DE LA RECHERCHE À L'INDUSTRIE

# AN IN-DEPTH ANALYSIS OF MINOR ACTINIDE FISSION CHAMBERS MEASUREMENTS IN THE FCA IX EXPERIMENTAL PROGRAMME.

**ND2016 | Gérald Rimpault, Virginie Huy**
**presented by Pierre Leconte**

11-16 SEPTEMBER 2016

# OBJECTIVES

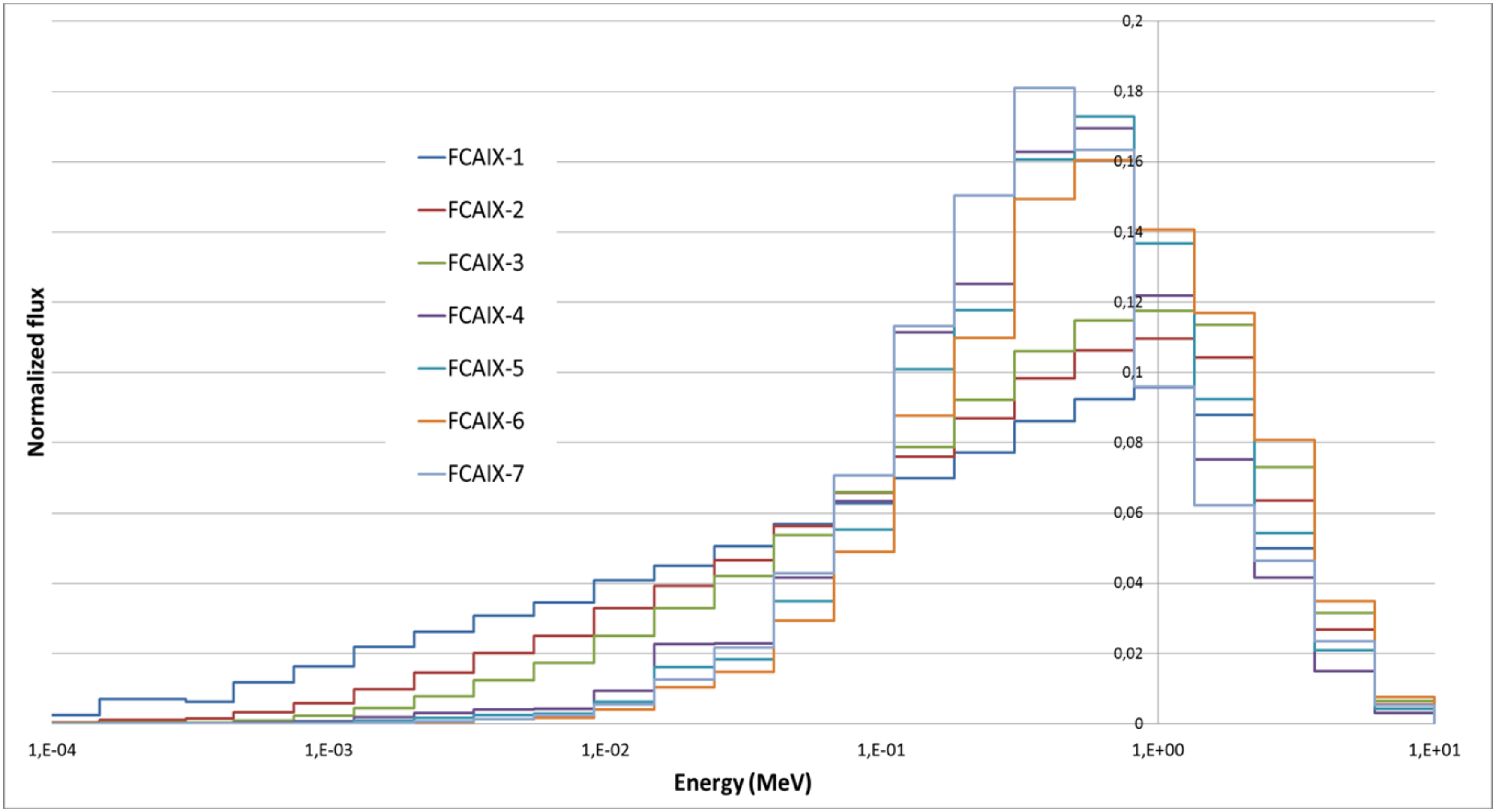
- FCA is a zero power facility located at Tokai in Japan. The FCA-IX experimental programme exhibits 7 different cores with a variety of different neutron spectra.
- Fission Chambers of seven different nuclides: $^{237}$Np, $^{238}$Pu, $^{239}$Pu, $^{242}$Pu, $^{241}$Am, $^{243}$Am and $^{244}$Cm were used to measure ratios of fission reaction rate.
- This is a good opportunity for identify the correctness of Minor Actinides Fission cross sections.
- Within CEA/JAEA collaboration, JAEA provided detailed description of experimental results performed within the FCA IX programme: Reference Document: Establishment of Benchmark Problems for TRU Fission Rate Ratios of FCA-IX Assemblies, M. Fukushima, A. Oizumi, H. Iwamoto, Y. Kitamura, Ref. JAEA-Data/Code/2014-030

