Neutronics Benchmark of CEFR Start-up Tests:
Temperature Coefficient, Sodium Void Worth, and Swap Reactivity

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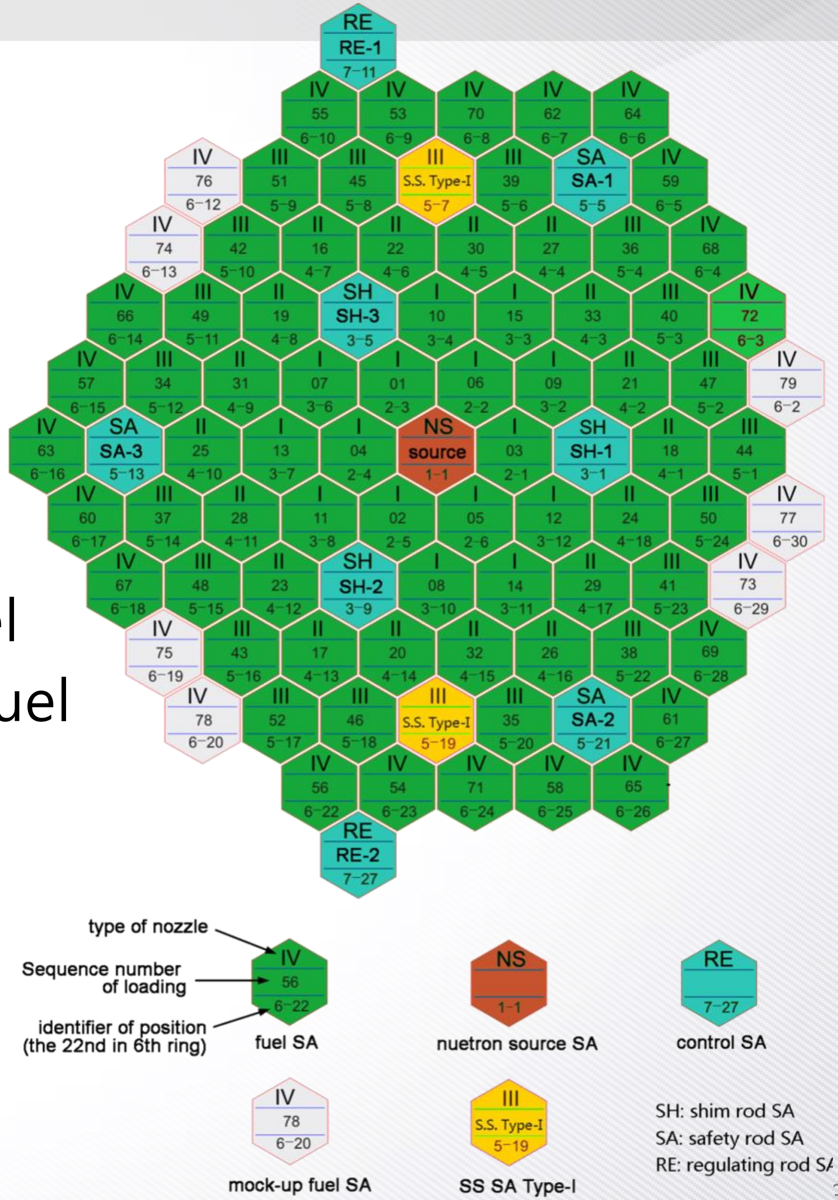
CEFR Start-up Test

- **China Experimental Fast Reactor (CEFR)**
  - 20 MW(e) Sodium Cooled Fast Reactor
  - Start-up tests from 2010 to 2011
    - Criticality, control rod worth, temperature coefficient, void reactivity, subassembly swap reactivity, reaction rates
- **Key specifications**
  - Fuel region of 450 mm with 64.4 wt.% ^{235}U of UO_2 fuel
  - Blanket region of 350 mm with 0.3 wt.% ^{235}U of UO_2 fuel
  - B_4C with different ^{10}B enrichment
    - Boron shielding subassemblies
    - Control rod subassemblies: regulating, shim and safety

