PWR 3D-Core Simulation using different ATF cladding materials

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Index

1. ATF Cladding Materials

Coatings

$\boldsymbol{Cr}$ 20 microns coating [1]; $\rho_{Cr} = 7.15\ g/cm^3$ [3]

$\boldsymbol{Ti_2AlC}$ 30 microns coating [2]; $\rho_{Ti_2AlC} = 4.11\ g/cm^3$ [4]

Homogenization of clad and coating into one single material

FeCrAl Clad

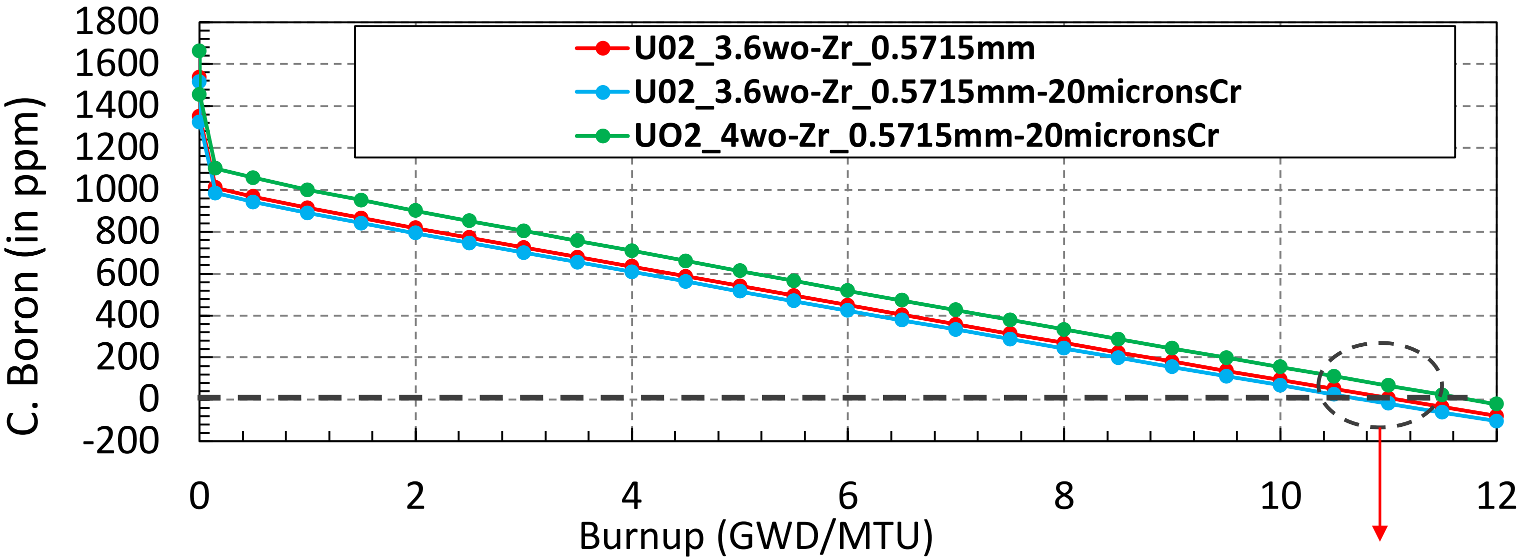
- Composition: **Fe** 80.80 wt%, **Cr** 13 wt%, **Al** 6.20 wt% [5]
- Clad thickness: $300\mu m$

SiC Clad

- Density: $\rho_{SiC} = 2.71\ g/cm^3$ [6]
- Clad thickness: $0.78mm$

2. Equivalent Cycle Length

Concept



Cycle length ~ 11.08 GWD/MTU

- “linear reactivity” approach in “Boron Concentration” at EOC
- … lower/higher enrichment in order to meet the cycle length

