# Verification and validation of neutronic codes using the start-up fuel load and criticality tests performed in the CEFR

## FR22: Sustainable Clean Energy for the Future


Armando Gomez, Roberto Lopez, Juan Galicia, et al.

Instituto Nacional de Investigaciones Nucleares
armando.gomez@inin.gob.mx


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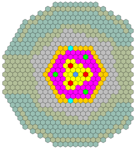
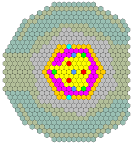
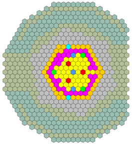
# Experiment description: prior criticality steps



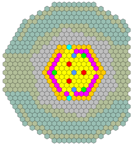
**Step 1: 24 F-SA**



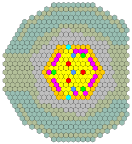
**Step 2: 40 F-SA**



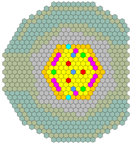
**Step 3: 46 F-SA**



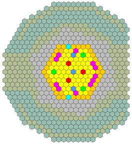
**Step 4: 55 F-SA**



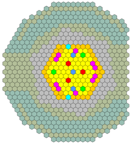
**Step 5: 61 F-SA**



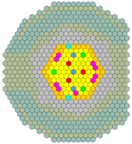
**Step 6: 65 F-SA**



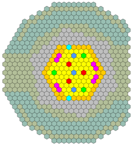
**Step 7: 68 F-SA**



**Step 8: 69 F-SA**

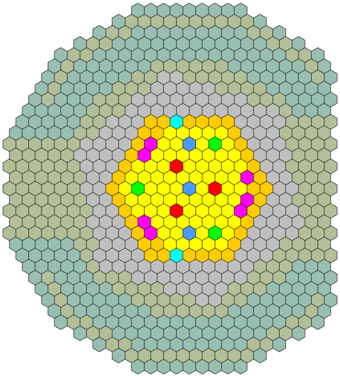


**Step 9: 70 F-SA**



**Step 10: 71 F-SA**

# Experiment description: critical core



- Sodium temperature of 245°$C$
- 72 F-SA loaded,
- Steps 11 to 13 were supercritical with only one of the regulating rods (RE2) inserted respectively at 190 mm, 170 mm, 151 mm.
- Criticality state reached at RE2 inserted at position 70 mm.
- 3 dedicated start-up detectors located near the active core were used to get the counting rate for the criticality approaching process.

# Expected output: net criticality

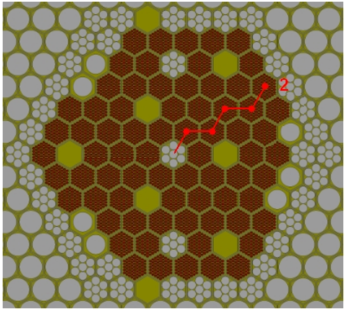
| No. of Fuel SA's loaded | Rod position/mm | | Core state | Expected output |
|---|---|---|---|---|
| | Other 7 CR's | RE2 | | |
| 70 | Out-of-core | Out-of-core | Subcritical | $k_{eff}$ |
| 71 | Out-of-core | Out-of-core | End of subcritical process | $k_{eff}$ |
| 72 | Out-of-core | 190 | Supercritical | $k_{eff}$ |
| 72 | Out-of-core | 170 | Supercritical | $k_{eff}$ |
| 72 | Out-of-core | 151 | Supercritical | $k_{eff}$ |
| 72 | Out-of-core | 70 | Critical (predicted) | $k_{eff}$ |

# Optional output

Steps to criticality

| No. of Fuel SA's loaded | Rod position/mm | | Core state | Expected output |
|---|---|---|---|---|
| | Other 7 CR's | RE2 | | |
| 24 | Out-of-core | Out-of-core | Subcritical | $k_{eff}$ |
| 40[a] | Out-of-core | Out-of-core | Subcritical | $k_{eff}$ |
| 46 | Out-of-core | Out-of-core | Subcritical | $k_{eff}$ |
| 55 | Out-of-core | Out-of-core | Subcritical | $k_{eff}$ |
| 61 | Out-of-core | Out-of-core | Subcritical | $k_{eff}$ |
| 65 | Out-of-core | Out-of-core | Subcritical | $k_{eff}$ |
| 68 | Out-of-core | Out-of-core | Subcritical | $k_{eff}$ |
| 69 | Out-of-core | Out-of-core | Subcritical | $k_{eff}$ |
| 70 | Out-of-core | Out-of-core | Subcritical | $k_{eff}$ |