# NUCLEAR DATA, TOOLS AND CORE MODELLING

- ERANOS 2.3 with ECCO Cell Calculation
  - RZ description of the cores
  - 1968 group energy scheme for homogenized cell calculations
  - JEFF3.2, JENDL4.0 and ENDFB7.1 nuclear data libraries
  - SN method with transport calculations (BISTRO solver)
  - EGPT for reaction rate ratio sensitivity calculations
  - COMAC V1 for nuclear data covariances when using JEFF3.2
- Heterogeneity corrections provided by JAEA
- TRIPOLI4 Monte Carlo calculation performed with JEFF3.2 in an XYZ geometrical description of the seven cores.

# NORMALIZED FCA-IX CORE SPECTRA

There are 7 FCA-IX cores, all Uranium enriched cores




FCA-IX-1 to FCA-IX-6 cores exhibit a 93% enrichment  while FCA-IX-7 has 20% enrichment

# CRITICAL MASSES

- Experimental values for criticality are being given in Masahiro Fukushima, Yasunori Kitamura, Teruhiko Kugo & Shigeaki Okajima (2015): Benchmark models for criticalities of FCA-IX assemblies with systematically changed neutron spectra, Journal of Nuclear Science and Technology, DOI: 10.1080/00223131.2015.1054911

| | FCA IX-1 | FCA IX-2 | FCA IX-3 | FCA IX-4 | FCA IX-5 | FCA IX-6 | FCA IX-7 |
|---|---|---|---|---|---|---|---|
| Experiment | 1.00490 | 1.00580 | 1.00270 | 1.00630 | 1.00730 | 1.00480 | 1.00610 |
| σ exp (pcm) | 240 | 190 | 110 | 50 | 40 | 60 | 70 |
| T4 JEFF32 homogeneous | 1.00994 | 1.00958 | 1.00823 | 1.00689 | 1.00921 | 1.00628 | 1.01112 |
| Heterogeneity correction (JENDL4.0) | 1.00440 | 1.00950 | 1.00770 | 1.01230 | 1.00930 | 1.00450 | 1.00010 |
| σ correction (pcm) | 70 | 70 | 70 | 70 | 70 | 70 | 70 |
| T4 JEFF32 Heterogeneous | 1.01438 | 1.01917 | 1.01599 | 1.01927 | 1.01859 | 1.01081 | 1.01122 |
| σ T4 (pcm) | 7 | 7 | 7 | 10 | 7 | 7 | 6 |
| C-E (pcm) | 930 | 1304 | 1305 | 1265 | 1100 | 592 | 503 |
| σ (pcm) | 250 | 203 | 131 | 87 | 81 | 92 | 99 |

- There is a significant and systematic bias on criticality with JEFF3.2

# CRITICAL MASSES

- E-C as well as uncertainties on Keff have been calculated for different libraries.

