# *PWR 3D-Core Simulation using different ATF fuels*

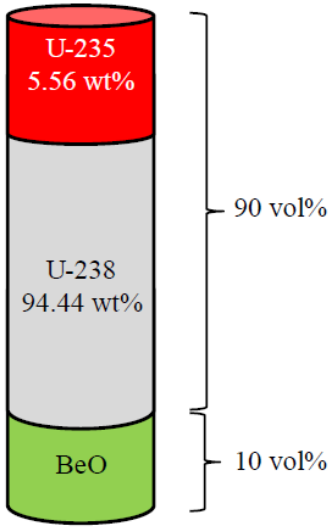
**M. Muñoz et al. (Grupo INGENIA 2019-2020)**
MASTER IN INDUSTRIAL ENGINEERING
E.T.S. de Ingenieros Industriales
Universidad Politécnica de Madrid (UPM), Madrid, Spain

**O. Cabellos**
Universidad Politécnica de Madrid (UPM), Madrid, Spain
E-mail: oscar.cabellos@upm.es

## ❑ ATF Fuels

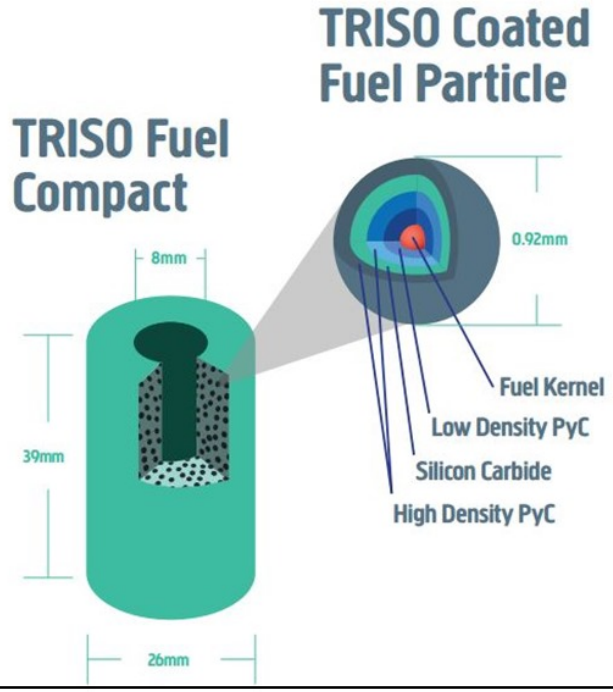
### $U_3Si_2$


### Doped-BeO




UBO 10vol%
Mass Equivalent

### TRISO



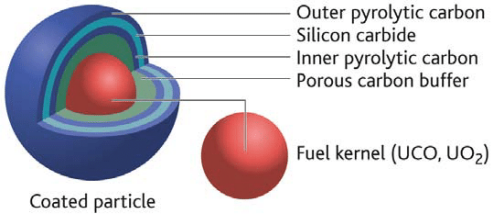

*Ref. Neutronbytes, "TRISO Fuel Drives Global Development of Advanced Reactors" (2017)*

*Ref. J. R. Smith, "Enhanced Thermal Conductivity $UO_2$-BeO Nuclear Fuel: Neutronic performance studies and economic analyses, MSc (2012)*

# ❑ Updates in SEANAP for TRISO

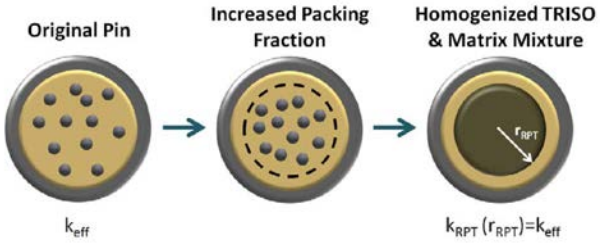
## ❑ Multi-coated TRISO fuel particles

- o Double-heterogeneity arises from the distribution of TRISO particles within the graphite matrix
- o The packing or volume factor




## ❑ Methodology Reactivity-equivalent Physical Transformation (RPT) Pin Cell

The RPT model creates a single-heterogeneous problem out of double-heterogeneous one



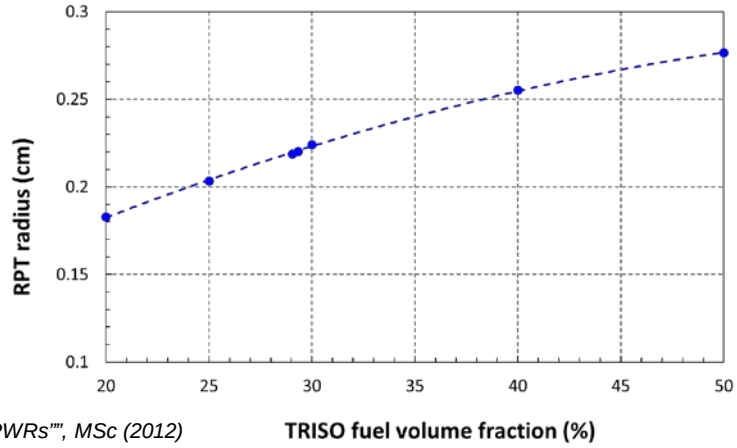

### ❑ RPT method of fuel zone homogenization

- o TRISO particles are condensed in the center of the fuel zone
- o Then, CSi and TRISOs are homogenized into a single mixture