Normalized power path



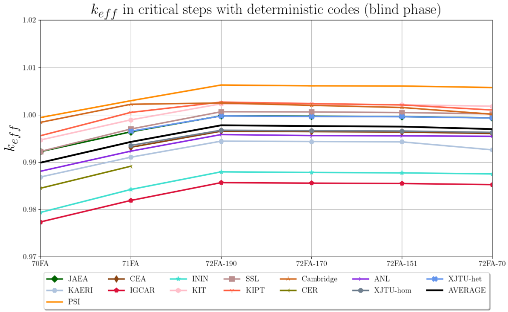
## Deterministic (17 participants)

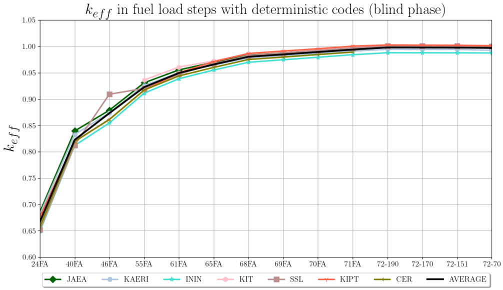
| Country | Institute | XS | Nodal Code | Lattice Code |
|---|---|---|---|---|
| China | **CIAE**: China Institute of Atomic Energy | ENDFB/VIII.0 | NAS | PASC |
| China | **XJTU**: Xi'an Jiaotong University | ENDF/B-VII.0 | SARAX-LAVENDER v1.5 | SARAX-TULIP v1.5 |
| France | **CEA**: Commissariat à l'Énergie Atomique | JEFF 3.1, JEFF 3.1.1 | ERANOS, APOLLO3 | ERANOS, APOLLO3 |
| Germany | **GRS**: Gesellschaft für Anlagen- und Reaktorsicherheit | ENDF/B-VII.0 | FENNECS | Serpent 2.1.31 |
| Germany | **KIT**: Karlsruhe Institute of Technology | JEFF.3.1 | VARIANT | ECCO |
| Hungary | **CER**: Centre for Energy Research | ENDFB/VIII.0 | KIKO3DMG | Serpent 2.1.31 |
| India | **IGCAR**: Indira Gandhi Centre for Atomic Research | ABBN-93, ERALIB-1 JEF-2.2 | FARCOB, ERANOS | FARCOB, ERANOS |
| Japan | **JAEA**: Japan Atomic Energy Agency | JENDL-4.0 | DIF3D10.0/PARTI SN5.97 | SLAROM-UF |
| Korea | **KAERI**: Korea Atomic Energy Research Institute | ENDF/B-V.II.0 | DIF3D-VARIANT 11.0 | MC2-3 |
| Korea | **UNIST**: Ulsan National Institute of Science and Technology | ENDF/B-VII.1 | RAST-K | MCS |
| Mexico | **ININ**: Instituto Nacional de Investigaciones Nucleares | ENDFB/VIII.0 | AZNHEX (SPL) | Serpent 2.1.31 |
| Russia | **NRCKI**: National Research Center: Kurchatov Institute | ABBN-93 | JARFR | JARFR |
| Russia | **SSL:** Simulation Systems Ltd. | ENDFB/VII | DYNCO | WIMSD4 |
| Switzerland | **PSI**: Paul Scherrer Institut | JEFF 3.1.1 | PARCS v27 | Serpent 2.1.30 |
| UK | **UoC**: University of Cambridge | JEFF3.1.2 | WIMS 11 | WIMS 11 |
| Ukraine | **KIPT**: Kharkov Institute of Physics & Technology | BNAB-76 | FANTENS-2 | |
| USA | **ANL**: Argonne National Laboratory | ENDF-B/VII.0 | MCC-3, DIF3D | MCC-3 |

