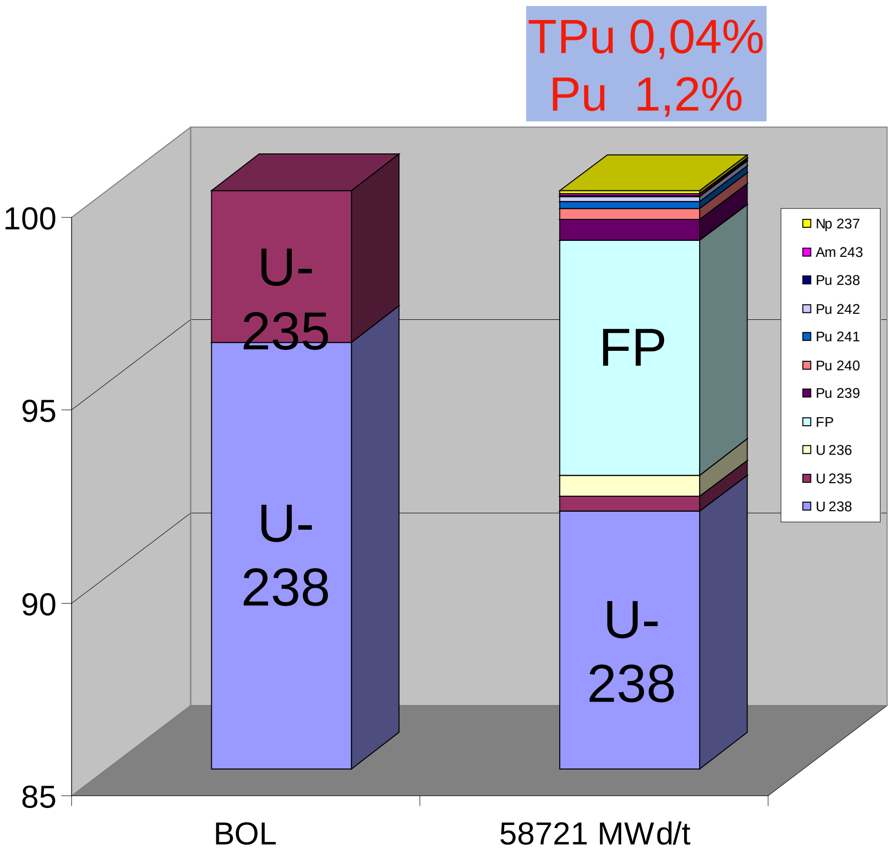
2) 0,2…0,3 w/0 U-235

# MOX - Handling Aspects

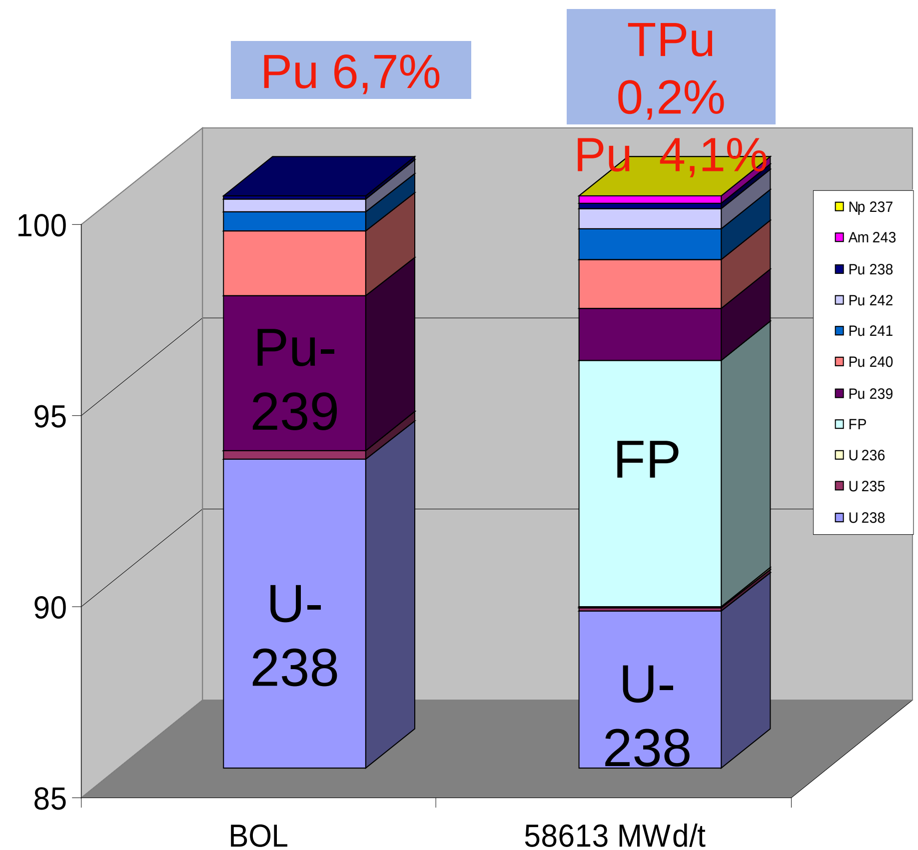
1. Manufacturing
2. Transport
3. Receiving inspection
4. On-site storage
5. Reactor-physics properties
6. Safeguards
7. Post-operation storage
8. Transport and intermediate storage