### ❑ Calculation of RPT Radius.

- o SCALE/KENO …. PWR Pin-cell with TRISO UO2/wo-VF%
- o WIMSD5 …… equivalent pin-cell (densities,….)

**Figure 1.** RPT radius TRISO/Csi-UO2-20.0%wt




*Ref. Steven T. Lynch, "Reactivity-Equivalent Physical Transformation Model for Pin Cell Arrays", MSc (2010)*

*Ref. C.A. Gentry, "An investigation of the use of Ceramic Microencapsulated Fuel for Transuranic Waste Recycling in PWRs"", MSc (2012)*

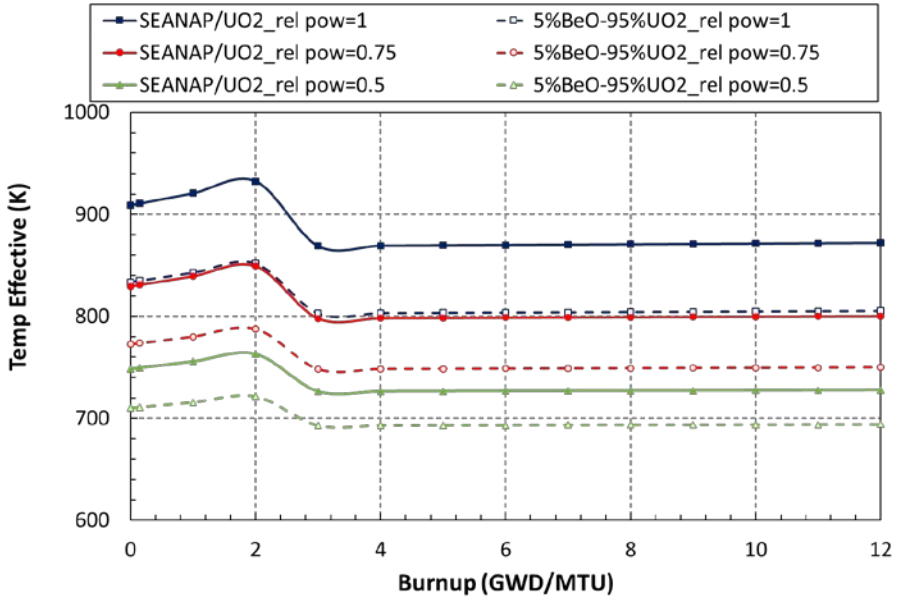
# ❑ Updates in SEANAP for ATF Fuel

- **The "Effective" fuel-temperature**
  - Assumption in Lattice code: the temperature profile across a fuel pin is spatially flat
  - Then, we need an "effective Doppler temperature". This value can be calculated using different approaches such that the Doppler feedback is properly accounted for
  - For instance, the "NEA"' effective fuel temperature: $T_{NEA}=0.7\cdot T_S+0.3\cdot T_C$

    $T_S$= temperature pellet surface

    $T_C$= temperature pin center-line
  - **$T_{eff}=f$(fuel, relative power, burnup)**

**Figure 2.** Teff as a function of burnup




Adjusted Teff value for Doped-BeO is based on temperature profiles of this work:

*Ref. J. R. Smith, "Enhanced Thermal Conductivity $UO_2$-BeO Nuclear Fuel: Neutronic performance studies and economic analyses, MSc (2012)*

# ❑ Modelisation of ATF Fuels: %wt enrich. for "equivalent cycle"

❑ **TRISO ATFs**

- o 84 FCM (CSi-UO2-5%wo-80%VF) fuel rods loaded on the periphery of the fuel assembly
- o 180 remaining fuel of enriched UO2 fuel rods