## Stochastic (20 participants)

| Country | Institute | XS | Code |
|---|---|---|---|
| Belgium | **SCK-CEN**: Belgian nuclear research centre | ENDF/B-VII.1 | OpenMC 0.10.0 |
| China | **CIAE:** China Institute of Atomic Energy | ENDFB/VIII.0 | RMC |
| China | **INEST**: Institute of Nuclear Energy Safety Technology | HENDL3.0 | SuperMC |
| Finland | **VTT**: Technical Research Centre of Finland | ENDF-B/VII.0, JEFF 3.1.2 | Serpent 2.1.31 |
| France | **CEA**: Commissariat à l'Énergie Atomique | JEFF3.1.1 | TRIPOLI4 |
| Germany | **HZDR**: Helmholtz Zentrum DresdenRossendorf | JEFF-3.1, JEFF-3.3, ENDF/B-VII.1, ENDF/B-VIII.0 | Serpent 2.1.31 |
| Germany | **GRS:** Gesellschaft für Anlagen- und Reaktorsicherheit | ENDF/B-VII.1 | Serpent 2.1.30 |
| Hungary | **CER**: Centre for Energy Research | ENDFB/VIII.0 | Serpent 2.1.31 |
| IAEA | **IAEA**: International Atomic Energy Agency | ENDF/B-VII.1 | OpenMC, Serpent 2.1.27 |
| India | **IGCAR**: Indira Gandhi Centre for Atomic Research | ENDF/B VIII.0, JEFF 3.3, JENDL 4.0, ROSFOND 2010, CENDL 3, TENDL 2017 | OpenMC 0.10.0 |
| Italy | **NINE-UNIPI**: Nuclear and Industrial Engineering-Università di Pisa | ENDFB/VIII.0 | Serpent 2.1.31 |
| Japan | **JAEA**: Japan Atomic Energy Agency | JENDL-4.0 | MVP-II |
| Korea | **KAERI**: Korea Atomic Energy Research Institute | ENDF/B-VII.1 | McCARD |
| Korea | **UNIST**: Ulsan National Institute of Science and Technology | ENDF/B-VII.1 | MCS |
| Mexico | **ININ**: Instituto Nacional de Investigaciones Nucleares | ENDFB/VIII.0 | Serpent 2.1.30 |
| Romania | **RATEN**: Institute for Nuclear Research | ENDFB/VIII.0 | Serpent 2.1.31, MCNP 6.1 |
| Russia | **IPPE**: Institute of Physics and Power Engineering | ROSFOND10+ | MMKC |
| Russia | **NRCKI**: National Research Center: Kurchatov Institute | JEFF-3.3 | Serpent 2.1.31, MCNP |
| Slovakia | **VUJE**: | ENDF/B-VII.1 | Serpent 2.1.31 |
| USA | **NRC**: Nuclear Regulatory Commission | ENDF/B-VII.1 | Serpent 2.1.30 |

# Deterministic $k_{eff}$

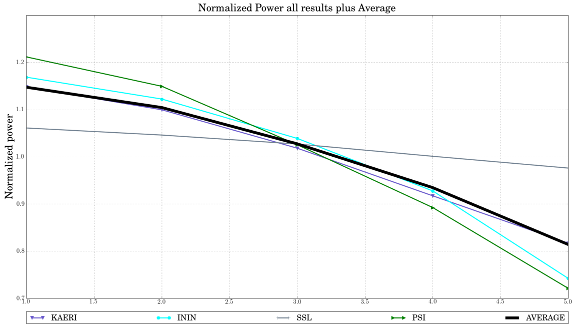


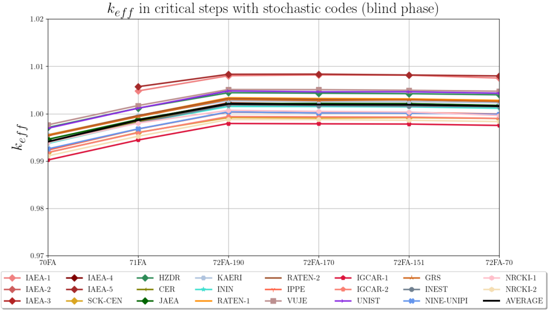

Deviations in pcm from average values up to 2000 pcms difference between participants.

