MOX@EON
EON Operational Experience

Fall 2011 Meeting of the
US Nuclear Waste Technical Review Board

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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 Utails	no. enr-levels not restricted, wet storage
KKU	16/20/24 (59/71/>71)	96	<= 81,4	3,5 4,5	Unat 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 58…71 [1]	3,07 4,65	Unat Utails [2]	no. enr-levels not restricted, wet storage
KKI-2	24	96	71,2 3,8 equivalent to 4,4 w/o U-235		Unat Utails	18x18-24-4, 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

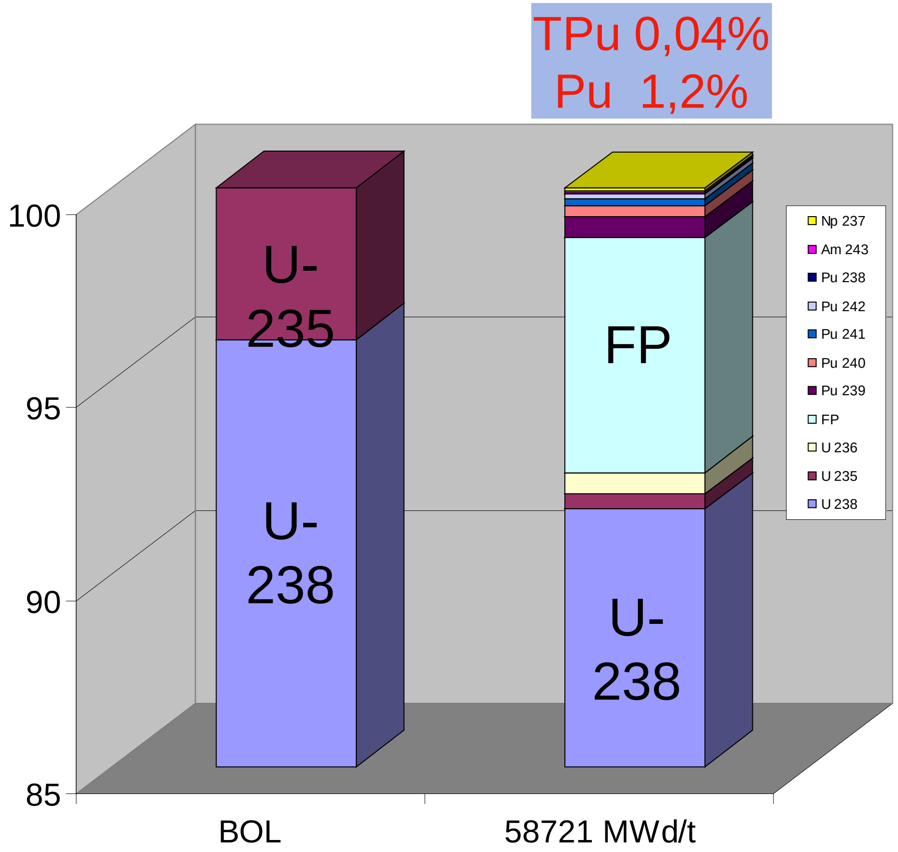
[2] 0,2…0,3 w/0 U-235

MOX - Handling Aspects

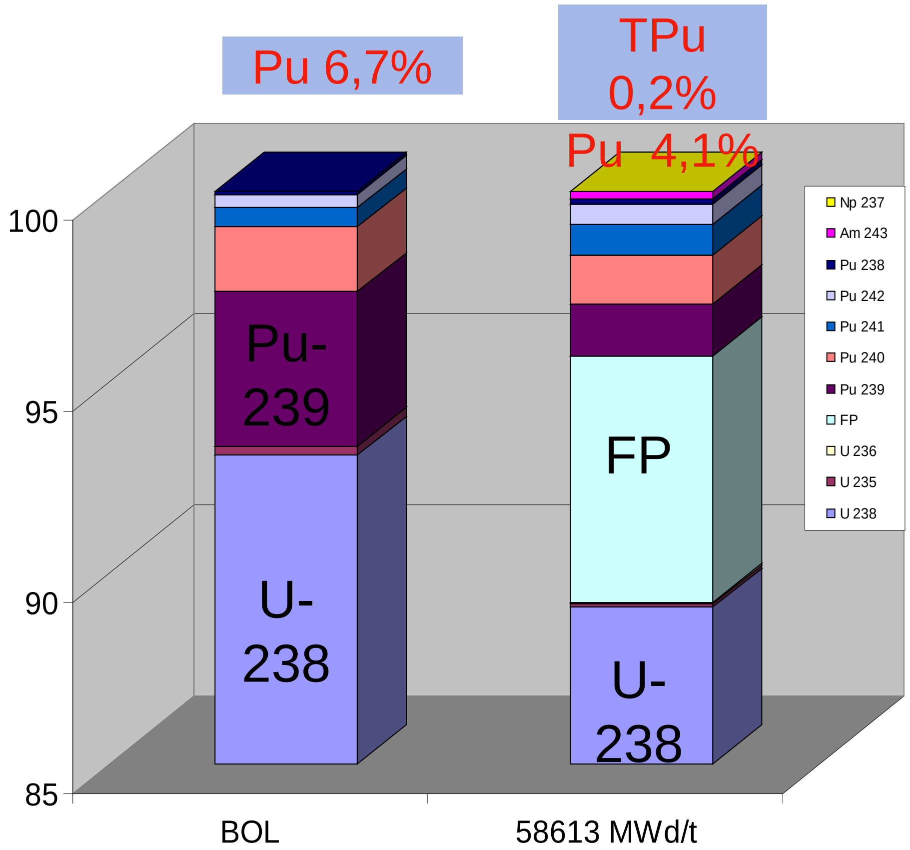
1. Manufacturing
2. Transport
3. Receiving inspection
4. On-site storage
5. Reactor-physics properties
6. Safeguards
7. Post-operation storage
8. Transport and intermediate storage