❑ **$U_3Si_2$ and Doped (UO2-BeO) ATFs**

- o 264 fuel rods

**Figure 3.** CORAIL type-fuel assembly

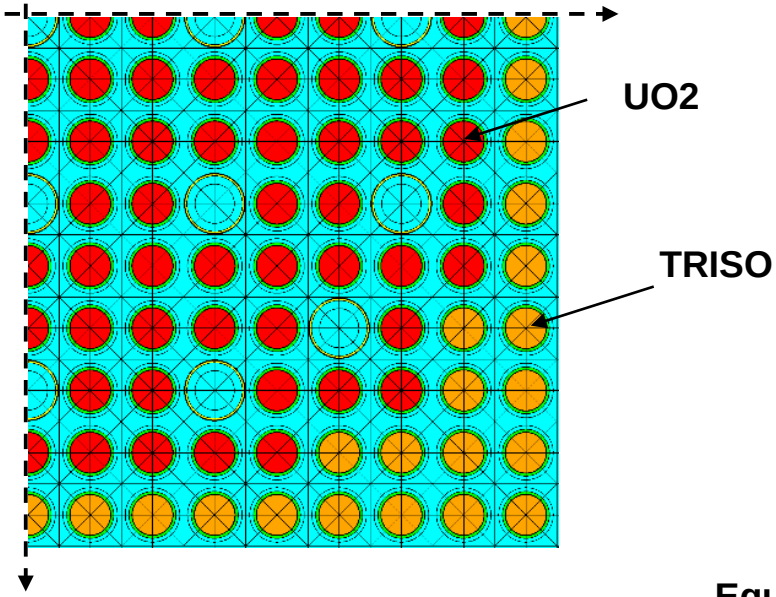
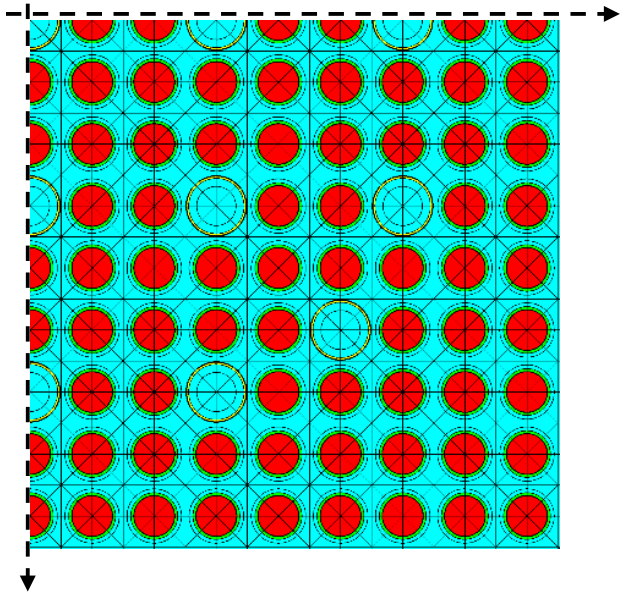



**Figure 4.** MIX type-fuel.



**Equivalent Enrichment ?**

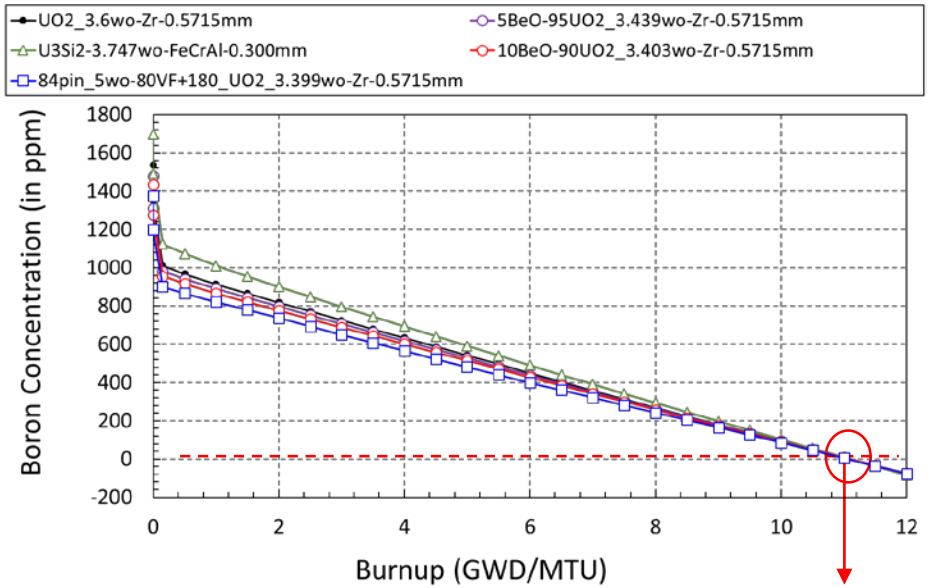
*Ref. C.A. Gentry, "An investigation of the use of Ceramic Microencapsulated Fuel for Transuranic Waste Recycling in PWRs"", MSc (2012)*