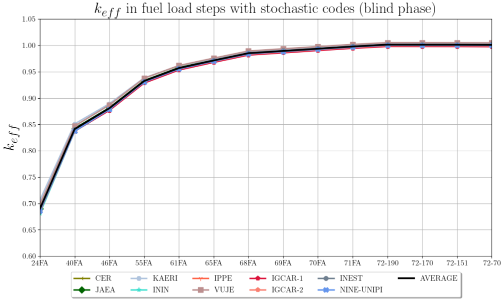
# Deterministic normalized power path

| Fuel SA | I-06 | | I-09 | | II-33 | | III-40 | | IV-68 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Value | Dev (%) | Value | Dev (%) | Value | Dev (%) | Value | Dev (%) | Value | Dev (%) |
| **Average** | **1.14654** | | **1.10129** | | **1.02453** | | **0.93199** | | **0.82340** | |
| **KAERI** | 1.14825 | -0.15 | 1.09960 | 0.15 | 1.01813 | 0.62 | 0.91719 | 1.59 | 0.81683 | 0.80 |
| **PSI** | 1.21179 | -5.69 | 1.14945 | -4.37 | 1.02547 | -0.09 | 0.89232 | 4.26 | 0.72097 | 12.44 |
| **ININ** | 1.16514 | -1.62 | 1.11009 | -0.80 | 1.02752 | -0.29 | 0.91743 | 1.56 | 0.77982 | 5.29 |
| **SSL** | 1.06100 | 7.46 | 1.04600 | 5.02 | 1.02700 | -0.24 | 1.00100 | -7.41 | 0.97600 | -18.53 |



# Stochastic $k_{eff}$

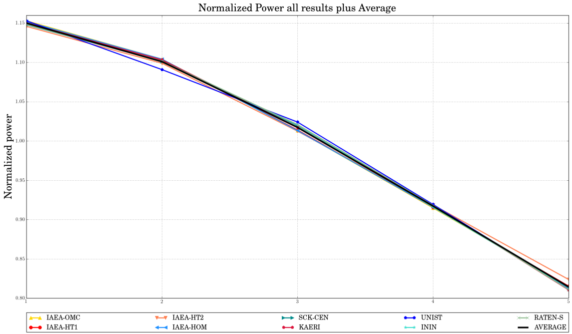



Deviations in pcm from average values ranked in $\pm 400$ pcm (800 pcms in the most extreme cases)

# Stochastic normalized power path

| Fuel SA | I-06 | | I-09 | | II-33 | | III-40 | | IV-68 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Value** | **Dev (%)** | **Value** | **Dev (%)** | **Value** | **Dev (%)** | **Value** | **Dev (%)** | **Value** | **Dev (%)** |
| **Average** | **1.1430** | | **1.0992** | | **1.0175** | | **0.9211** | | **0.8192** | |
| **RATEN-1** | 1.1483 | -0.46 | 1.1016 | -0.22 | 1.0210 | -0.35 | 0.9181 | 0.32 | 0.8110 | 1.01 |
| **ININ** | 1.1488 | -0.50 | 1.1017 | -0.23 | 1.0205 | -0.30 | 0.9159 | 0.57 | 0.8131 | 0.75 |
| **SCK-CEN** | 1.1479 | -0.43 | 1.1014 | -0.20 | 1.0198 | -0.23 | 0.9183 | 0.30 | 0.8126 | 0.81 |
| **IAEA-1** | 1.1699 | -2.35 | 1.1214 | -2.02 | 1.0291 | -1.14 | 0.8959 | 2.73 | 0.7837 | 4.34 |
| **IAEA-2** | 1.1520 | -0.79 | 1.1042 | -0.46 | 1.0133 | 0.41 | 0.9158 | 0.57 | 0.8146 | 0.57 |
| **IAEA-3** | 1.1530 | -0.87 | 1.1042 | -0.46 | 1.0133 | 0.41 | 0.9149 | 0.67 | 0.8146 | 0.57 |
| **IAEA-4** | 1.1518 | -0.77 | 1.1031 | -0.36 | 1.0141 | 0.34 | 0.9157 | 0.59 | 0.8154 | 0.47 |
| **IAEA-5** | 1.1460 | -0.26 | 1.0990 | 0.01 | 1.0126 | 0.48 | 0.9187 | 0.26 | 0.8238 | -0.55 |
| **UNIST** | 1.1531 | -0.88 | 1.0909 | 0.75 | 1.0241 | -0.66 | 0.9193 | 0.20 | 0.8126 | 0.81 |
| **KAERI** | 1.1499 | -0.60 | 1.1034 | -0.39 | 1.0177 | -0.03 | 0.9185 | 0.28 | 0.8105 | 1.07 |
| **NINE-UNIPI** | 1.1490 | -0.52 | 1.1032 | -0.37 | 1.0201 | -0.25 | 0.9175 | 0.38 | 0.8103 | 1.10 |
| **NRCKI-1** | 1.0410 | 8.93 | 1.0520 | 4.29 | 1.0012 | 1.60 | 0.9876 | -7.22 | 0.9182 | -12.08 |
| **NRCKI-2** | 1.1489 | -0.51 | 1.1029 | -0.34 | 1.0202 | -0.27 | 0.9180 | 0.34 | 0.8100 | 1.13 |