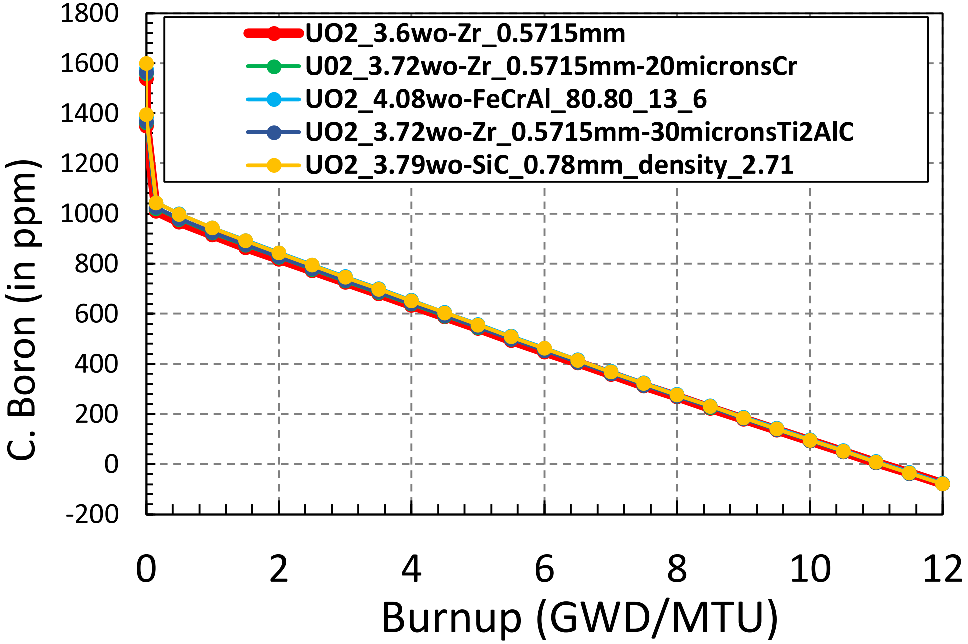
Results

	JEFF-3.3	**ENDF/B-VIII.0**	Comparison
Zr_0,5715mm-Cr_20microns	**3.72**	3.72	0.00
Zr_0,5715mm-Ti2AlC_30microns	3.76	3.77	-0.01
FeCrAl_80.80_13_6	4.08	4.08	0.00
SiC_78mm - dens_2.71	3.79	3.79	0.00

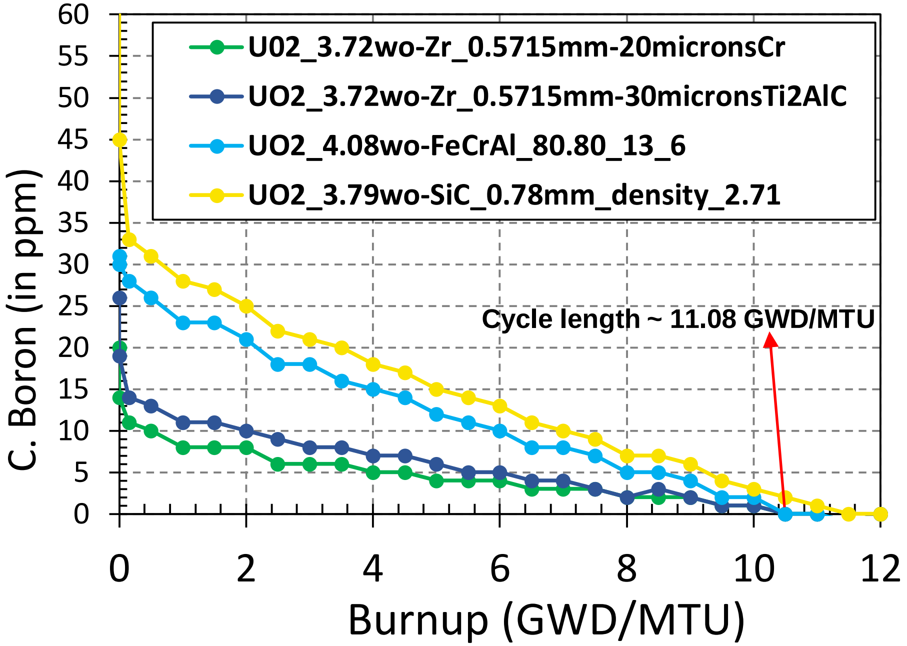
Table 1. Equivalent Enrichment of the ATF material for different libraries