# The "equivalent cycle" length as UO2 fuel

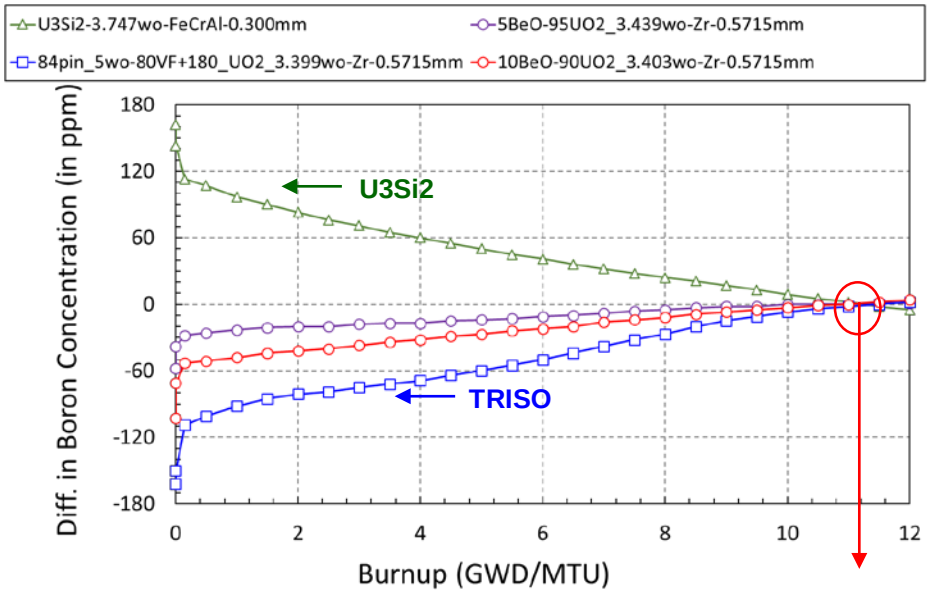
- **Core average burnup analysis with "equivalent cycle length "**

**Table 1.** Enrichment for each technology

| | $UO_2$-Zr | $U_3Si_2$-FeCrAl | TRISO-Zr | 5% BeO + 95% $UO_2$-Zr | 10% BeO + 90% $UO_2$-Zr |
|---|---|---|---|---|---|
| **Enrichment (% wo)** | 3.60 | 3.75 | 3. 40 | 3.44 | 3.40 |




**Cycle length ~ 11.08 GWD/MTU**




**Cycle length ~ 11.08 GWD/MTU**

# Axial Offset for the Cycle Depletion

## Axial Offset

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

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

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

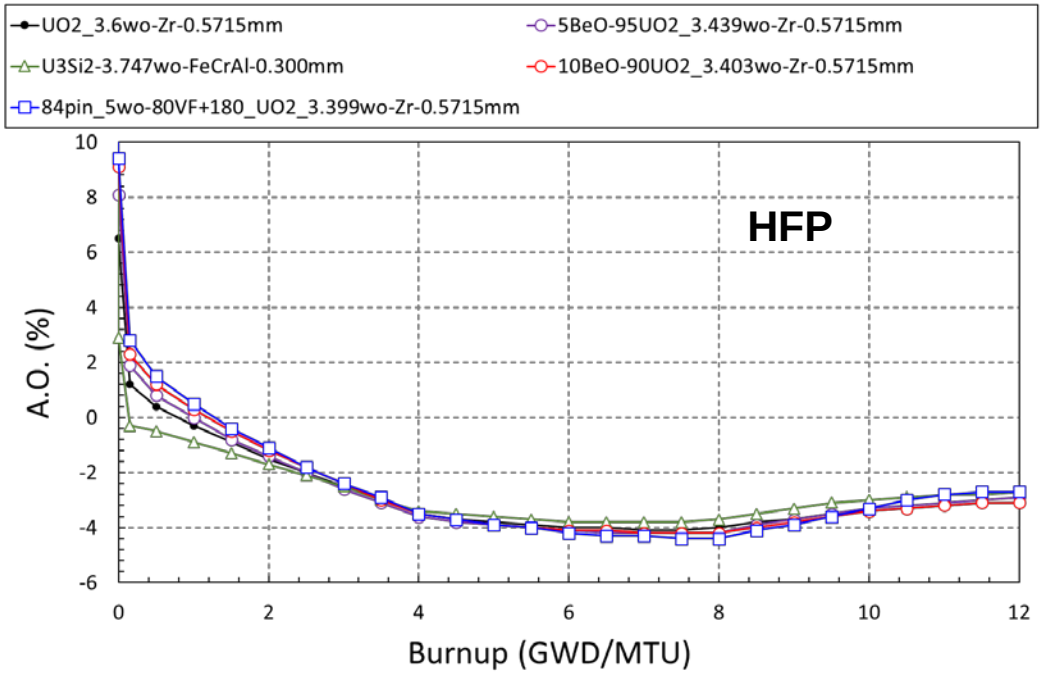



**Table 2.** A.O.(%) at BOC/HZP

| Case | A.O. (%) BOC/HZP |
|---|---|
| UO2/3.60wo – Zr/0.5715mm | 33.9 |
| U3Si2/3.747wo – FeCrAl-300μm | 29.2 |
| 95%UO2/3.439wo+5%BeO – Zr/0.5715mm | 36.2 |
| 90%UO2/3.403wo+10%BeO – Zr/0.5715mm | 37.8 |
| TRISO – Zr/0.5715mm<br>84FCM: 5%wo-80%VF<br>180UO2: 3.4wo | 40.0 |