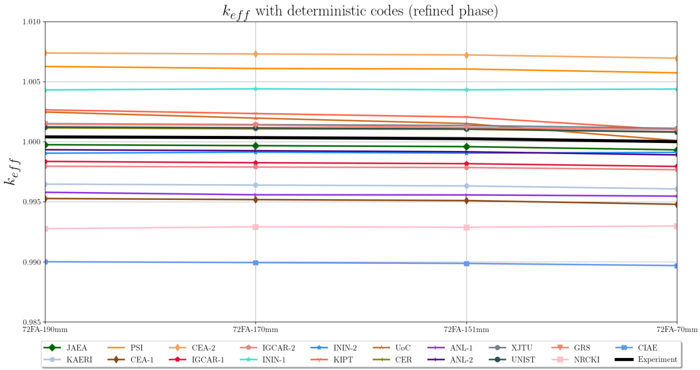
# Experimental results

| RE2 position [mm] | $\rho\ (\frac{\Delta k}{k})$ | $\rho\ (\frac{\Delta k}{k})$ [pcm] |
|---|---|---|
| 190 | 3.95E-04 | 40 |
| 170 | 3.35E-04 | 34 |
| 151 | 2.45E-04 | 25 |
| 70 | 0.0 Estimated | 0 |

$$\rho = \frac{k_{eff} - 1{,}0}{k_{eff}}$$

# Deterministic refined results

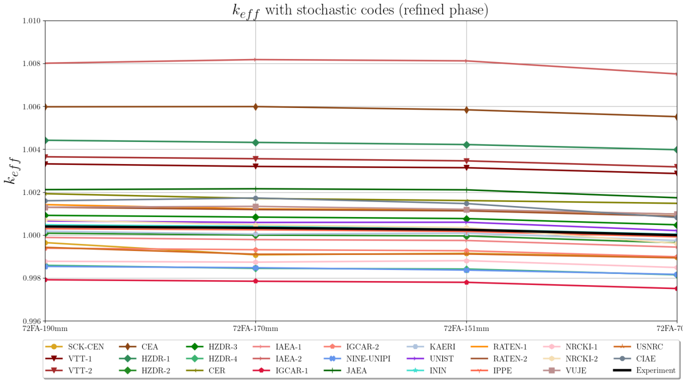
| FA CR | 72 190mm | Dev (pcm) | 72 170mm | Dev (pcm) | 72 151mm | Dev (pcm) | 72 70mm | Dev (pcm) |
|---|---|---|---|---|---|---|---|---|
| Exp. | 40.0 | | 34.0 | | 25.0 | | 0.0 | |
| XJTU | 150.2 | -110 | 142.1 | -108 | 135.1 | -110 | 110.7 | -111 |
| CEA-1 | -475.2 | 515 | -484.3 | 518 | -492.4 | 517 | -523.7 | 524 |
| CEA-2 | 732.6 | -693 | 724.3 | -690 | 716.8 | -692 | 689.7 | -690 |
| GRS | 145.8 | -106 | 136.8 | -103 | 117.9 | -93 | 99.9 | -100 |
| CER | 114.8 | -75 | 107.2 | -73 | 102.7 | -78 | 79.2 | -79 |
| IGCAR-1 | -164.3 | 204 | -175.5 | 210 | -183.0 | 208 | -206.7 | 207 |
| IGCAR-2 | -204.1 | 244 | -210.9 | 245 | -215.4 | 240 | -233.2 | 233 |
| JAEA | -24.6 | 65 | -32.9 | 67 | -40.6 | 66 | -67.7 | 68 |
| KAERI | -354.6 | 395 | -362.4 | 396 | -369.8 | 395 | -395.0 | 395 |
| UNIST | 122.9 | -83 | 114.9 | -81 | 107.3 | -82 | 81.0 | -81 |
| ININ-1 | 429.4 | -389 | 438.8 | -405 | 430.8 | -406 | 436.5 | -436 |
| ININ-2 | -95.9 | 136 | -86.5 | 120 | -94.6 | 119 | -88.7 | 89 |
| NRCKI | -728.9 | 769 | -713.5 | 748 | -717.2 | 742 | -705.6 | 706 |
| PSI | 622.1 | -582 | 605.3 | -571 | 601.4 | -576 | 569.7 | -570 |
| UoC | 246.4 | -206 | 195.6 | -162 | 150.8 | -126 | 8.9 | -9 |
| ANL-1 | -423.2 | 463 | -443.8 | 478 | -444.6 | 470 | -455.3 | 455 |
| ANL-2 | -66.6 | 107 | -75.1 | 109 | -84.5 | 110 | -110.6 | 111 |
| CIAE | -1009.0 | 1049 | -1016.2 | 1050 | -1023.4 | 1048 | -1041.7 | 1042 |
| KIPT | 264.3 | -224 | 233.4 | -199 | 204.7 | -180 | 98.3 | -98 |




Adjustments in XS's generation and further developments in numerical solvers implied significant improvements ±320 pcm from experimental data.