The layout of the core loading operation



Participants with Stochastic Codes

- **20 Organizations**
- **16 Codes**
- **13 XS libs**

Country	Organization	Cross-section	Simulation Code
Belgium	SCK-CEN	ENDF/B-VII.1	OpenMC-0.10.0
China	CIAE	ENDF/B-VIII.0	RMC
China	INEST	HENDL3.0	SuperMC
Finland	VTT	ENDF-B/VII.0, JEFF 3.1.2	Serpent 2.1.31
France	CEA	JEFF 3.1.1	TRIPOLI4
Germany	HZDR	JEFF 3.1, JEFF 3.3, ENDF/B-VII.1, ENDF/B-VIII.0	Serpent 2.1.31
Germany	GRS	ENDF/B-VII.1	Serpent
Hungary	CER	ENDF/B-VIII.0	Serpent 2.1.31
IAEA	IAEA	ENDF/B-VII.1	OpenMC, Serpent 2.1.27
India	IGCAR	ENDF/B-VIII.0, JEFF 3.3, JENDL-4.0, ROSFOND 2010, CENDL 3, TENDL 2017	OpenMC-0.10.0
Italy	NINE-UNIPI	ENDF/B-VIII.0	Serpent 2.1.31
Japan	JAEA	JENDL-4.0	MVP-II
Korea	KAERI	ENDF/B-VII.1	McCARD 1.0
Korea	UNIST	ENDF/B-VII.1	MCS
Mexico	ININ	ENDF/B-VIII.0	Serpent 2.1.30
Romania	RATEN	ENDF/B-VIII.0	Serpent 2.1.31, MCNP6.1
Russian Federation	IPPE	ROSFOND10+	MMKC
Russian Federation	NRCKI	JEFF 3.3	Serpent 2.31, MCNP
Slovakia	VUJE	ENDF/B-VII.1	Serpent 2.1.31
USA	NRC	ENDF/B-VII.1	Serpent 2.1.30

Participants with Deterministic Codes

- **17 Organizations**
- **15 Codes**
- **12 XS libs**

Country	Organization	Cross-section	Simulation Code (Lattice/Nodal)
China	CIAE	ENDF/B-VIII.0	PASC/NAS
China	XJTU	ENDF/B-VII.0	SARAX (TULIP v1.5/LAVENDER v1.5)
France	CEA	JEFF 3.1, JEFF 3.1.1	ECCO/ ERANOS, APOLLO3
Germany	GRS	ENDF/B-VII.0	Serpent 2.1.31/FENNECS
Germany	KIT	JEFF 3.1	ECCO/VARIANT
Hungary	CER	ENDF/B-VIII.0	Serpent 2.1.31/KIKO3DMG
India	IGCAR	ABBN-93, ERALIB-1 JEF-2.2	FARCOB/ERANOS
Japan	JAEA	JENDL-4.0	SLAROM-UF/DIF3D10.0/PARTISN5.97
Korea	KAERI	ENDF/B-VII.0	MC2-3/DIF3D-VARIANT11.0
Korea	UNIST	ENDF/B-VII.1	MCS/RAST-K
Mexico	ININ	ENDF/B-VIII.0	Serpent2.1.31/AZNHEX
Russian Federation	NRCKI	ABBN-93	JARFR
Swiss	PSI	JEFF 3.1.1	Serpent 2/PARCS v27
UK	UoC	JEFF 3.1.2	WIMS 11
USA	ANL	ENDF/B-VII.0	MC2-3/DIF3D
Russian Federation	SSL	ENDF/B-VII.0	DYNCO/DYNCO
Ukraine	KIPT	BNAB-76	FANTENS-2 (2D code)

How to get reactivity worth?

- **Following Experimental Process**

$$\rho_w = \sum_{i=1}^{N} \rho_{rod}^{i} + \left(\frac{1}{k_o} - \frac{1}{k_p}\right) \times 10^5 \; [pcm] \quad (1)$$

ρ_w = reactivity worth (w= temperature, sodium void, or swap reactivity)
N = the number of control rod used in the measurement
ρ_{rod}^{i} = control rod worth of i bank
k_o = measured k_{eff} before perturbation
k_p = measured k_{eff} after perturbation,
i.e., changing temperature, replacing by sodium void fuel SA, or swapped SA

Temperature Coefficient

Core states at temperature coefficients

Process	Temp. [℃]	Control rod positions [mm]				
		RE1	RE2	SH1	SH2	SH3
Increasing	250	207.2	207.7	247.9	247.7	248.0
	275	212.3	212.9	253.6	253.1	253.8
	283	239.7	239.3	253.4	253.1	254.0
	293	282.8	283.4	253.4	253.0	253.7
	302	307.5	307.0	254.7	254.6	255.9
Decreasing	300	407.7	408.5	501.5	162.3	162.2
	290	283.4	283.8	254.0	253.7	254.4
	281	285.2	284.6	502.0	162.2	162.2
	270	232.4	232.2	501.9	162.2	162.2
	250	118.5	118.9	501.8	162.2	163.0