# Peaking Factors

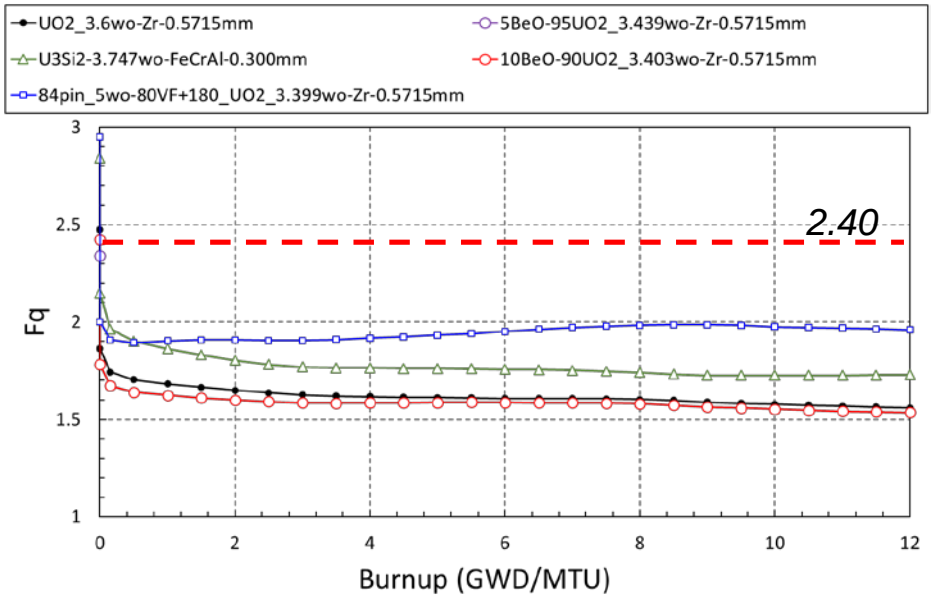
## Heat flux hot channel factor ($F_Q$)

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

LHGR is Linear Heat Generation Rate (W/cm)

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

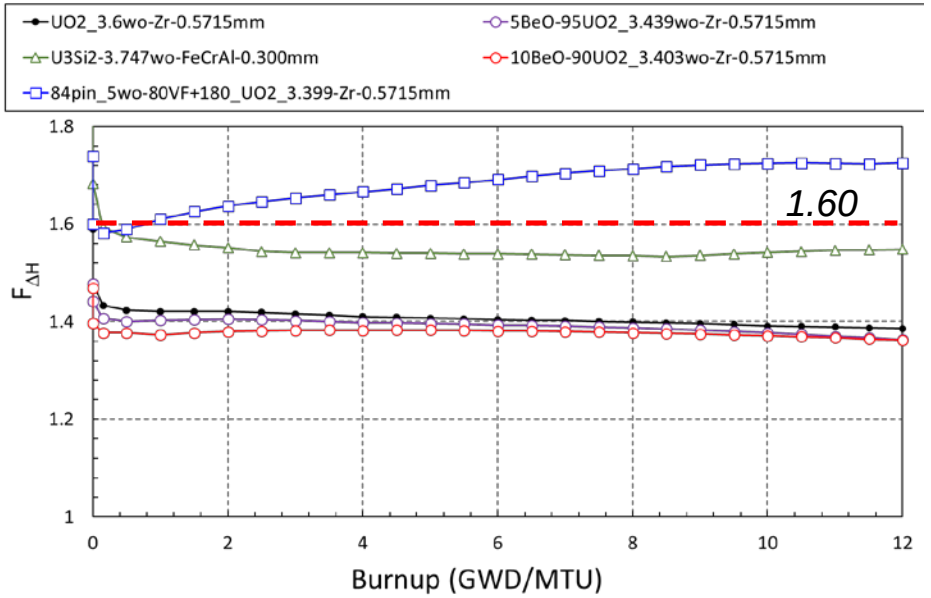
*Design Limit: $F_Q \cdot P < F_Q^{max} = 2.40$*