| E-C (pcm) | FCA IX-1 | FCA IX-2 | FCA IX-3 | FCA IX-4 | FCA IX-5 | FCA IX-6 | FCA IX-7 |
|---|---|---|---|---|---|---|---|
| JENDL40 | -574 | -376 | -139 | -258 | -168 | 179 | 289 |
| ND Uncertainty | 731 | 623 | 592 | 671 | 654 | 608 | 813 |
| ENDFB71 | -375 | -711 | -760 | -400 | -400 | -161 | -412 |
| ND Uncertainty | 2694 | 2900 | 2686 | 2467 | 2207 | 1800 | 1840 |
| JEFF32 | -930 | -1304 | -1305 | -1265 | -1100 | -592 | -503 |
| ND Uncertainty | 2694 | 2909 | 2687 | 2391 | 2138 | 1775 | 1639 |

- Uncertainties are calculated with COMAC V1 covariances associated for the JEFF32 library, with their own covariances for ENDFB71 and for JENDL40

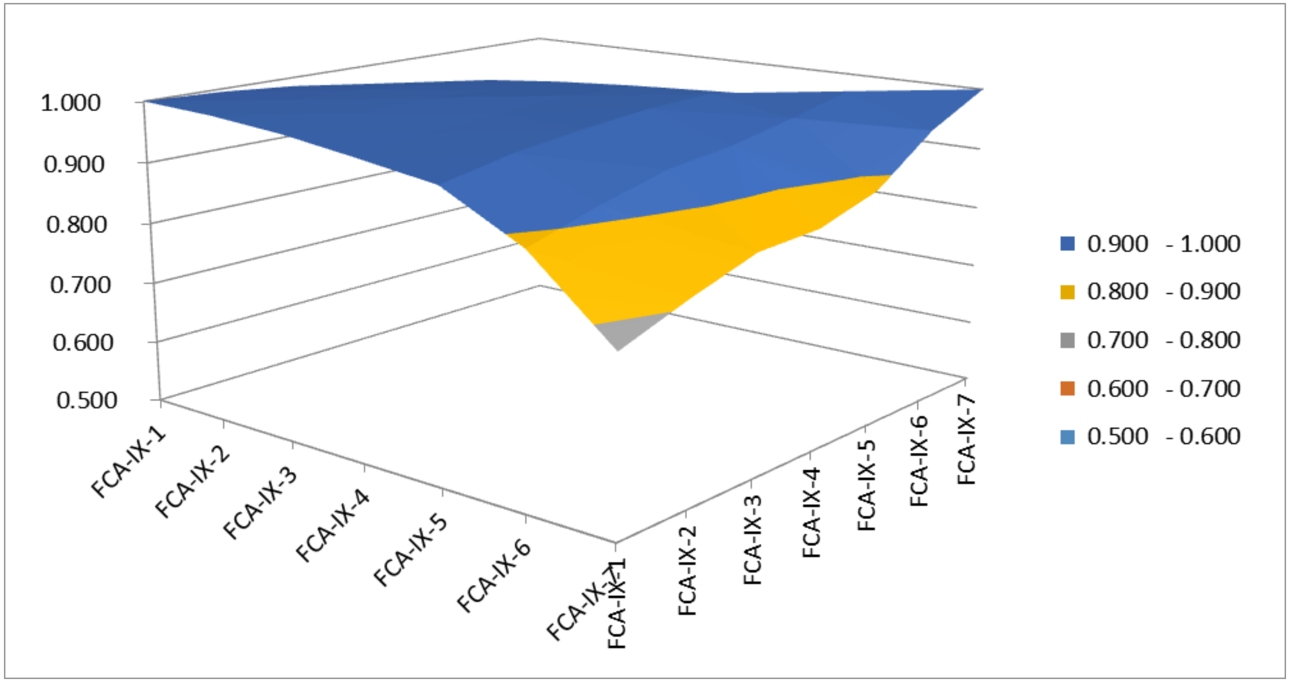
- The critical mass uncertainties are dominated by $U^{235}$ capture contribution for JEFF3.2 and ENDFB71.

- However, uncertainties with JENDL4.0 are much lower due to a much reduced $U^{235}$ capture contribution.

- Marginalisation techniques will be used in order to get reduced U235 capture contribution.