# Stochastic refined results

| FA<br>CR | 72<br>190mm | Dev<br>(pcm) | 72<br>170mm | Dev<br>(pcm) | 72<br>151mm | Dev<br>(pcm) | 72<br>70mm | Dev<br>(pcm) |
|---|---|---|---|---|---|---|---|---|
| **Exp.** | **40.0** | | **34.0** | | **25.0** | | **0.0** | |
| SCK-CEN | -35.0 | 75.0 | -92.1 | 126.1 | -85.1 | 110.1 | -102.1 | 102.1 |
| VTT-1 | 330.9 | -290.9 | 319.0 | -285.0 | 313.0 | -288.0 | 286.2 | -286.2 |
| VTT-2 | 363.7 | -323.7 | 354.7 | -320.7 | 344.8 | -319.8 | 317.0 | -317.0 |
| CEA | 594.4 | -554.4 | 595.4 | -561.4 | 580.6 | -555.6 | 549.0 | -549.0 |
| HZDR-1 | 440.1 | -400.1 | 430.1 | -396.1 | 420.2 | -395.2 | 396.4 | -396.4 |
| HZDR-2 | 9.0 | 31.0 | -0.2 | 34.2 | -4.4 | 29.4 | -35.9 | 35.9 |
| HZDR-3 | 91.9 | -51.9 | 83.9 | -49.9 | 76.9 | -51.9 | 48.0 | -48.0 |
| HZDR-4 | -140.9 | 180.9 | -155.3 | 189.3 | -158.1 | 183.1 | -185.5 | 185.5 |
| CER | 192.6 | -152.6 | 170.7 | -136.7 | 160.7 | -135.7 | 147.8 | -147.8 |
| IAEA-1 | -11.0 | 51.0 | -21.0 | 55.0 | -25.0 | 50.0 | -56.0 | 56.0 |
| IAEA-2 | 794.6 | -754.6 | 811.4 | -777.4 | 805.5 | -780.5 | 745.4 | -745.4 |
| IGCAR-1 | -208.4 | 248.4 | -215.5 | 249.5 | -220.5 | 245.5 | -249.6 | 249.6 |
| IGCAR-2 | -61.0 | 101.0 | -68.0 | 102.0 | -73.1 | 98.1 | -101.1 | 101.1 |
| IGCAR-3 | ---- | ---- | ---- | ---- | ---- | ---- | 275.2 | -275.2 |
| IGCAR-4 | ---- | ---- | ---- | ---- | ---- | ---- | -461.1 | 461.1 |
| IGCAR-5 | ---- | ---- | ---- | ---- | ---- | ---- | 963.6 | -963.6 |
| IGCAR-6 | ---- | ---- | ---- | ---- | ---- | ---- | 826.1 | -826.1 |
| NINE-UNIPI | -146.2 | 186.2 | -152.0 | 186.0 | -163.8 | 188.8 | -183.2 | 183.2 |
| JAEA | 211.6 | -171.6 | 215.5 | -181.5 | 210.6 | -185.6 | 173.7 | -173.7 |
| KAERI | 18.0 | 22.0 | 5.0 | 29.0 | 9.0 | 16.0 | -25.0 | 25.0 |
| UNIST | 66.0 | -26.0 | 59.0 | -25.0 | 60.0 | -35.0 | 21.0 | -21.0 |
| ININ | 48.0 | -8.0 | 41.0 | -7.0 | 28.0 | -3.0 | 4.0 | -4.0 |
| RATEN-1 | 141.8 | -101.8 | 121.9 | -87.9 | 116.9 | -91.9 | 97.9 | -97.9 |
| RATEN-2 | 129.8 | -89.8 | 118.9 | -84.9 | 112.9 | -87.9 | 87.9 | -87.9 |