Calculation Approaches

1. Experimental

$$\rho_w = \sum_{i=1}^{N} \rho_{rod}^{i} + \left(\frac{1}{k_o} - \frac{1}{k_p}\right) \times 10^5 \, [pcm] \qquad (1)$$

- Calculation according to the experiment
- CR reactivity correction should be performed according to the integral rod worth

2. Fixed

$$\rho_w = \left(\frac{1}{k_o} - \frac{1}{k_p}\right) \times 10^5 \, [pcm] \qquad (3)$$

1. Calculation with fixed control rod positions

3. 3-step

$$\rho_w = \rho_{rod_A}^{T_B} + \left(\frac{1}{k_A} - \frac{1}{k_B}\right) \times 10^5 \, [pcm] \qquad (2)$$

- Summation of three reactivities;
  1. Reactivity with the temperature and rod position at the A state
  2. Reactivity with the temperature at the B state and rod position at the A state
  3. Reactivity with the temperature and rod position at the B state

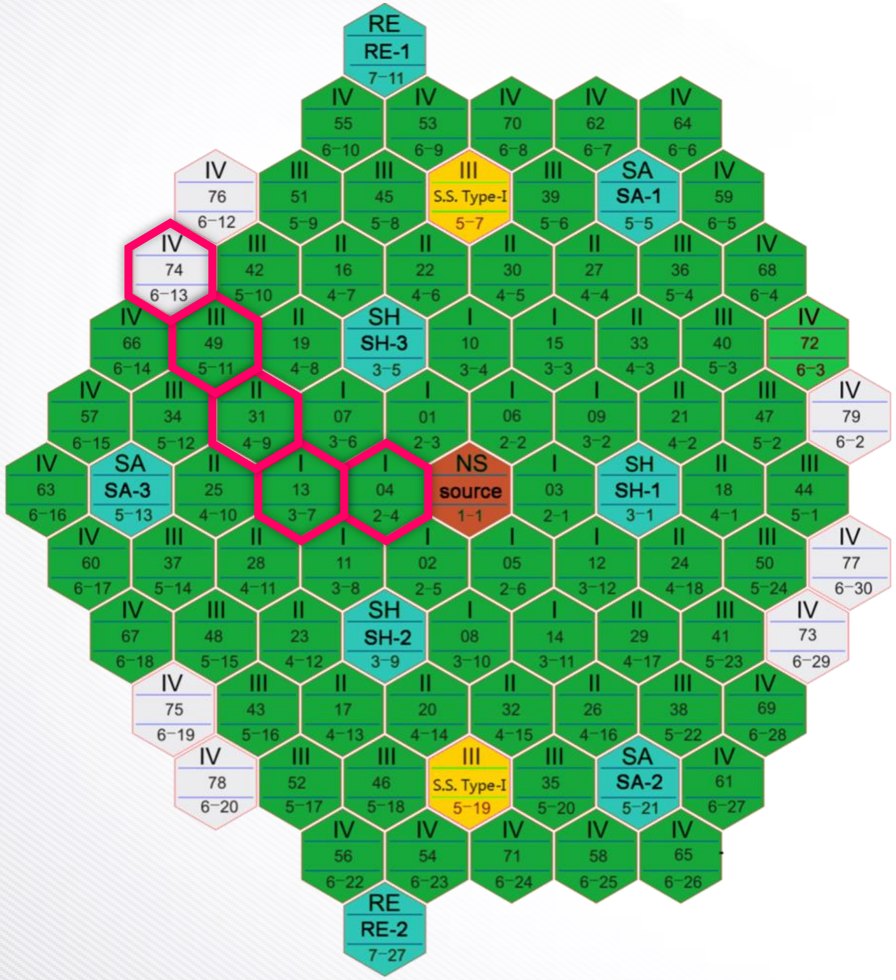
Temperature Coefficient

- **Mean value of temperature coefficients [pcm/K]**

Calculation Way	Process	Measurement	Mean value	Stochastic	Deterministic
Experimental	Increasing	-3.76±0.51	-3.95±0.31	-3.40±1.05	-4.20±0.72
	Decreasing	-4.38±0.61	-3.85±0.57	-3.43±1.09	-4.29±0.72
3-step method	Increasing	-3.76±0.51	-3.91±0.42	-3.64±0.27	-4.10±0.60
	Decreasing	-4.38±0.61	-3.97±0.46	-3.27±0.46	-4.16±0.93