our area of expertise

# MOX - Physical Properties (1): Pu-Balance




Uranium-FA



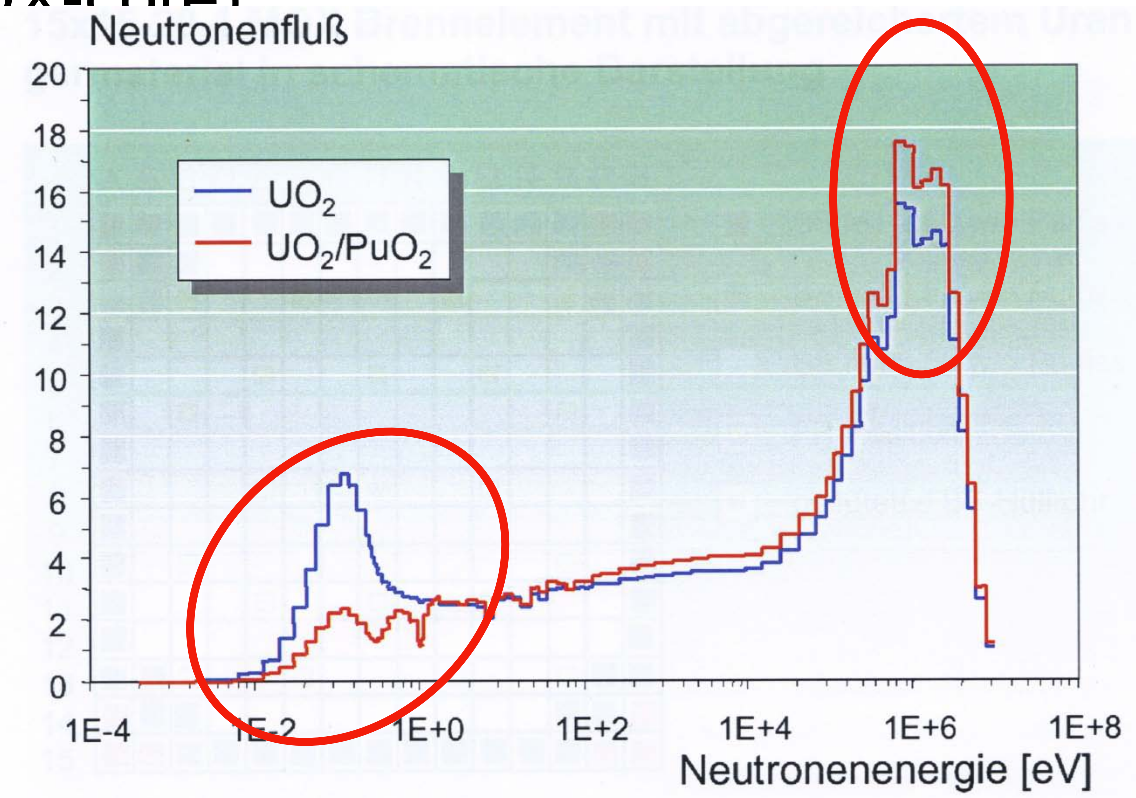

MOX-FA

# MOX - Physical Properties (2): General Overview

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

1) $$\chi_p(E) = \frac{2}{\sqrt{\pi}\left(\frac{2}{3}E_{avg}\right)^{3/2}}\sqrt{E}\,e^{-E/T}$$

# MOX - Physical Properties (3): PWR n-spectra (U and MOX-core)




Zry-properties

transient
reaction

# MOX - Physical Properties (4): Consequences

| Parameter | Affected Area | Consequence |
|---|---|---|
| n-energy | fast fluence in structural materials | irr.-hardening |
| | lower n-absorption | criticality, CRW |
| | moderator-condition (density, void) | $\Gamma_T$ |
| lower fraction delayed n ($\beta$) | faster transient response | transients |
| higher fission energy | less fission-products | effectively none |
| Pu-241, Am-241 | heating of unirradiated material | manufacturing |
| | dose-rate | transport, inspection |
| ceramics | heat conductivity, inhomogeneous matrix | fuel rod design |

# Practical Aspects of MOX - Handling (1): Delivery

<u>on-site receiving inspection:</u>

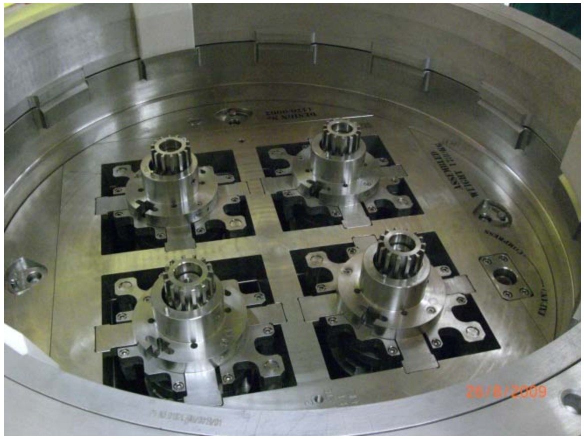
1) radiation dose for staff about 50-100μSv/MOX-FA
2) cooling in rack prior to wet-storage (about 1 hour per bundle)