## Enthalpy Peaking factor ($F_{\Delta H}$)

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

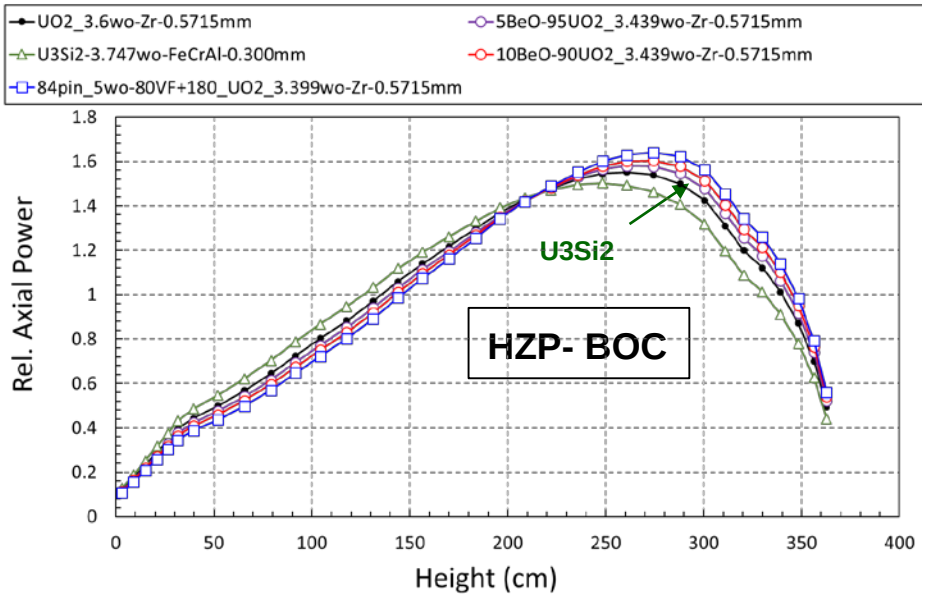
*Design Limit: $F_{\Delta H} < F_{\Delta H}^{max} \approx 1.60 \cdot [1+0.3(1-P)]$*

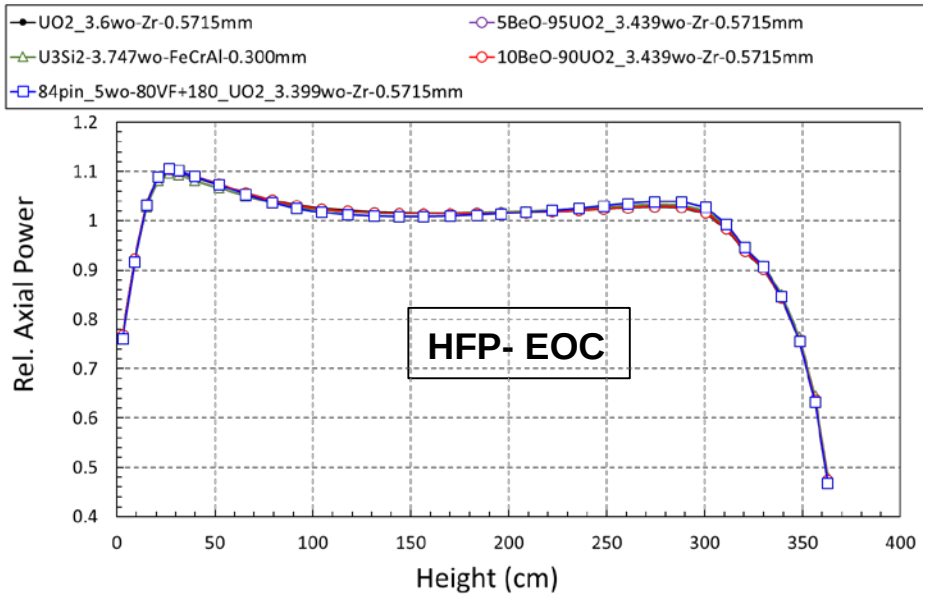


# Axial power distribution

## 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 ….
  - UO2/Zr ⇒ A.O.(%) = **33.9%**
  - U3Si2 ⇒ A.O.(%) = **29.2%**
  - TRISO ⇒ A.O.(%) = **40.0%**
- At EOC, the axial power becomes flattened