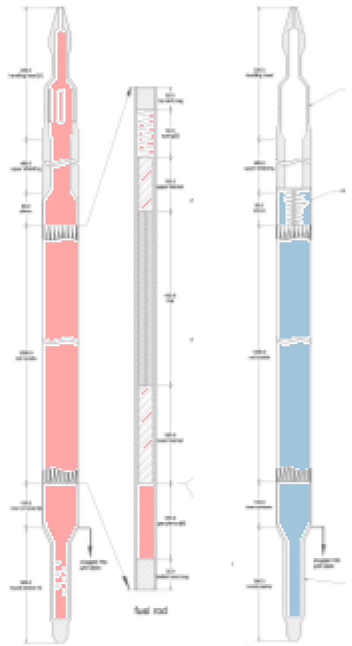
Sodium Void Reactivity

Location to measure SVR



Calculation Approaches

1. Get k-eff at the critical state
2. Replacing fuel SA as sodium void fuel SA
3. Change control rod position to reach critical
4. Get k-eff at the critical state again



Fuel SA

Sodium void fuel SA

sodium   vacuum

Measurement position in core		Control rod positions [mm]							
		RE1	RE2	SH1	SH2	SH3	SA1	SA2	SA3
(2-4)	Original	278	277						
	Voided	337	337						
(3-7)	Original	278	277						
	Voided	338	338						
(4-9)	Original	278	278	239	239	240	498	500	499
	Voided	338	338						
(5-11)	Original	278	276						
	Voided	338	338						
(6-13)	Original	303	303						
	Voided	338	338						

Sodium Void Reactivity

- **Mean value of sodium void worth [pcm]**

Position	Case1: (2-4)	Case2: (3-7)	Case3: (4-9)	Case4: (5-11)	Case5: (6-13)
Experimental	-39±6	-43±6	-41±6	-40±6	-33±6
Deterministic	-31.6	-36.4	-34.1	-34.3	-27.6
Stochastic	-32.2	-37.4	-36.1	-36.2	-27.3

Subassembly Swap Reactivity

Location to measure SVR

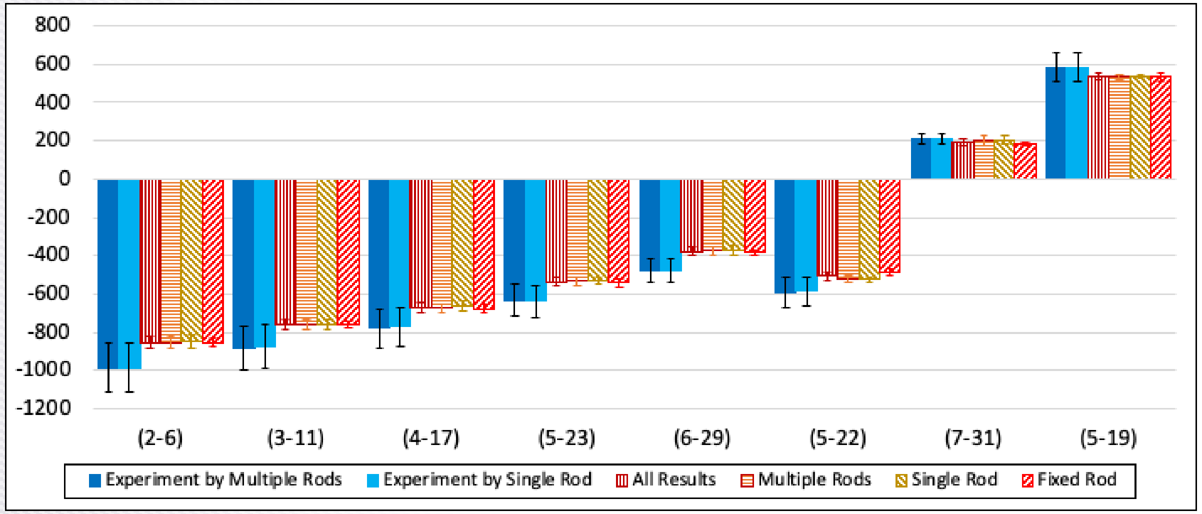
Calculation Approaches

1. Get k-eff at the critical state
2. Swap subassemblies
    1. Fuel SA to SS SA or SS SA to fuel SA
3. Change control rod position to reach critical
    1. Multiple rods movement
    2. Single rod movement
    3. Fixed rod
4. Get k-eff at the critical state again