3. Boron curves

Boron curves



Relative difference with conventional clad



4. Axial Offset Curves

$$\text{Axial Offset } (\%) = \frac{P_T - P_S}{P_T + P_S} * 100$$

P_T is the power fraction in the top-half of the core

P_S is the power fraction in the bottom-half of the core

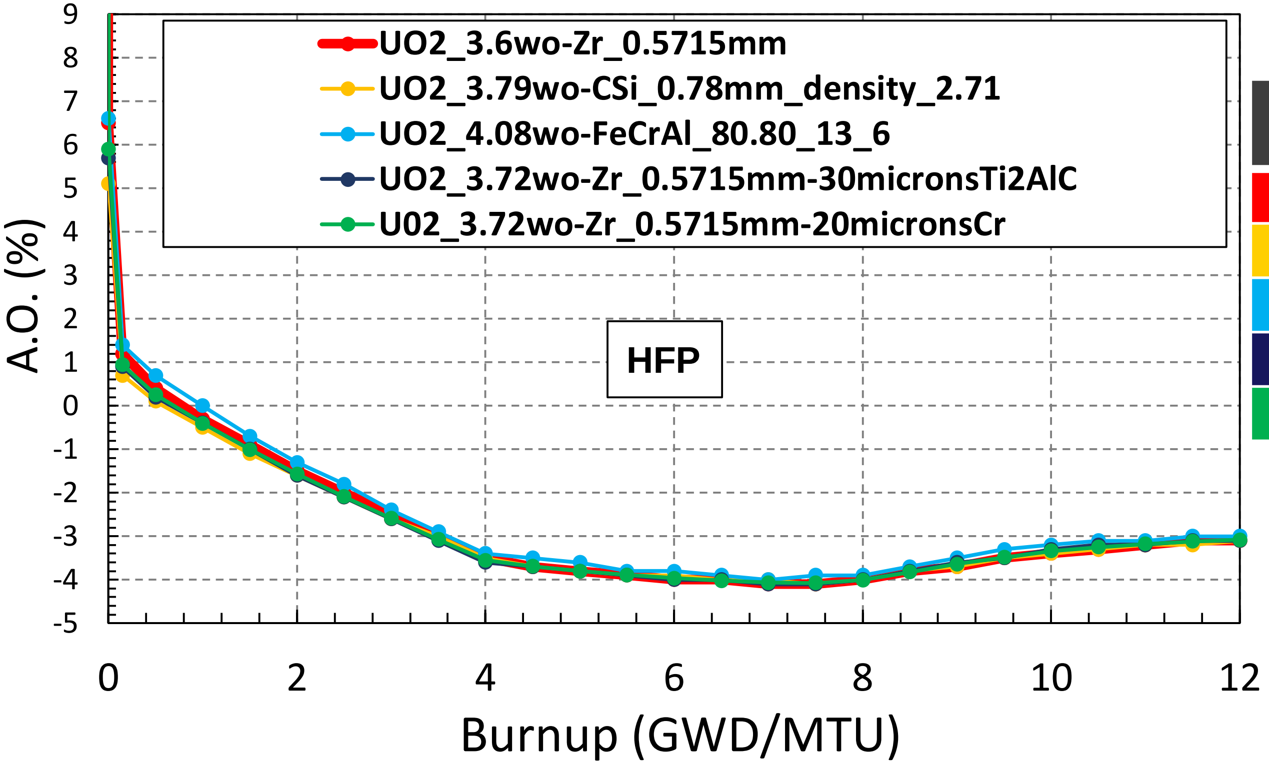


Table 2. A.O.(%) at BOC/HZP

Case	A.O. (%) BOC/HZP
UO2_3.60wo – Zr_0.5715mm	33.9
UO2_3.79wo – SiC_0.78mm	**31.9**