our area of expertise

MOX - Physical Properties (1): Pu-Balance



Uranium-FA



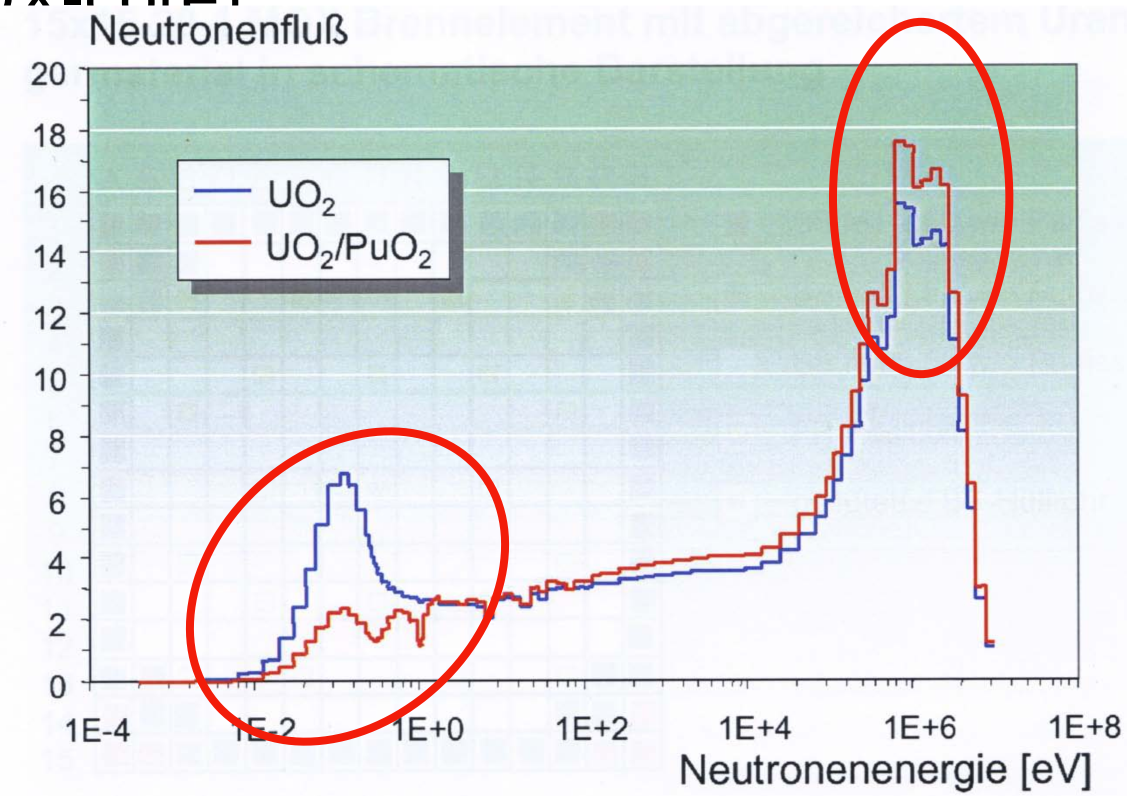
MOX-FA

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		
ν_{th}	2,4				2,9		3,0		
β_{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)



<u>Zry-properties</u>

<u>transient reaction</u>

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)	Γ_T
lower fraction delayed n (β)	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

on-site receiving inspection:

1) radiation dose for staff about 50-100μSv/MOX-FA

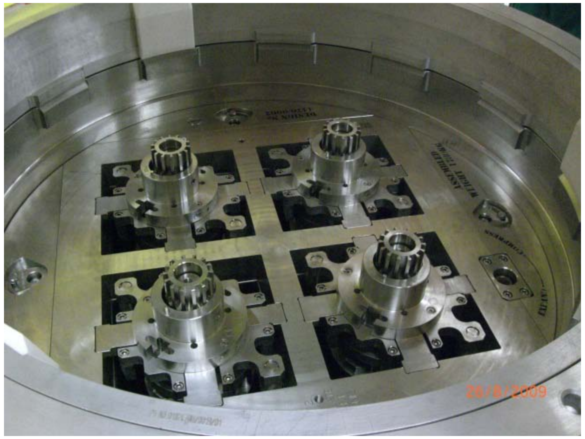
2) cooling in rack prior to wet-storage (about 1 hour per bundle)

on site storage of fresh MOX:

only wet-, not dry- storage (capacity)