<u>on site storage of fresh MOX:</u>

only wet-, not dry- storage (capacity)

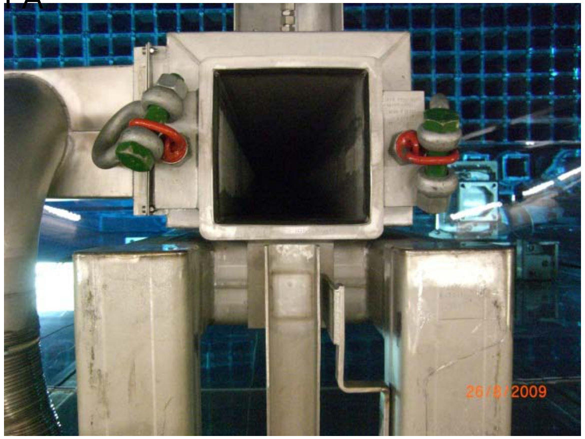
# Practical Aspects of MOX - Handling (1): Delivery


SIFA (truck) and MX4 (cask)




MX4 loaded with 4 MOX-FA


loading of cooling-rack




cooling-rack

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

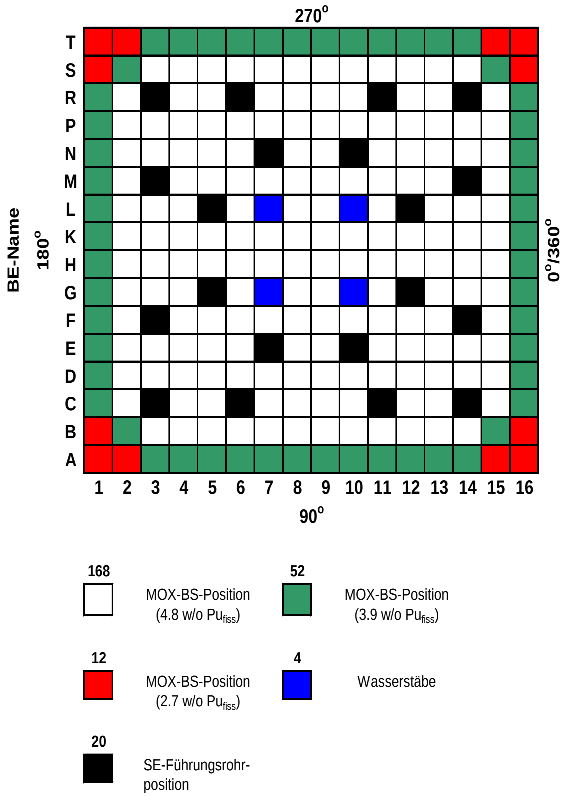
Reactor-Physics Properties:

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

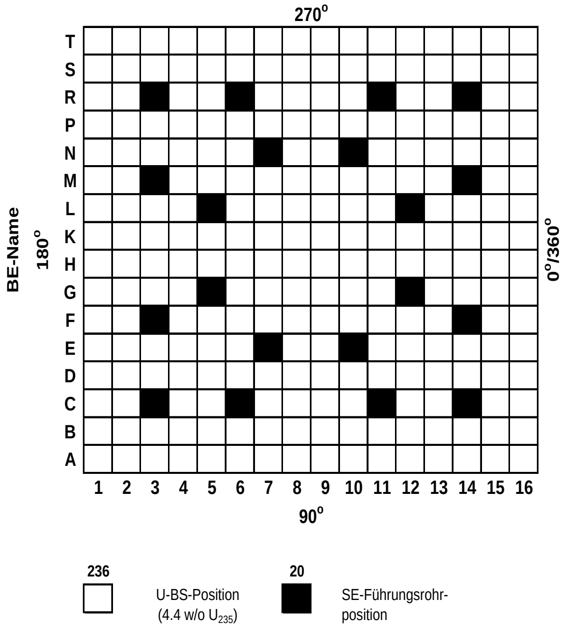
fuel rod design properties:

1. heat-conductivit
2. fuel temperature
3. fission-gas release

# Practical Aspects of MOX - Handling (2): Bundle Design

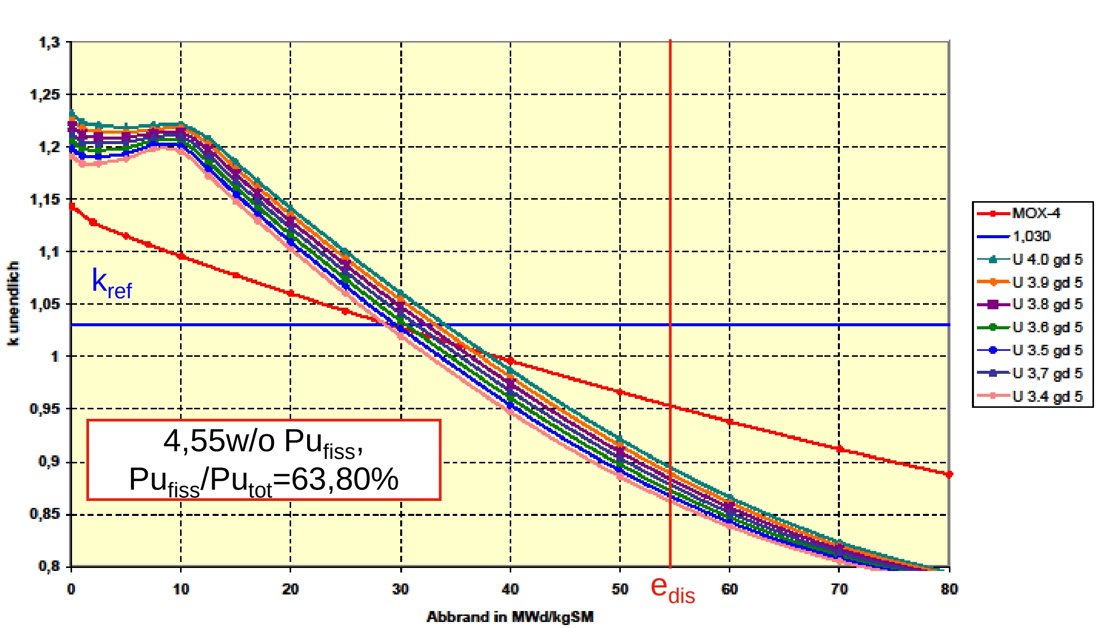



MOX-FA




U-FA

# Practical Aspects of MOX - Handling (2): MOX-Reactivity




Excess reactivity less pronounced – Pu-238, Pu-240, Pu-242

reactivity decline slower – in-situ breed&burn of Pu-241

reactivity-equivalence:

$$\int_0^{e_{dis}} k_\infty^{(U)}(e)de = \int_0^{e_{dis}} k_\infty^{(MOX)}(e)de$$

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.:

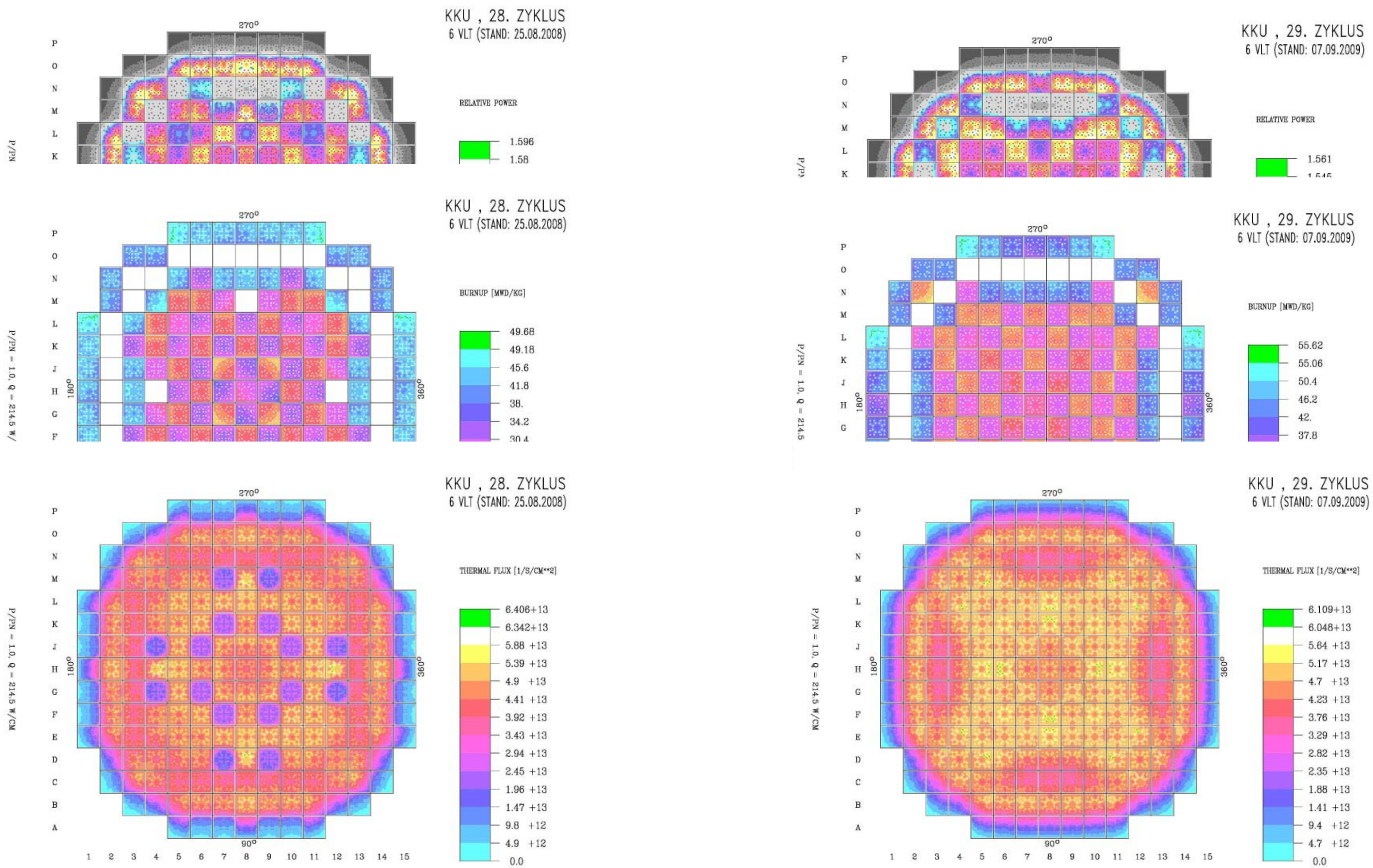
| | | |
|---|---|---|
| 4,6 | 4,6 | 4,6 |
| 4,6 | 4,0 | 4,6 |
| 4,6 | 4,6 | 4,6 |