UO2_4.08wo – FeCrAl_0.30mm	32.6
UO2_3.72wo – Zr+30mcTi2AlC	33.1
UO2_3.72wo – Zr+20mcCr	33.3

5. Peaking Factors

Heat flux hot channel factor (F_Q)

$$F_Q = \frac{max.\,local\ LHGR}{average\ LHGR} = \max[Q(z)]$$

LHGR is Linear Heat Generation Rate (W/cm)

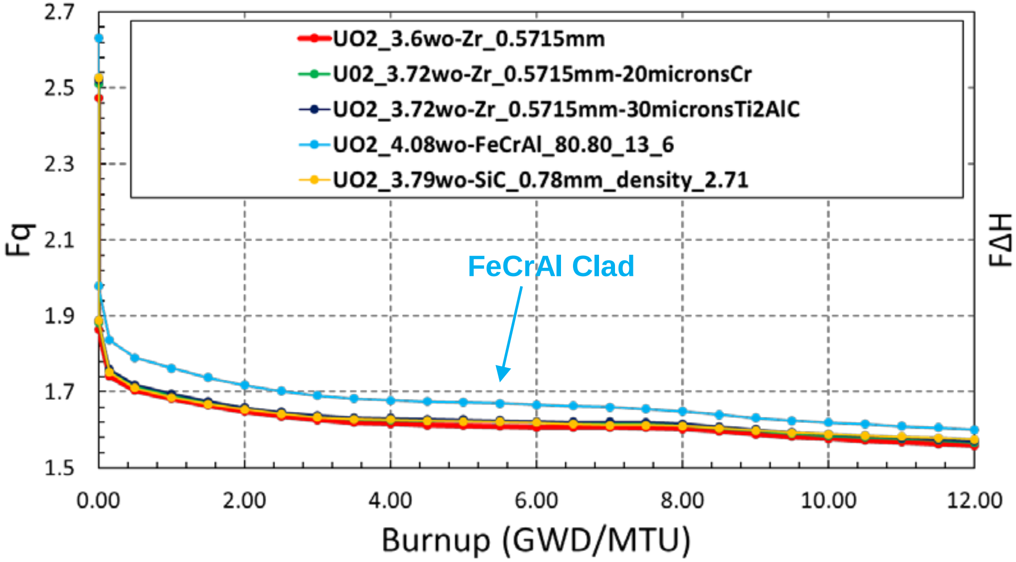
Q(z) is the máximum linear power at elevation z

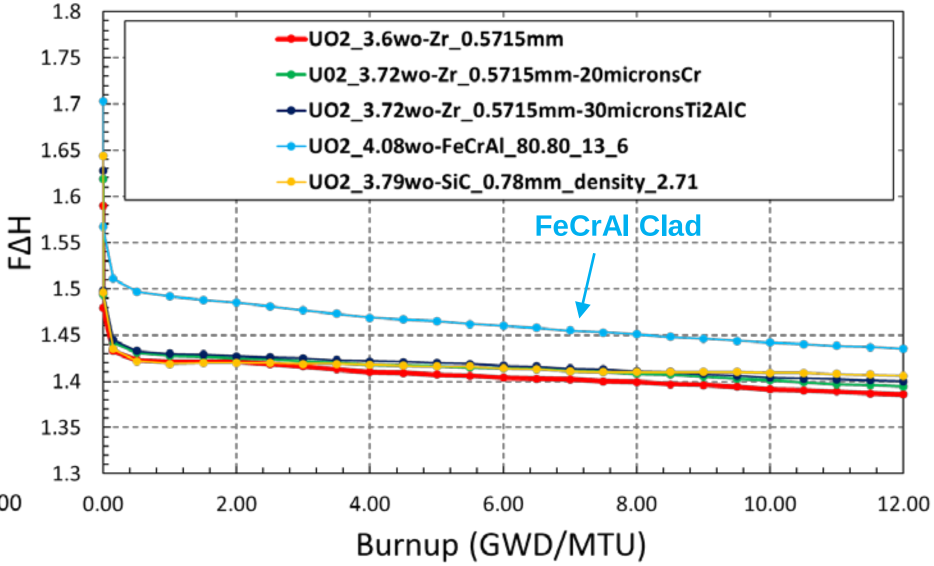
Design Limit: $F_Q < F_Q^{max} \approx 2.40/P$