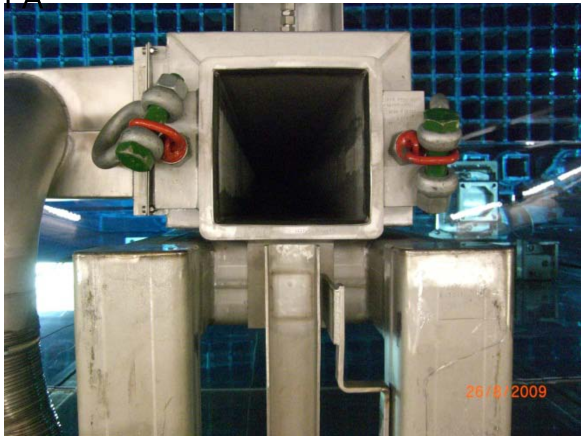
Practical Aspects of MOX - Handling (1): Delivery

SIFA (truck) and MX4 (cask)



MX4 loaded with 4 MOX-FA

loading of cooling-rack



cooling-rack

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

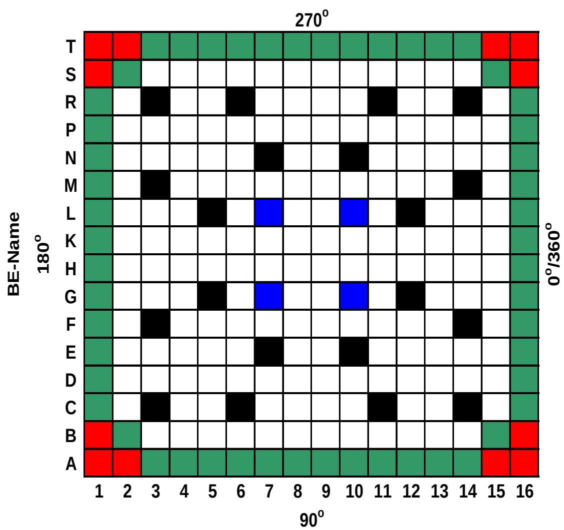
Reactor-Physics Properties:

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



168 MOX-BS-Position (4.8 w/o Pu_{fiss})

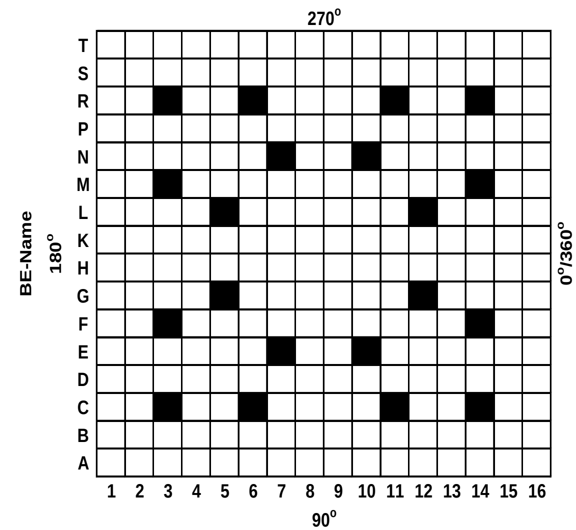
52 MOX-BS-Position (3.9 w/o Pu_{fiss})