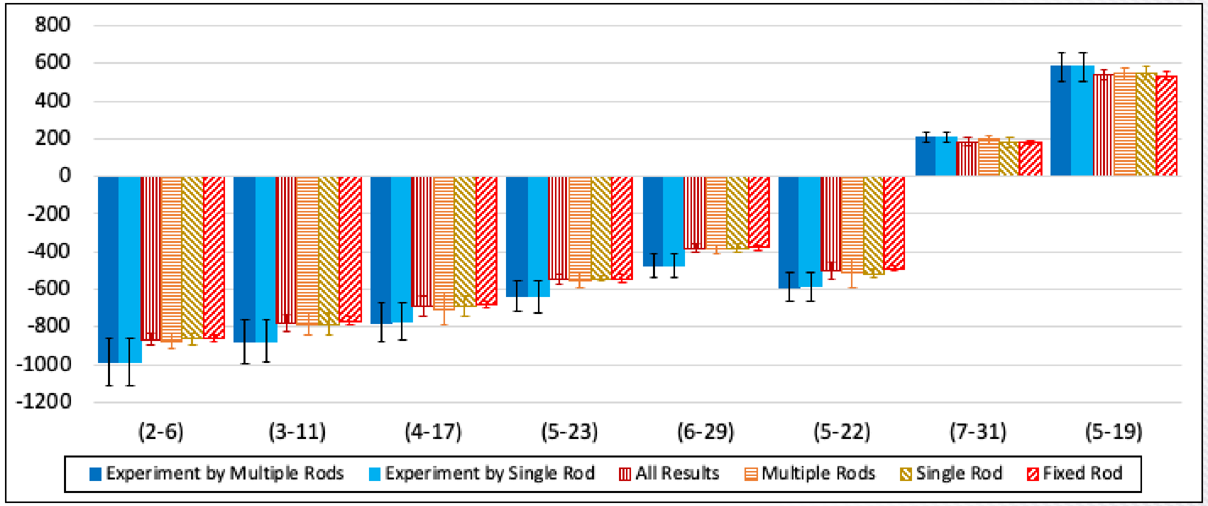
Measured Position	SAs Loaded After Swap							
	(2-6)	(3-11)	(4-17)	(5-23)	(6-29)	(5-22)	(7-31)	(5-19)
(2-6)	SS	Fuel	Fuel	Fuel	Fuel	Fuel	SS	SS
(3-11)	Fuel	SS	Fuel	Fuel	Fuel	Fuel	SS	SS
(4-17)	Fuel	Fuel	SS	Fuel	Fuel	Fuel	SS	SS
(5-23)	Fuel	Fuel	Fuel	SS	Fuel	Fuel	SS	SS
(6-29)	Fuel	Fuel	Fuel	Fuel	SS	Fuel	SS	SS
(5-22)	Fuel	Fuel	Fuel	Fuel	Fuel	SS	SS	SS
(7-31)	Fuel	Fuel	Fuel	Fuel	SS	Fuel	Fuel	SS
(5-19)	Fuel	Fuel	Fuel	SS	Fuel	Fuel	SS	Fuel

Subassembly Swap Reactivity

Average Calculation Results (Deterministic)



Average Calculation Results (Stochastic)



Conclusions

- Compilation results of the IAEA coordinated research project (CRP) on "Neutronics Benchmark of CEFR Start-Up Tests“ has been introduced

- 29 participating research organizations with
  16 deterministic codes, 15 stochastic codes, 16 cross-section libraries

- Reactivity coefficients are in good agreement with the experimental data mostly, but the absolute mean value of the calculated results is lower than in the experiment

References and Acknowlegements

- **References**

[1] HUO, X., HU, Y., CHEN, X., XU, L., ZHANG, J., CHEN X., CAO, P., LIU, X., ZHU, Q., GUO, M., DUAN, T., Technical Specifications for Neutronics Benchmark of CEFR Start-Up Tests (CRP-I31032), Presentation at 2nd RCM of the IAEA CRP I31032 in China Institute of Atomic Energy, Beijing, 2019.

[2] **INTERNATIONAL ATOMIC ENERGY AGENCY, Neutronics Benchmark of CEFR Start-Up Tests, IAEA-TECDOC-TBD, IAEA, Vienna, 2022.**

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Thank you very much