Entalphy Peaking factor ($F_{\Delta H}$)

$$F_{\Delta H} = \frac{max.\,chhanel\ enthalpy\ rise}{core\ average\ entalpy\ rise} = \max[\frac{\Delta H}{avg\ \Delta H}]$$

Design Limit: $F_{\Delta H} < F_{\Delta H}^{max} \approx 1.60 \cdot [1+0.3(1-P)]$

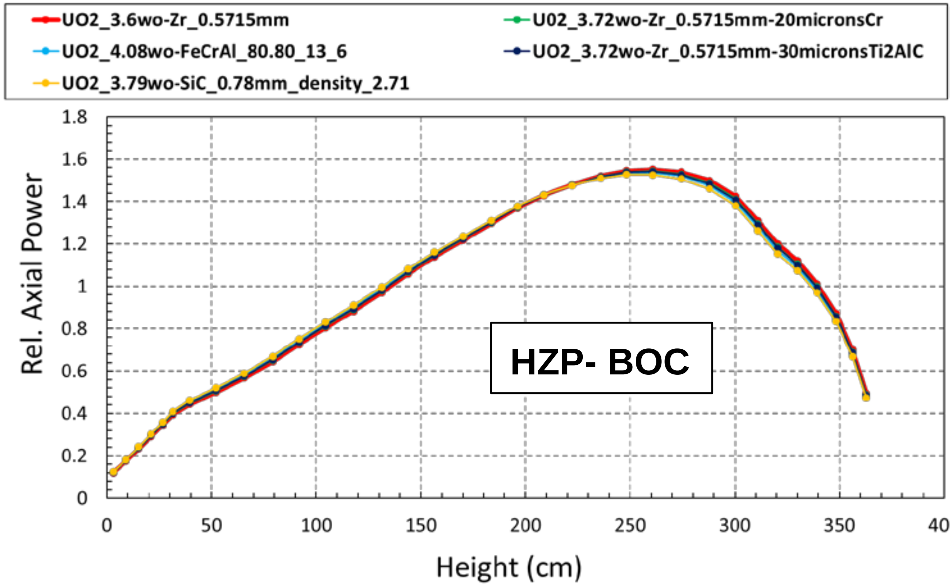


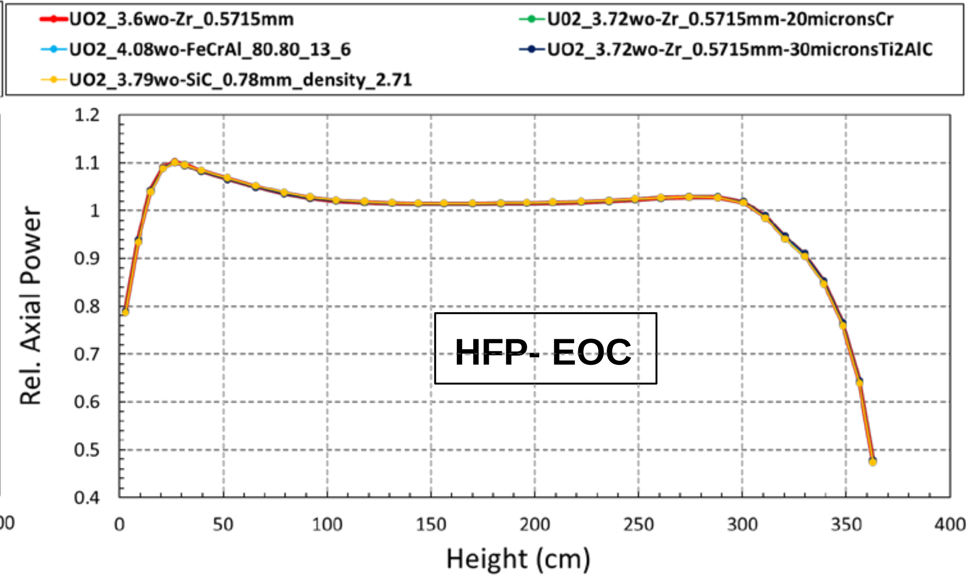


6. Axial Power Distribution

Axial power distribution: HZP/HFP – BOC/EOC

- Axial power distribution change with cycle depletion
- At BOC/HZP is peaked at the bottom of the core …
  - similar values for all ATFs: A.O.(%) for UO2/Zr is 33.9%
  - slightly different for SiC: A.O.(%) is 31.9%
- At EOC, the axial power becomes flattened