12 MOX-BS-Position (2.7 w/o Pu_{fiss})

4 Wasserstäbe

20 SE-Führungsrohr-position

MOX-FA

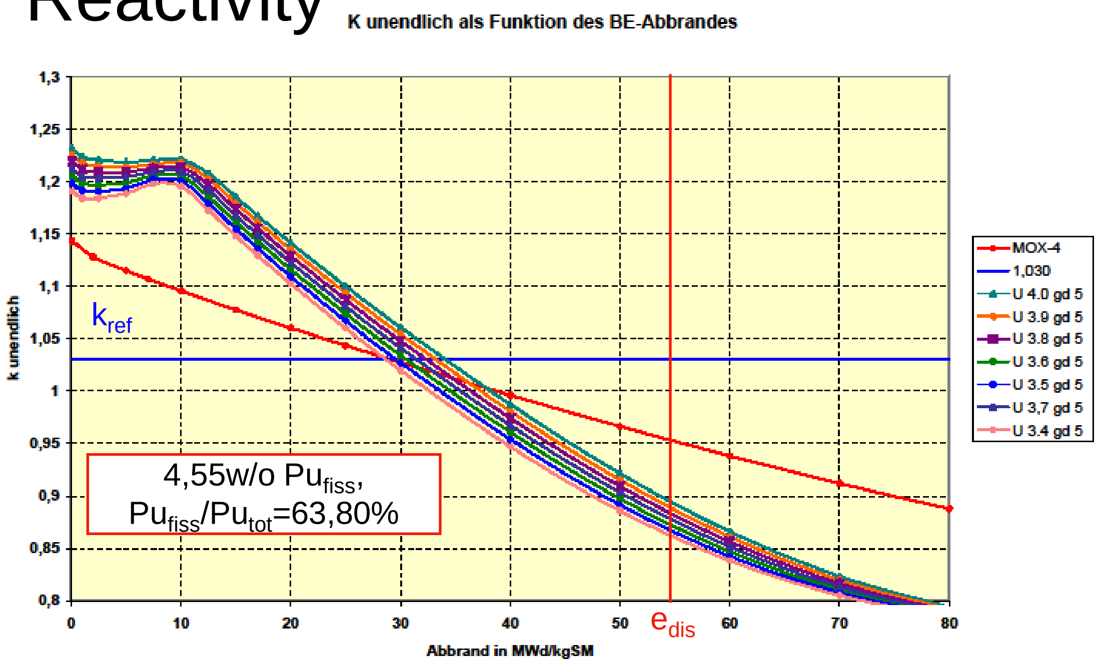


236 U-BS-Position (4.4 w/o U_{235})

20 SE-Führungsrohr-position

U-FA

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



reactivity-equivalence:

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

alternative

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

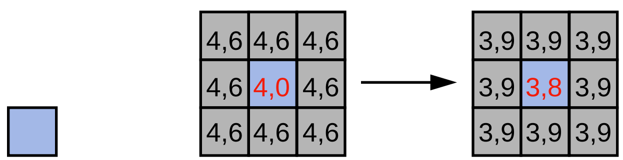
or:

- OECD
- equilibrium-cycles (EKK-study)

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

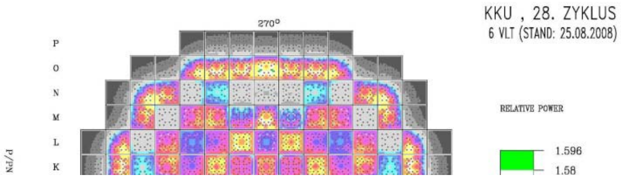
reactivity decline slower – in-situ breed&burn of Pu-241

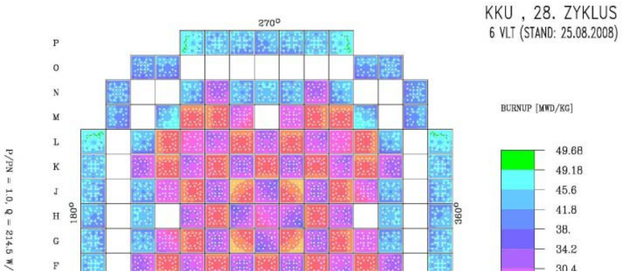
Equivalence dependent on surrounding U-235 enr.:

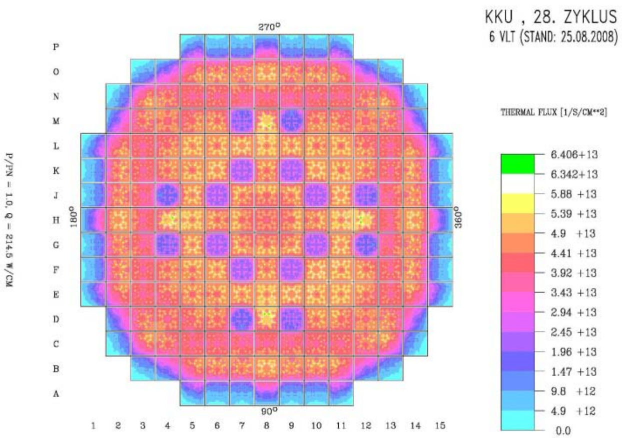


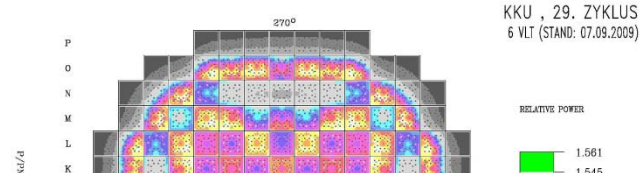
MOX-4 and equivalent U-235 enrichment

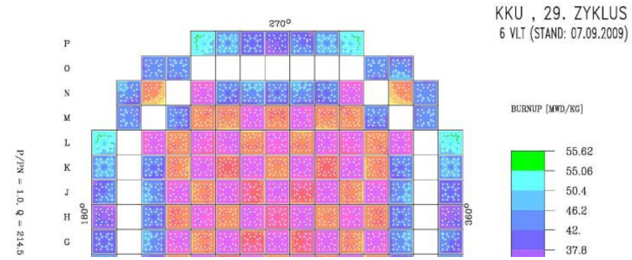
Practical Aspects of MOX - Handling (2): Power Distribution