→

| | | |
|---|---|---|
| 3,9 | 3,9 | 3,9 |
| 3,9 | 3,8 | 3,9 |
| 3,9 | 3,9 | 3,9 |

MOX-4 and equivalent U-235 enrichment

# Practical Aspects of MOX - Handling (2): Power Distribution



# Practical Aspects of MOX - Handling (2): Exp. vs Prediction

Accuracy of core-simulator prediction:

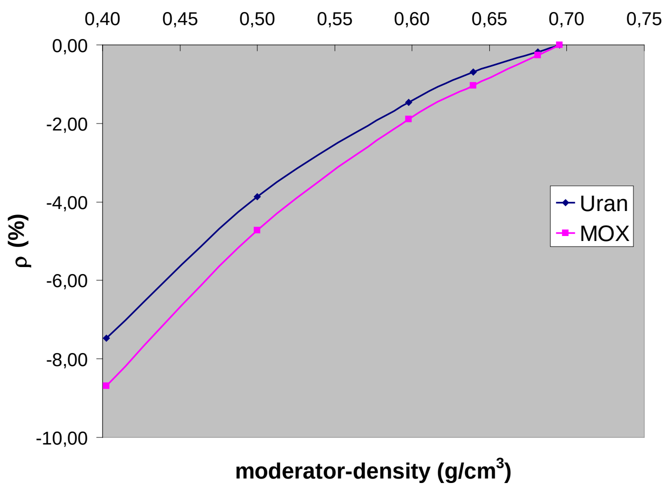
1. no influence of MOX loading on difference calculation – aeroball-measurement
2. apparent influence on prediction of critical boron-concentration, but code specific: only AREVAs CASCADE-simulator affected, not e.g. CMS (Studsvik-Scandpower)

# 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;



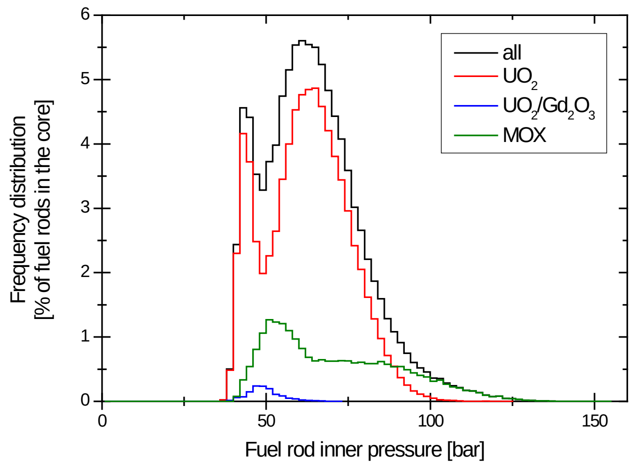
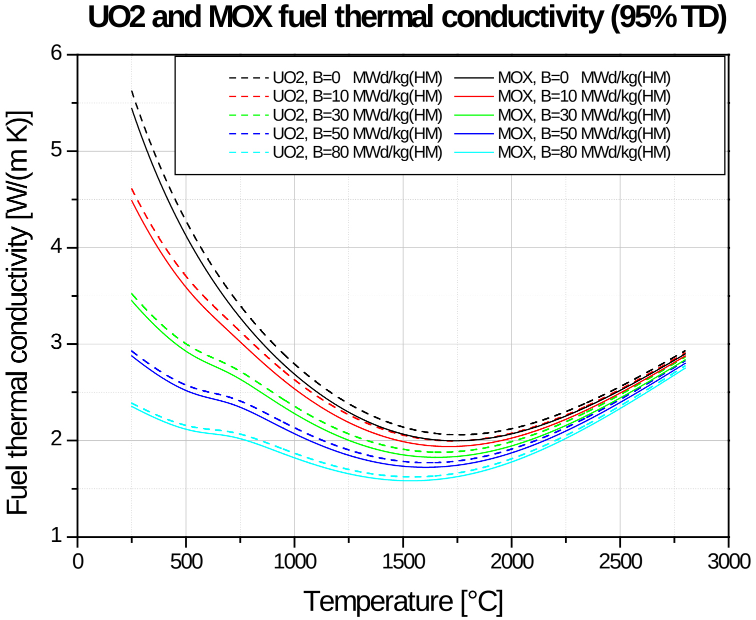




*FIG. 5. Resulting distribution of rod internal pressures in the core of a German 16x16 PWR with 45370 FRs containing $UO_2$, $UO_2/Gd_2O_3$, and MOX fuel*