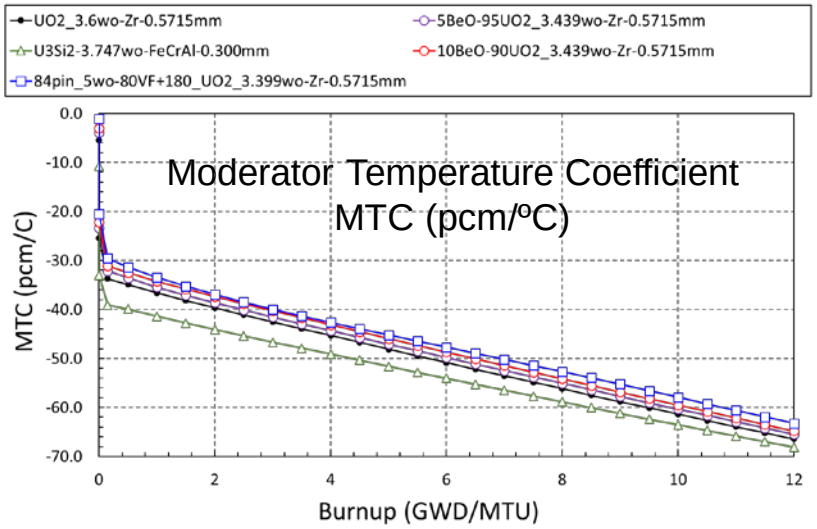



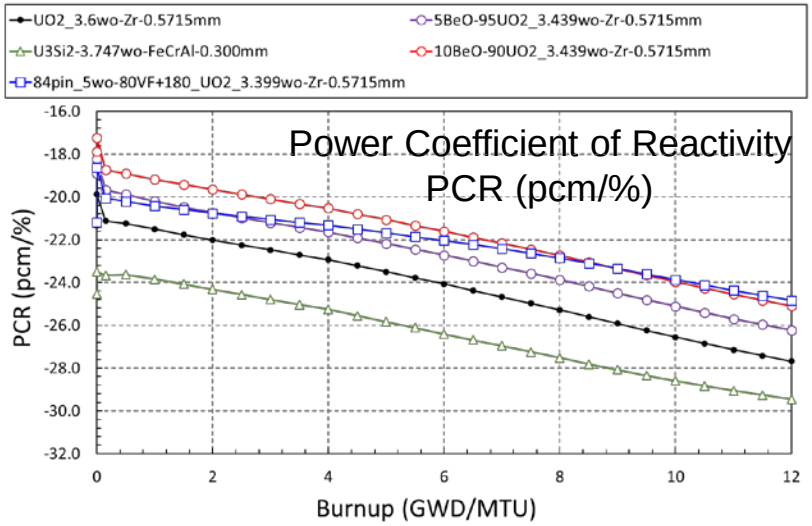
# ❑ Reactivity Coefficients

*VALBOR* = *Boron worth coefficient*
*MTC* = *Moderator temperature coefficient*
*DOP* = *Power coefficient of reactivity (only Doppler)*
*FTC* = *Fuel temperature coefficient*
*PCR* = *Power coefficient of reactivity*

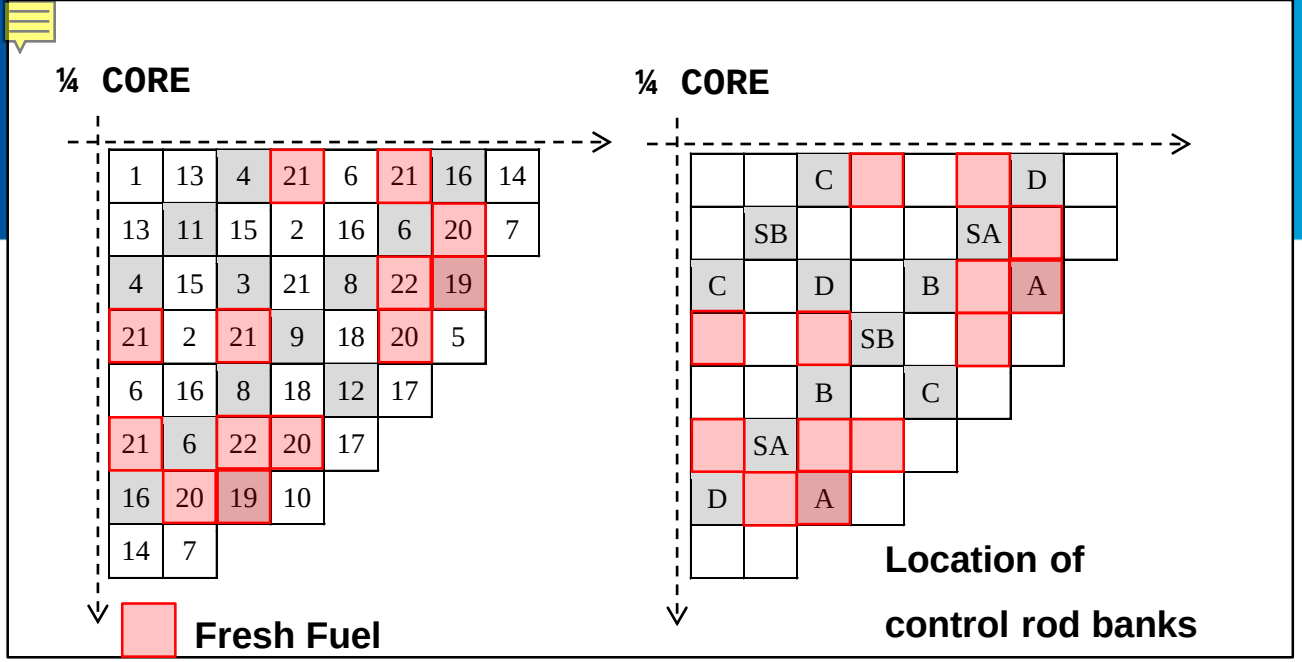
**Table 3.** Reactivity coefficients at BOC/HZP