# CRITICAL MASSES

- Correlations between critical masses are close to one except for FCA-IX-7 with all the others

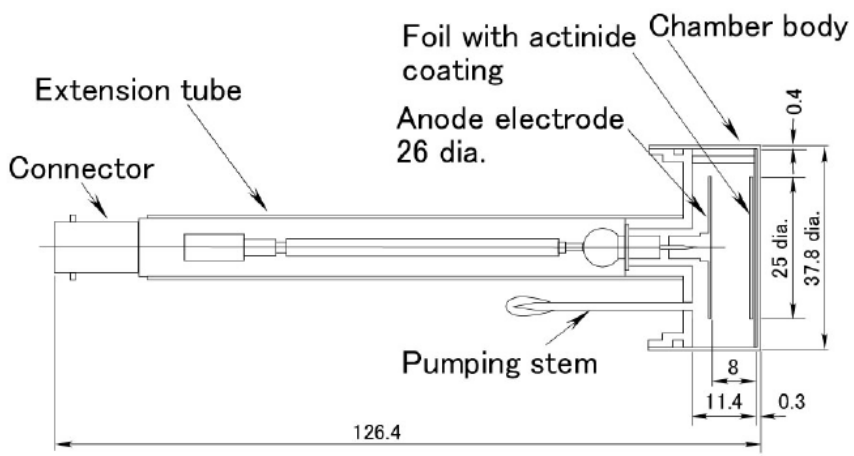


# SPECTRUM INDICES

- Fission Chambers were used to measure seven nuclides:
  $^{237}$Np, $^{238}$Pu, $^{239}$Pu, $^{242}$Pu, $^{241}$Am, $^{243}$Am and $^{244}$Cm.

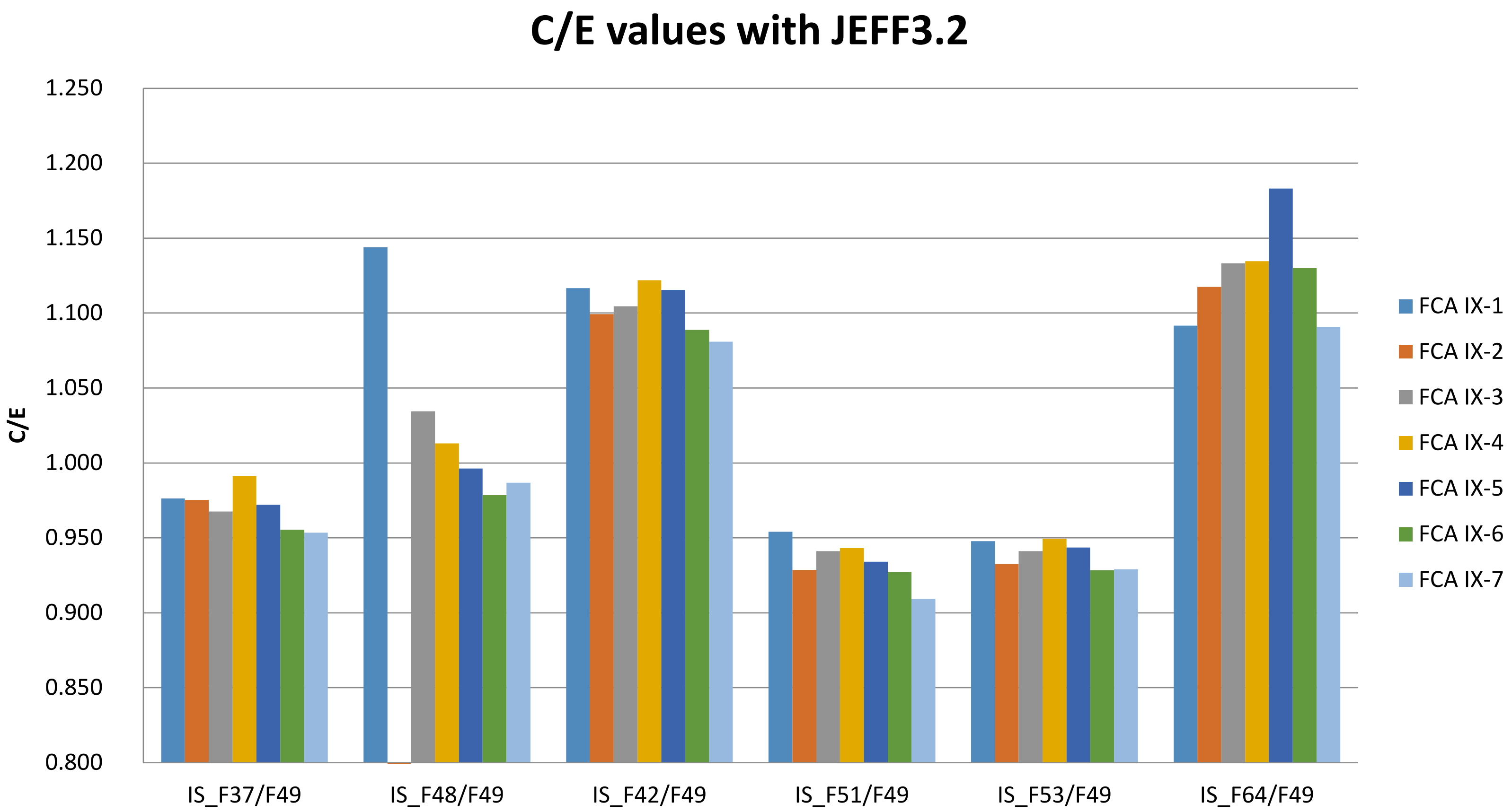
- In order to reduce alpha pulse pile-up in $^{238}$Pu, $^{241}$Am and $^{244}$Cm, where alpha ray specific radioactivity is extremely high, the electrode plate deposit mass is 10 μg or less.
- For the other nuclides, the deposit mass is in the range 40–120 μg.