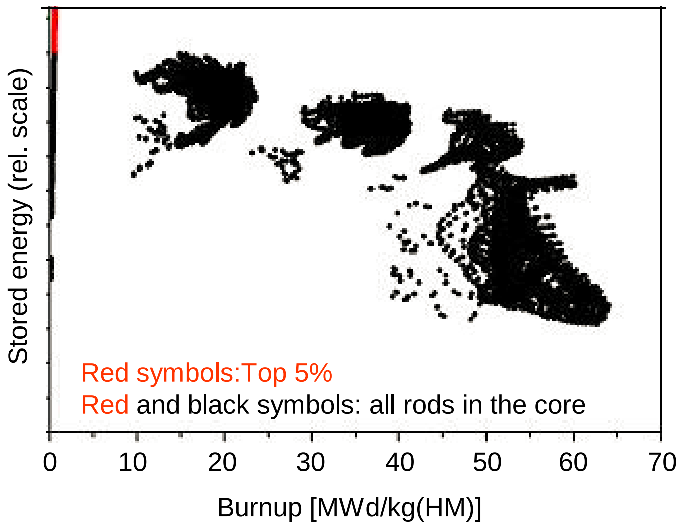
# Practical Aspects of MOX - Handling (2): Fuel-Rod-Design

- 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 bup (reflecting $k_{inf}$(burnup))
- higher fuel temperature
- more fission gas release
- KWU-plants: generally additional lower fuel-rod-plenum!

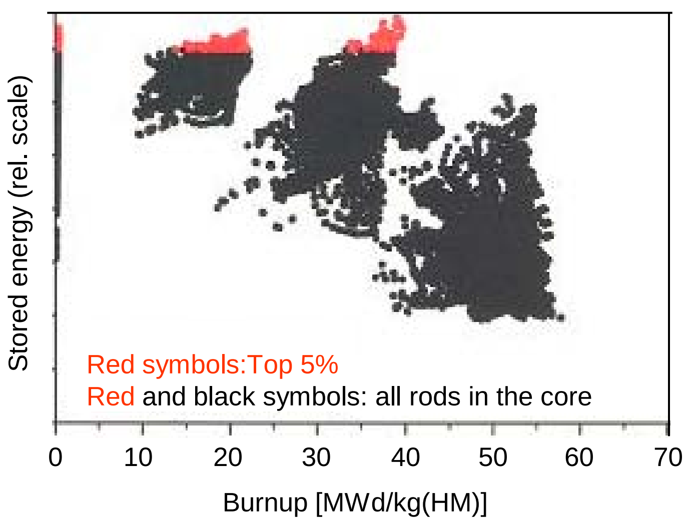


# Practical Aspects of MOX - Handling (2): Fuel-Rod-Design

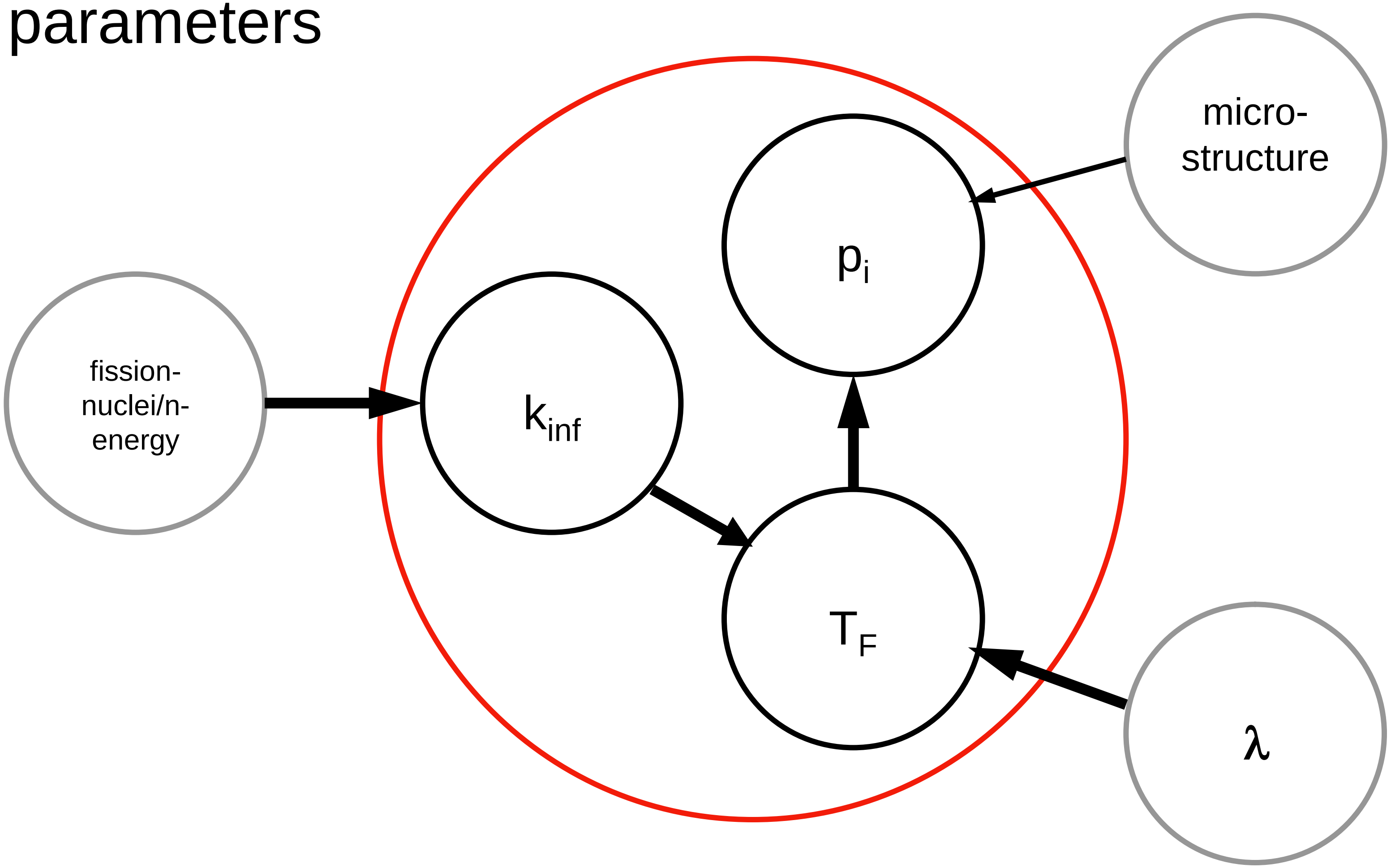
**Stored energy in the rods of a UO2 core at BOC**