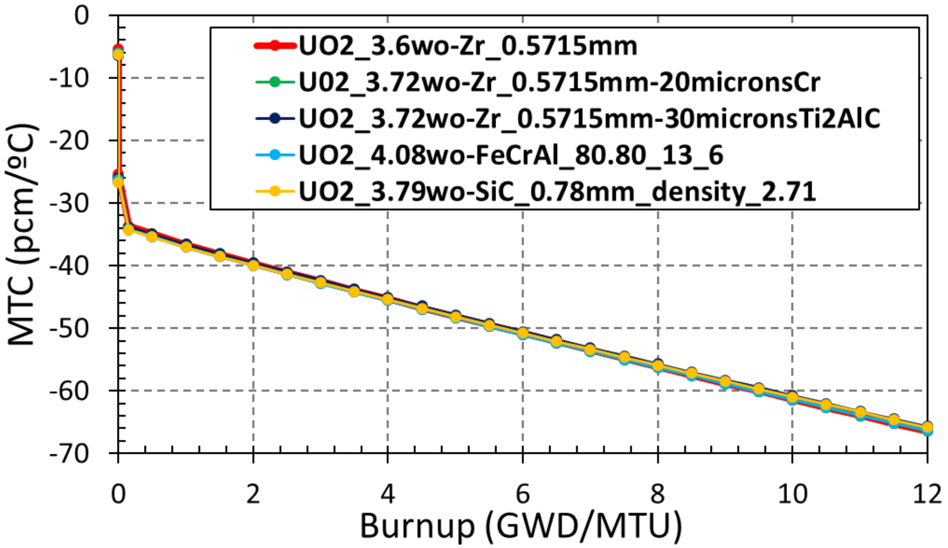


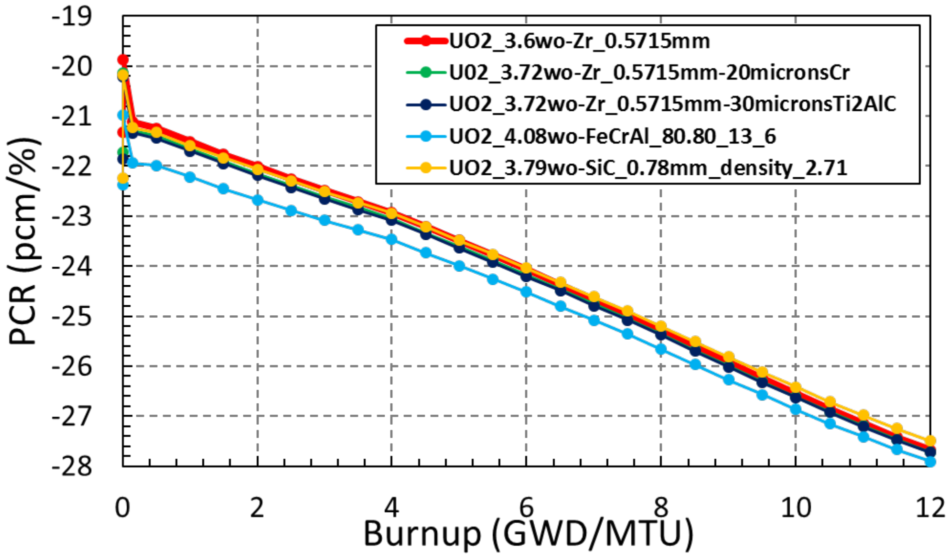


7. Reactivity Coefficients

Table 3. Reactivity coefficients at BOC/HZP

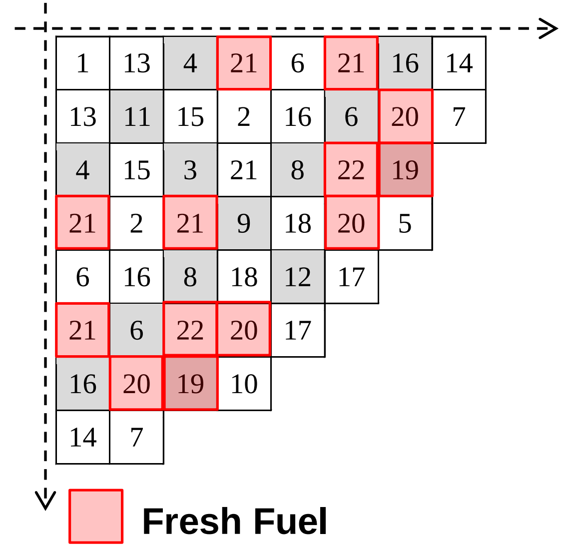
Reactivity Coefficients at BOC/HZP	MTC (pcm/ºC)	FTC (pcm/ºC)	CISO (pcm/ºC)	DOP (pcm/%)	PCR (pcm/%)
UO2_3.60wo – Zr_0.5715mm	-5.5	-5.1	-10.5	-16.0	-21.3
UO2_3.72wo – Zr+20mcCr	-6.1	-5.1	-11.1	-16.1	-21.7