| Reactivity Coefficients at BOC/HZP | Boron Worth (pcm/ppm) | MTC (pcm/ºC) | FTC (pcm/ºC) | CISO (pcm/ºC) | DOP (pcm/%) | PCR (pcm/%) |
|---|---|---|---|---|---|---|
| UO2/3.60wo – Zr/0.5715mm | -8.3 | -5.5 | -5.1 | -10.5 | -16.0 | -21.3 |
| U3Si2/3.747wo – FeCrAl-300μm | -7.3 | -10.8 | -5.1 | -15.9 | -15.4 | -24.6 |
| 95%UO2/3.439wo+5%BeO – Zr/0.5715mm | -8.6 | -3.9 | -5.1 | -9.1 | -14.4 | -18.9 |
| 90%UO2/3.403wo+10%BeO – Zr/0.5715mm | -8.8 | -3.0 | -5.3 | -8.3 | -13.8 | -17.9 |
| TRISO – Zr/0.5715mm<br>84FCM: 5%wo-80%VF<br>180UO2: 3.4wo | -9.1 | -1.0 | -5.7 | -6.8 | -17.6 | -21.2 |



# ❑ Bank Worths




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

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

| Control rod bank worth (in ppm) | UO2 3.6wo | U3Si2 3.747wo | 95%UO2_3.439wo +5%BeO | 90%UO2_3.403wo +10%BeO | TRISO 84FCM: 5%wo-80%VF 180UO2: 3.4wo |
|---|---|---|---|---|---|
| | Zr-0.5715mm | FeCrAl-300mm | Zr-0.5715mm | Zr-0.5715mm | Zr-0.5715mm |
| BANK D-in | 114 | 118 | 111 | 109 | 106 |
| BANK C-in | 87 | 80 | 96 | 102 | 107 |
| BANK B-in | 135 | 143 | 127 | 120 | 110 |
| BANK A-in | 90 | 106 | 71 | 62 | 51 |
| BANk SB-in | 86 | 78 | 98 | 106 | 113 |
| BANK SA-in | 120 | 138 | 102 | 92 | 80 |
| BANK D+C-in | 221 | 220 | 228 | 231 | 232 |
| BANK D+C+B-in | 400 | 403 | 403 | 402 | 396 |
| BANK D+C+B+A-in | 542 | 565 | 517 | 502 | 481 |
| BANK D+C+B+A+SA-in | 664 | 674 | 657 | 653 | 637 |
| ARI (all rods in) | 884 | 910 | 865 | 854 | 829 |

# ❑ Impact of nuclear data evaluations

- **Core average burnup analysis with "equivalent cycle length "**
  - Impact nuclear data: JEFF-3.3, JEFF-3.1, JEF-2.2, ENDF/B-VII.1 and ENDF/B-VIII.0

**Table 5.** Value of wt% for the ATF to maintain an "equivalent cycle" length as UO2/3.6wo fuel

| Nuclear Data Evaluations | U3Si2 | 95%UO2+5%BeO | 90%UO2+10%BeO | TRISO 84rods 5%wo-80%VF |
|---|---|---|---|---|
| | FeCrAl-300μm | Zr-0.5715mm | Zr-0.5715mm | Zr-0.5715mm |
| JEFF-3.3 | 3.75 | 3.44 | 3.40 | 3.40 |
| JEFF-3.1 | 3.75 | 3.43 | 3.39 | 3.38 |
| JEF-2.2 | 3.76 | **3.47** | **3.47** | 3.39 |
| ENDF/B-VII.1 | 3.76 | 3.44 | 3.40 | 3.41 |
| ENDF/B-VIII.0 | 3.76 | 3.44 | 3.40 | 3.40 |

# ❑ Summary

## ❑ Conclusions

- **ATFs may get simulated in SEANAP**
  - an updated Teff correlation will be needed
- **TRISO must be specially adapted to get simulated**
  - an optimal layout must be found to make it suitable in our simulation
- **General speaking …. good performance for doped fuels, uranium silicide and TRISO**

- **Assessing the impact of nuclear data**
  - ND Evaluations: JEFF-3.3, JEFF-3.1, JEF-2.2, ENDF/B-VII.1 and ENDF/B-VIII.0
  - low differences are found searching the %wt for the “equivalent cycle”
  - slightly differences were found in JEF-2.2 due to Be nuclear data?
  - other core parameters to be investigated: power distributions, etc…
  - impact of new nuclear data: new Thermal Scattering Laws for graphite in TRISO?