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

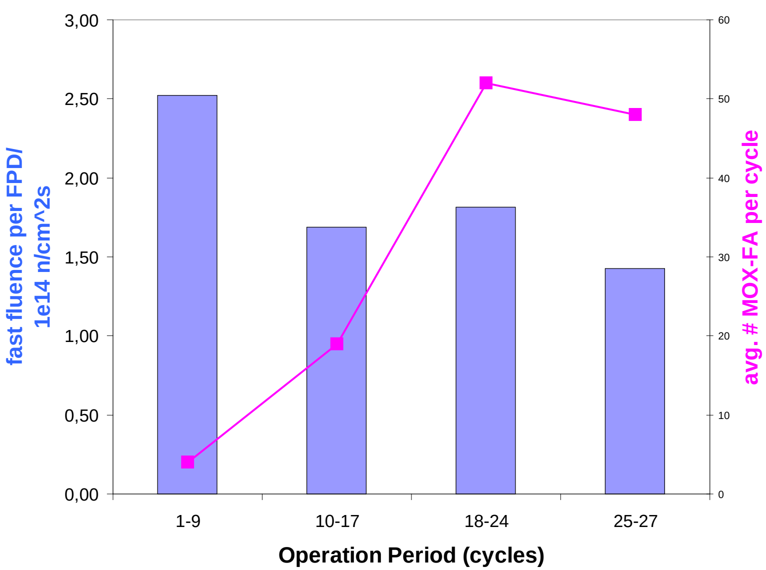


# Practical Aspects of MOX - Handling (2): key parameters

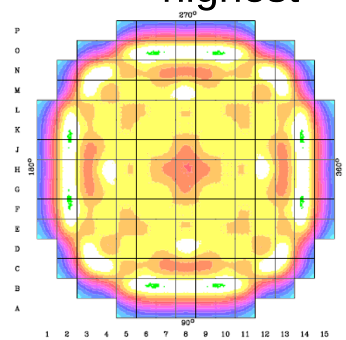


# Practical Aspects of MOX - Handling (3): Fast Fluence

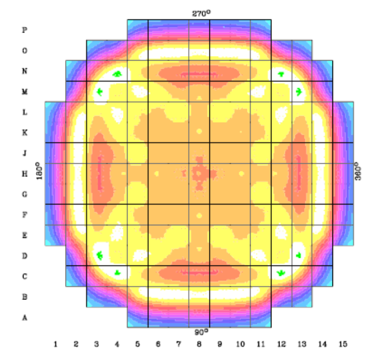
- RPV-Fluence in U- and U/MOX-core: no practical impact of MOX - effect of different loading schemes dominant (in-out-loading vs. out-in)




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

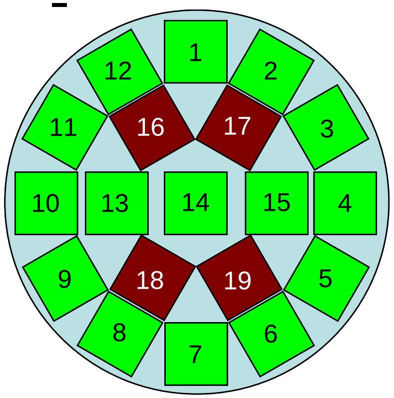
1. camera-surveillance system: additional cameras
2. IAEA inspections: monthly inspections