UO2_3.72wo – Zr+30mcTi2AlC	-6.2	-5.1	-11.3	-16.1	-21.9
UO2_4.08wo – FeCrAl_0.30mm	-6.3	-5.0	-11.3	-16.1	-22.4
UO2_3.79wo – SiC_0.78mm	-6.4	-5.2	-11.6	-16.4	-22.2





8. Bank Worths

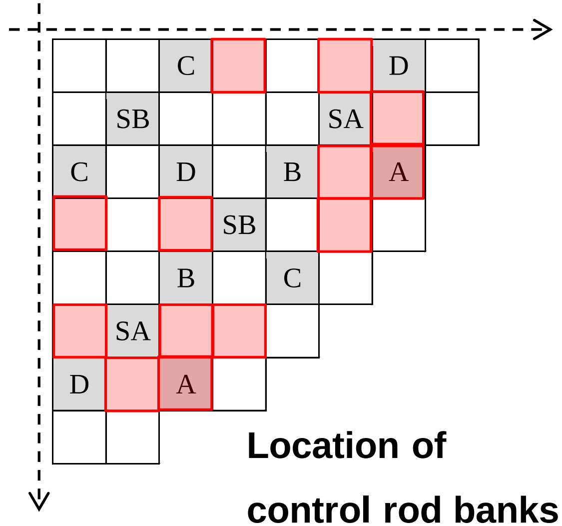
¼ CORE



1	13	4	21	6	21	16	14
13	11	15	2	16	6	20	7
4	15	3	21	8	22	19	
21	2	21	9	18	20	5	
6	16	8	18	12	17		
21	6	22	20	17			
16	20	19	10				
14	7						