- Quantitative determination of the electrodeposited nuclides was carried out through spectral analysis using a surface barrier silicon detector and a pulse height analyzer.
- The quantitative determination error for electrodeposited nuclides was 3% for $^{244}$Cm and 1.5% for the other

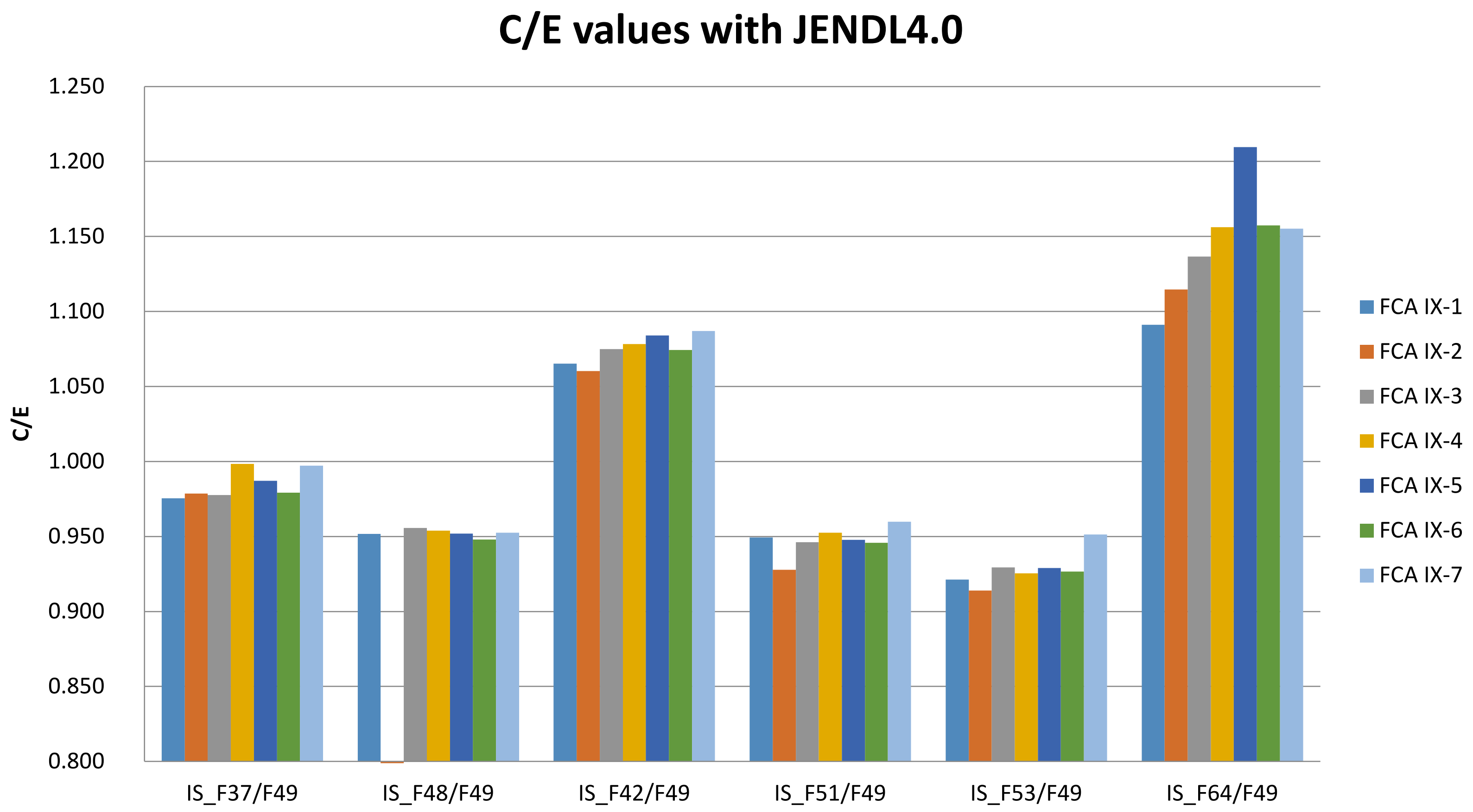



Dimensions in mm

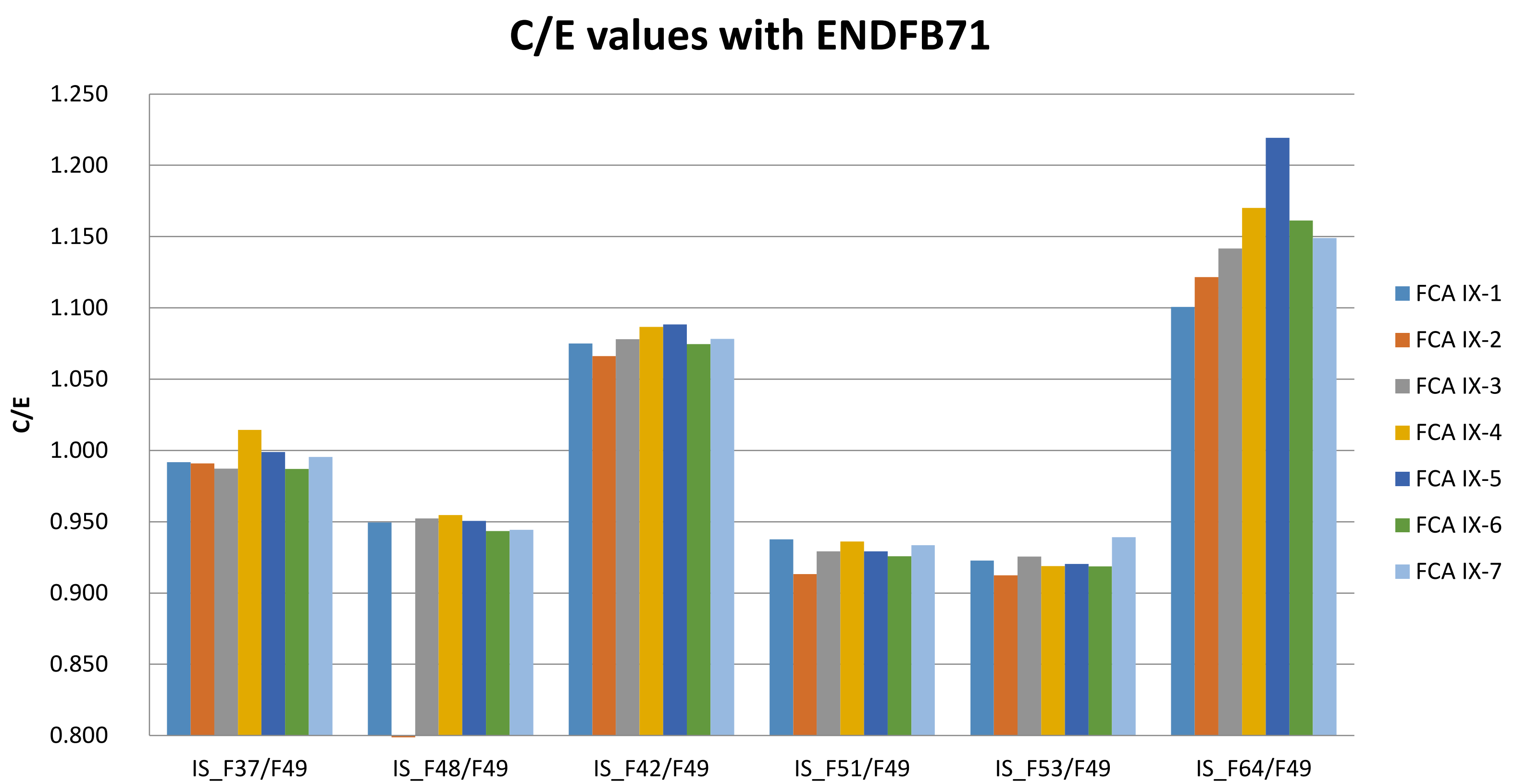
# C/E VALUES FOR JEFF 3.2



# C/E VALUES FOR JENDL 4.0



# C/E VALUES FOR ENDF B 71



# EXP + CALC UNCERTAINTIES ON C/E VALUES FOR JEFF 3.2

| JEFF3.2 | FCA IX-1 | FCA IX-2 | FCA IX-3 | FCA IX-4 | FCA IX-5 | FCA IX-6 | FCA IX-7 |
|---|---|---|---|---|---|---|---|
| IS_F37/F49 | 0.976 | 0.975 | 0.968 | 0.991 | 0.972 | 0.956 | 0.953 |
| Exp Unc | 0.022 | 0.026 | 0.024 | 0.024 | 0.024 | 0.019 | 0.024 |