# Practical Aspects of MOX - Handling (6): Back-End

<u>transport and storage container:</u>

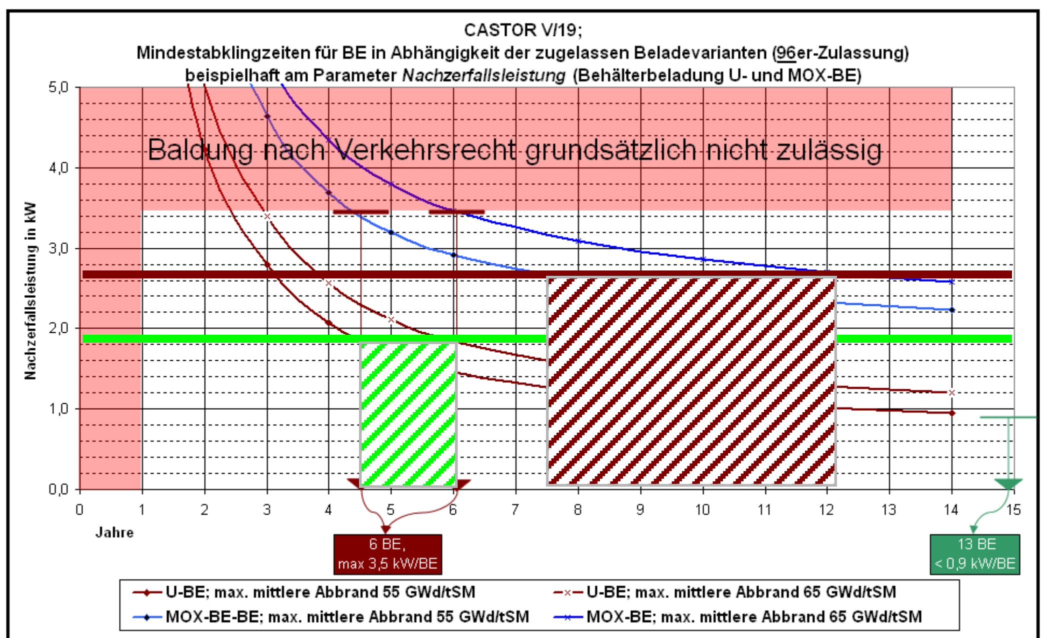
- max 4 MOX-FA out of 19 FA per cask (expected 6 starting in 2012)
- burnup restricted to 55 MWd/kg (U: 65 MWd/kg)
- heat load restriction requires longer storage time: MOX-free cores EOPL!!!

<u>today:</u>



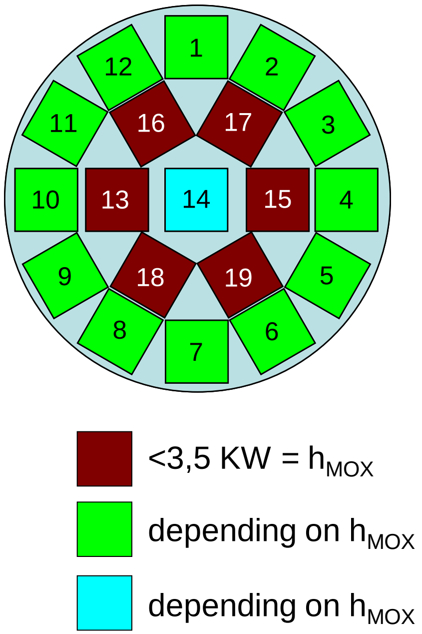

<2,65 KW

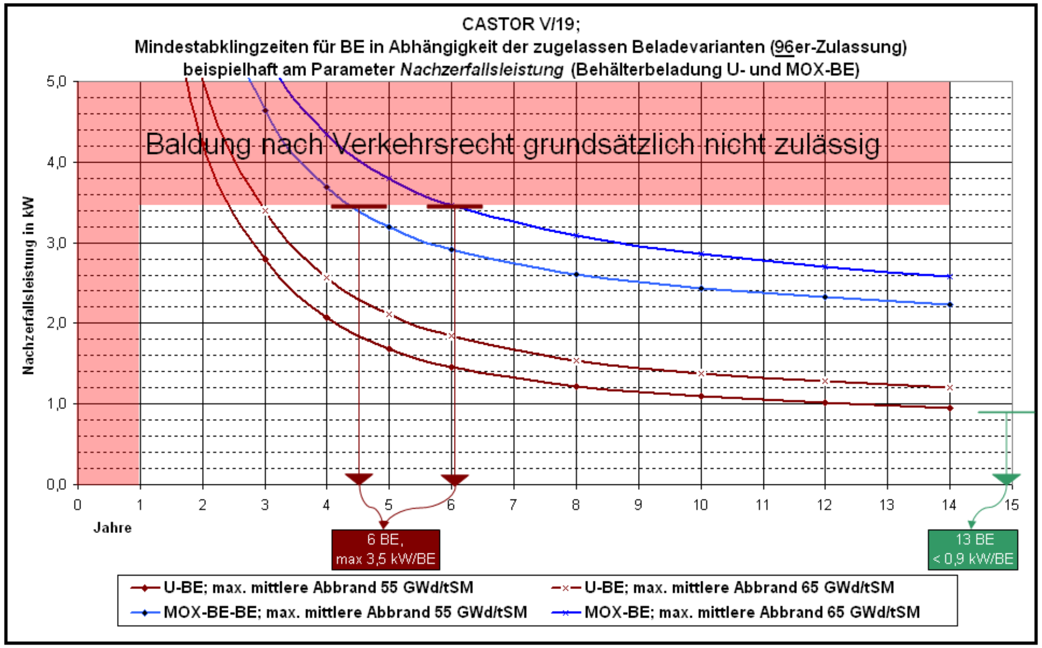
<1,83 KW



# Practical Aspects of MOX - Handling (6): Back-End

<u>future (a little bit more fortunate):</u>



# 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.