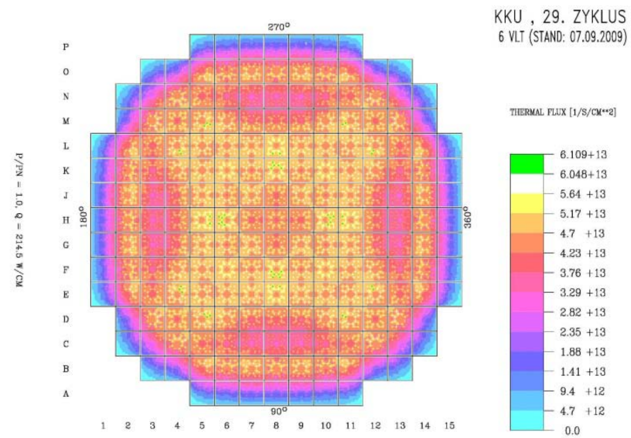












Practical Aspects of MOX - Handling (2): Exp. vs Prediction

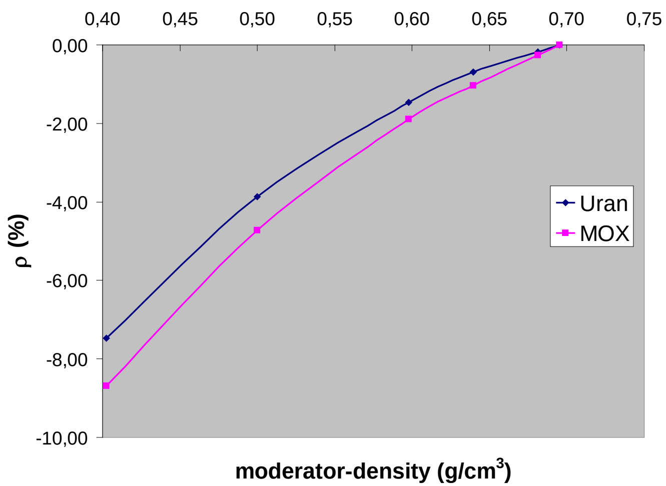
Accuracy of core-simulator prediction:

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 Γ_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;



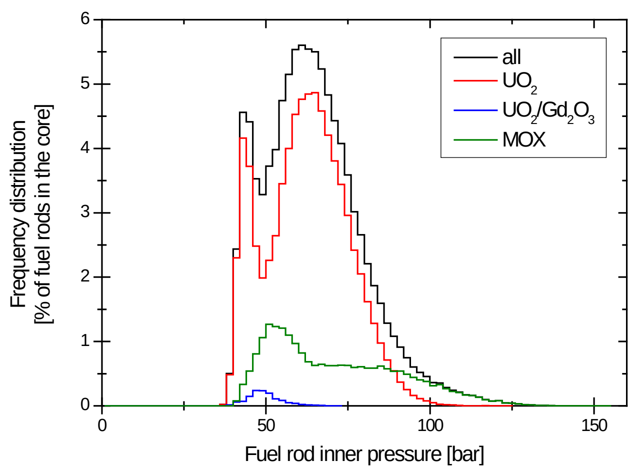
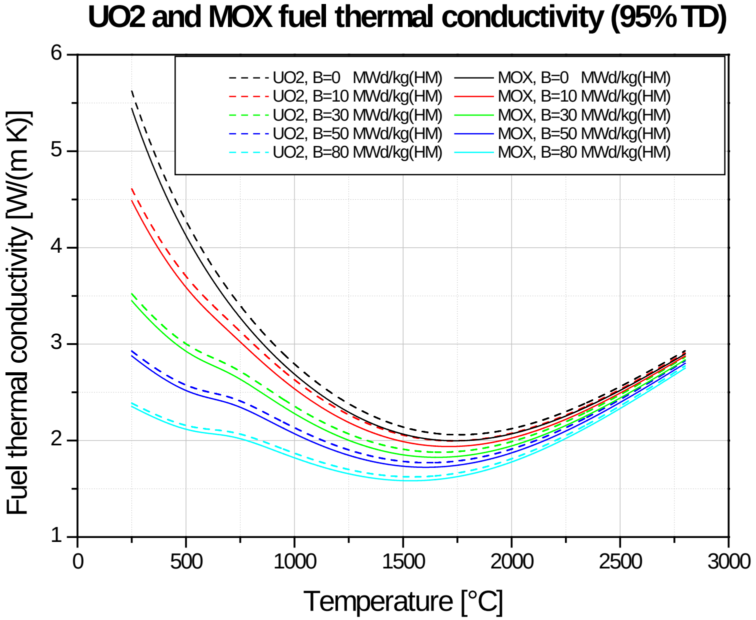


FIG. 5. Resulting distribution of rod internal pressures in the core of a German 16x16 PWR with 45370 FRs containing UO_2, UO_2/Gd_2O_3, and MOX fuel