| Calc Unc | 0.041 | 0.040 | 0.039 | 0.041 | 0.145 | 0.040 | 0.052 |
| Total Unc | 0.046 | 0.048 | 0.046 | 0.047 | 0.147 | 0.044 | 0.057 |
| IS_F48/F49 | 1.144 | - | 1.034 | 1.013 | 0.996 | 0.978 | 0.987 |
| Exp Unc | 0.035 | - | 0.026 | 0.026 | 0.026 | 0.026 | 0.026 |
| Calc Unc | 0.018 | - | 0.019 | 0.020 | 0.020 | 0.020 | 0.023 |
| Total Unc | 0.039 | - | 0.032 | 0.033 | 0.033 | 0.033 | 0.035 |
| IS_F42/F49 | 1.117 | 1.099 | 1.104 | 1.122 | 1.115 | 1.089 | 1.081 |
| Exp Unc | 0.022 | 0.026 | 0.024 | 0.019 | 0.019 | 0.019 | 0.024 |
| Calc Unc | 0.034 | 0.033 | 0.032 | 0.032 | 0.032 | 0.030 | 0.047 |
| Total Unc | 0.041 | 0.042 | 0.040 | 0.037 | 0.037 | 0.035 | 0.053 |
| IS_F51/F49 | 0.954 | 0.929 | 0.941 | 0.943 | 0.934 | 0.927 | 0.909 |
| Exp Unc | 0.022 | 0.027 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 |
| Calc Unc | 0.031 | 0.030 | 0.029 | 0.029 | 0.029 | 0.027 | 0.050 |
| Total Unc | 0.038 | 0.040 | 0.038 | 0.037 | 0.037 | 0.036 | 0.055 |
| IS_F53/F49 | 0.948 | 0.933 | 0.941 | 0.949 | 0.944 | 0.928 | 0.929 |
| Exp Unc | 0.022 | 0.026 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 |
| Calc Unc | 0.091 | 0.092 | 0.092 | 0.088 | 0.089 | 0.091 | 0.099 |
| Total Unc | 0.093 | 0.095 | 0.095 | 0.092 | 0.092 | 0.094 | 0.102 |
| IS_F64/F49 | 1.092 | 1.118 | 1.133 | 1.135 | 1.183 | 1.130 | 1.091 |
| Exp Unc | 0.036 | 0.038 | 0.036 | 0.036 | 0.036 | 0.038 | 0.037 |
| Calc Unc | 0.052 | 0.052 | 0.052 | 0.058 | 0.057 | 0.053 | 0.067 |
| Total Unc | 0.063 | 0.065 | 0.063 | 0.068 | 0.067 | 0.065 | 0.077 |