| IPPE | 30.0 | 10.0 | 25.0 | 9.0 | 17.0 | 8.0 | -8.0 | 8.0 |
| NRCKI-1 | -122.1 | 162.1 | -126.2 | 160.2 | -119.1 | 144.1 | -151.2 | 151.2 |
| NRCKI-2 | 70.9 | -30.9 | 48.0 | -14.0 | 35.0 | -10.0 | -39.0 | 39.0 |
| VUJE | 129.8 | -89.8 | 133.8 | -99.8 | 119.9 | -94.9 | 97.9 | -97.9 |
| USNRC | -57.3 | 97.3 | -88.7 | 122.7 | -88.5 | 113.5 | -106.2 | 106.2 |
| CIAE | 159.7 | -119.7 | 172.7 | -138.7 | 146.8 | -121.8 | 81.9 | -81.9 |
| INEST | 185.7 | -145.7 | 170.7 | -136.7 | 158.7 | -133.7 | 146.8 | -146.8 |




Average deviation from all participants was only 167 pcms from experiment.

# Conclusions

- All refined results presented improvements in the comparisons against experiment values.
- For deterministic:
  - In the blind phase calculation ranked from $-900$ to $+1000$ pcms, almost 2000 pcms of difference in the more extreme cases.
  - Reason: Very different numerical approaches implemented in the deterministic solvers going from pure diffusion in some cases to more complex transport solvers (18 different codes).
  - For refined phase: adjustments in XS's generation and further developments in numerical solvers implied significant improvements $\pm 320$ pcm´s.

# Conclusions

- For stochastic:
  - 11 out of 20 participants used Serpent Monte Carlo code.
  - In blind phase, deviations in pcm from average values ranked in $\pm$400 pcm (800 pcms in the most extreme cases) with just some exceptions with over 600 pcms as an absolute value for the homogeneous model.
  - In the refined phase, significant improvement was obtained in calculations, average deviation from all participants was only 167 pcms.
  - Improvements in this case come directly from model adjustments.

# Conclusions

- Although stochastic results are more accurate, it is more notorious the improvement on refined phase in the case of deterministic codes

| | **Blind phase** | **Refined phase** | **Improvement** |
|---|---|---|---|
| **Deterministic codes** | 448 pcm | 320 pcm | 128 pcm |
| **Stochastic codes** | 224 pcm | 167 pcm | 57 pcm |

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