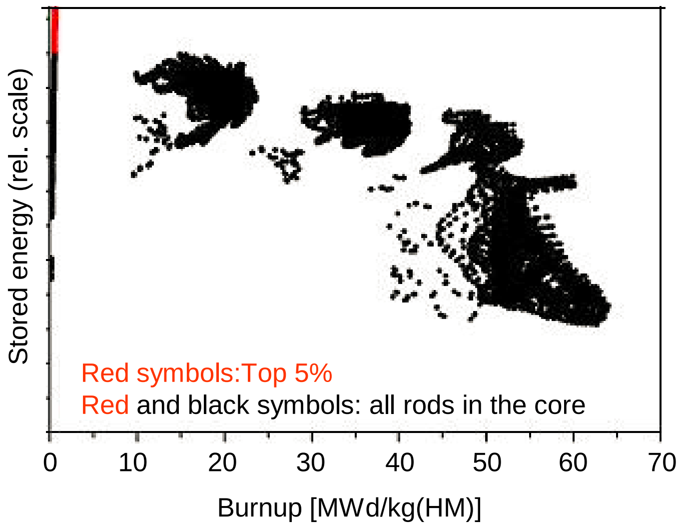
Practical Aspects of MOX - Handling (2): Fuel-Rod-Design

- 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!

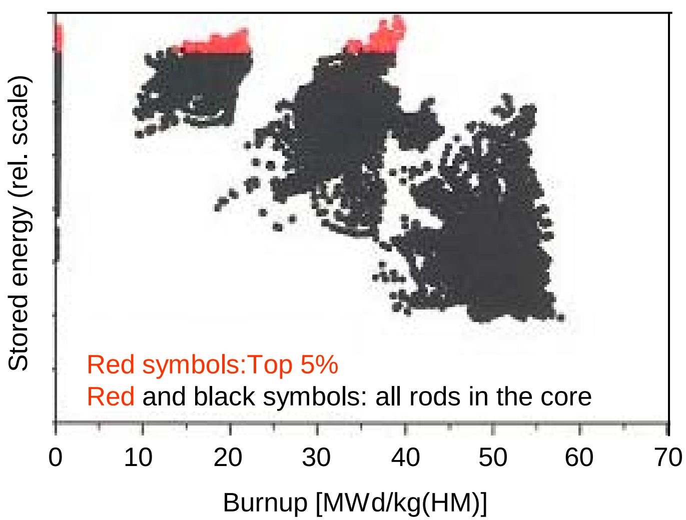


Practical Aspects of MOX - Handling (2): Fuel-Rod-Design

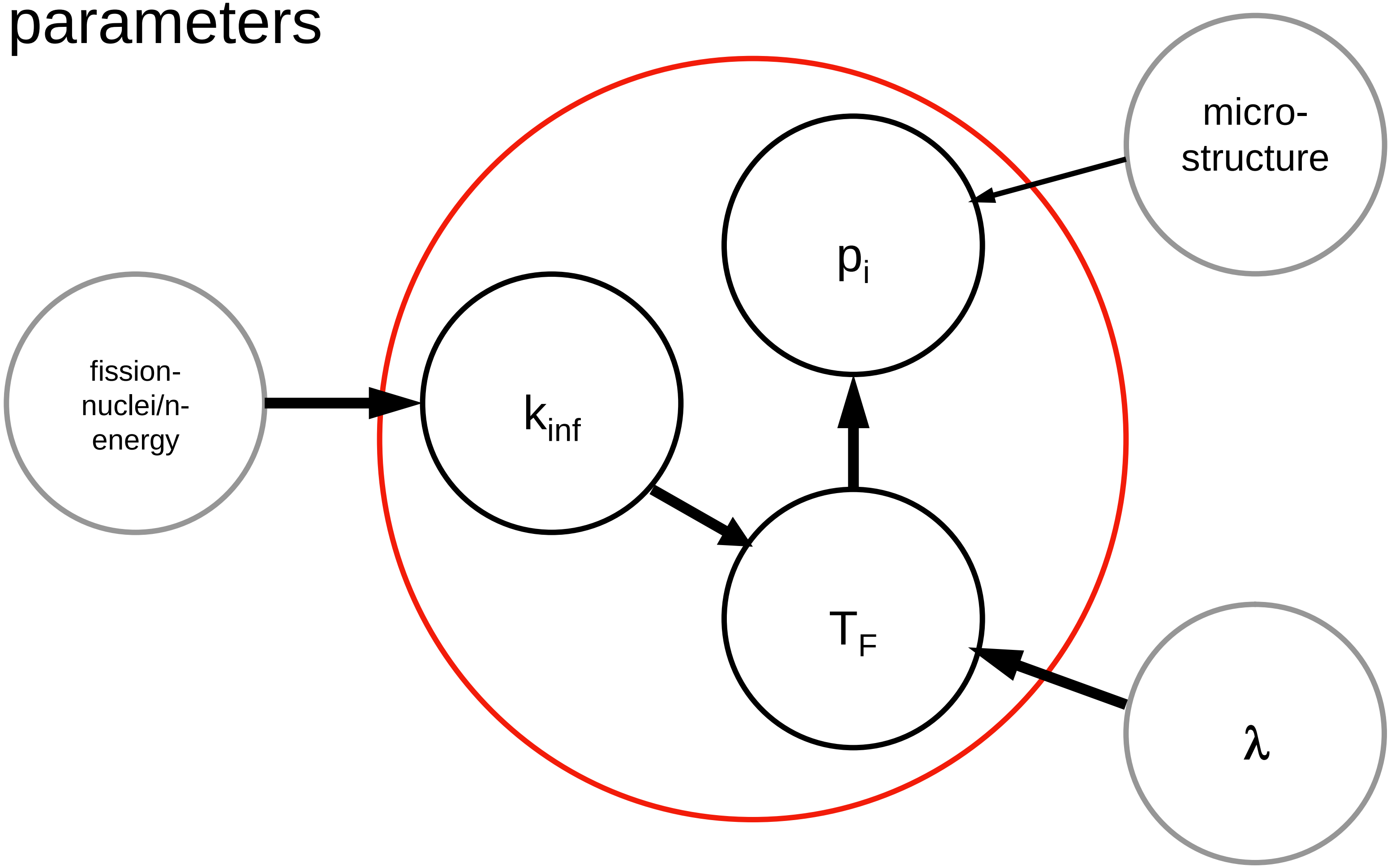
Stored energy in the rods of a UO2 core at BOC