🟥 **Fresh Fuel**

¼ CORE



		C				D	
	SB				SA		
C		D		B		A	
			SB				
		B		C			
	SA						
D		A					

Location of control rod banks

- **Note:** the worth of control bank rods are calculated at HZP/BOC using Rod Swap and boron dilution technique.

Table 4. Bank Worths (in Boron ppm) at HZP/BOC

	Conventional Clad			Cr Coated Clad			FeCrAl Clad			CSi Clad		
	UO2_3.6wo-Zr_0.5715mm			UO2_3.72wo-Cr_20microns			UO2_4.08wo-FeCrAl_80.80_13_6			UO2_3.79wo-CSi_78mm-dens_2.71		
Control rod Bank Worth (ppm)	**JEFF-3.3**	**ENDF/B-VIII.0**	Comparison	**JEFF-3.3**	**ENDF/B-VIII.0**	Comparison	**JEFF-3.3**	**ENDF/B-VIII.0**	Comparison	**JEFF-3.3**	**ENDF/B-VIII.0**	Comparison
BANK D-in	114	115	**-1**	116	116	**0**	114	115	**-1**	120	121	**-1**
BANK C-in	87	90	**-3**	86	89	**-3**	82	86	**-4**	85	88	**-3**
BANK B-in	135	135	**0**	138	137	**1**	137	137	**0**	144	144	**0**
BANK A-in	90	84	**6**	94	88	**6**	96	89	**7**	105	98	**7**
BANK SB-in	86	91	**-5**	85	90	**-5**	80	86	**-6**	83	88	**-5**
BANK SA-in	120	116	**4**	125	121	**4**	127	122	**5**	136	132	**4**
BANK D+C-in	221	226	**-5**	222	227	**-5**	216	221	**-5**	227	231	**-4**
BANK D+C+B-in	400	406	**-6**	403	409	**-6**	392	399	**-7**	415	421	**-6**
BANK D+C+B+A-in	542	539	**3**	550	547	**3**	544	541	**3**	573	569	**4**
BANK D+C+B+A+SA-in	664	668	**-4**	671	675	**-4**	656	659	**-3**	694	696	**-2**
ARI (all rods in)	884	887	**-3**	896	898	**-2**	880	882	**-2**	928	929	**-1**

9. Conclusions

Simulator

Ability to simulate different clad materials and designs, with coherent results.

Results

Great agreement between the different ATF materials and the conventional clad design.

10. References

- [1] **KG Geelhood and WG Luscher (2019)**, *Degradation and Failure Phenomena of Accident Tolerant Fuel Concepts.*
- [2] **F. Boylan et al (XXXX)**, *Evaluation of Coatings for Nuclear Fuel Rods for Improved Accident Tolerance.*
- [3] **Jefferson Lab**, U.S. Department of Energy, *The Element Chromium* https://education.jlab.org/itselemental/ele024.html
- [4] **I. M. Younker (2015)**, *Neutronic and economic evaluation of accident tolerant fuel concepts for light water reactors.*
- [5] **F. Fejt et al (2019)**, *Study on neutronics of VVER-1200 with accident tolerant fuel cladding.*
- [6] **T. Koyanagi et al (2018)**, *Handbook of LWR SiC/SiC Cladding Properties - Revision 1.*

Thank you very much!

¡Muchas gracias!

Merci beaucoup!

Clad Coatings
INGENIA UPM

Fe
Cr
Al

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SiC Group