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

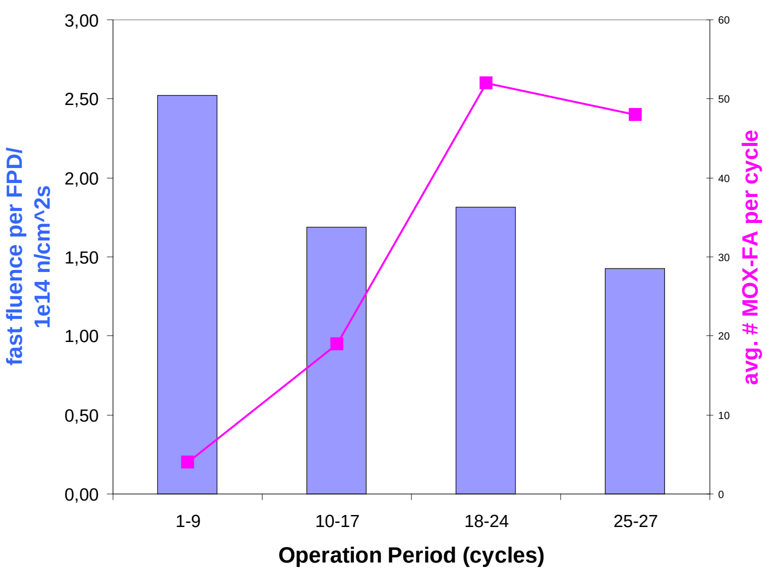


Practical Aspects of MOX - Handling (2): key parameters

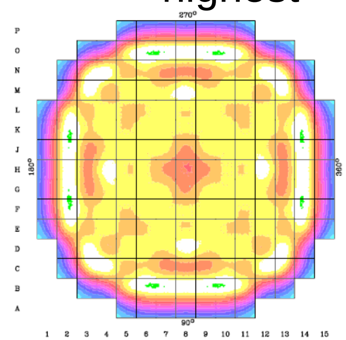


Practical Aspects of MOX - Handling (3): Fast Fluence

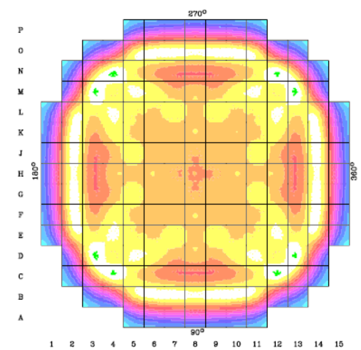
- RPV-Fluence in U- and U/MOX-core: no practical impact of MOX - effect of different loading schemes dominant
  (in-out-loading vs. out-in)



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

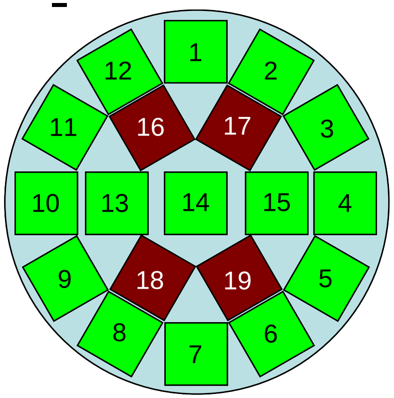
1. camera-surveillance system: additional cameras
2. IAEA inspections: monthly inspections

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

transport and storage container:

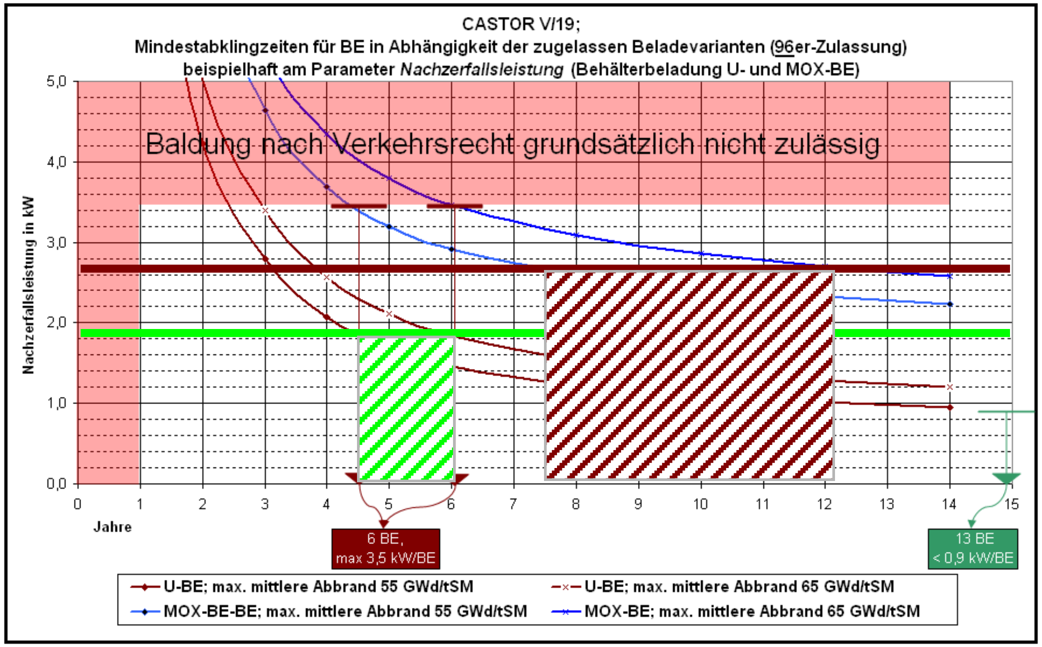
- max 4 MOX-FA out of 19 FA per cask (expected 6 starting in 2012)
- burnup restricted to 55 MWd/kg (U: 65 MWd/kg)
- heat load restriction requires longer storage time: MOX-free cores EOPL!!!

today:



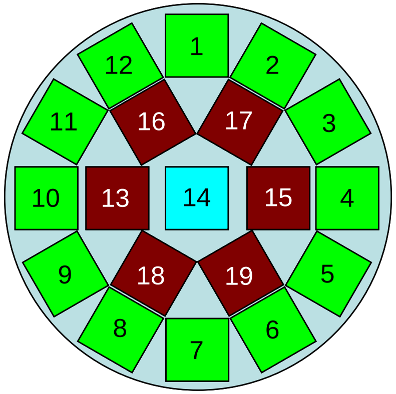
<2,65 KW

<1,83 KW



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

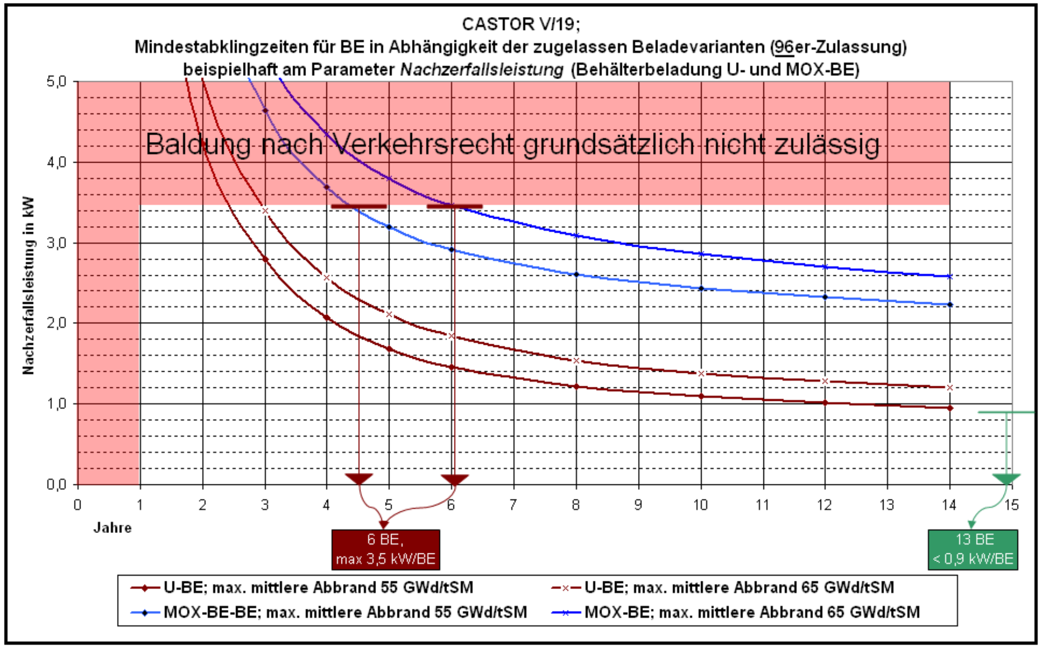
<u>future (a little bit more fortunate):</u>



<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.