Calculated Uncertainty account for both direct and indirect Nuclear Data Uncertainty

# DIRECT & INDIRECT UNCERTAINTIES FOR JEFF 3.2

Calculated Uncertainty account for both direct and indirect Nuclear Data Uncertainties: Indirect is an important contribution to the total calculated effect (except for $^{238}$Pu): This is mainly due to $^{235}$U capture.

Example for $^{237}$Np / $^{239}$Pu total uncertainty in %:

| COMAC V1 | CAPTURE | ELASTIC | INELASTIC | NU | FISSION | N,XN | TOTAL |
|---|---|---|---|---|---|---|---|
| Fe54 | 0.006 | 0.016 | 0.008 | - | - | 0.000 | 0.019 |
| Fe56 | 0.040 | 0.071 | 0.128 | - | - | 0.000 | 0.152 |
| Cr52 | 0.003 | 0.003 | 0.010 | - | - | 0.000 | 0.011 |
| Ni58 | 0.012 | 0.012 | 0.007 | - | - | 0.000 | 0.018 |
| Ni60 | 0.005 | 0.005 | 0.003 | - | - | 0.000 | 0.008 |
| C0 | 0.007 | 0.425 | 0.243 | - | - | - | 0.489 |
| Np237 | 0.000 | 0.000 | 0.000 | 0.000 | 2.911 | 0.000 | 2.911 |
| Pu239 | 0.000 | 0.000 | 0.000 | 0.000 | 1.588 | 0.000 | 1.588 |
| U235 | 2.256 | 0.192 | 0.374 | 0.007 | 0.276 | 0.002 | 2.312 |
| U238 | 0.282 | 0.074 | 0.117 | 0.015 | 0.126 | 0.000 | 0.339 |
| TOTAL | 2.274 | 0.478 | 0.479 | 0.016 | 3.330 | 0.002 | 4.089 |

$^{237}$Np and $^{239}$Pu are direct contributions to the total uncertainty while $^{235}$U is an indirect effect to the total uncertainty

# DIRECT & INDIRECT UNCERTAINTIES FOR JENDL4.0

Calculated Uncertainty account for both direct and indirect Nuclear Data Uncertainties: Indirect remains an important contribution to the total calculated effect but not as much as with JEFF3.2 and ENDFBVII.1: This time, $^{235}U$ capture contribution is smaller but $^{235}U$ inelastic and fission contributions larger.

Example for $^{237}Np$ / $^{239}Pu$ total uncertainty in %:

| JENDL4.0 | CAPTURE | ELASTIC | INELASTIC | NU | FISSION | N,XN | TOTAL |
|---|---|---|---|---|---|---|---|
| Fe56 | 0.047 | 0.085 | 0.490 | - | - | 0.000 | 0.500 |
| Cr52 | 0.001 | 0.012 | 0.029 | - | - | 0.000 | 0.031 |
| Ni58 | 0.005 | 0.008 | 0.016 | - | - | 0.000 | 0.019 |
| Ni60 | 0.001 | 0.002 | 0.007 | - | - | 0.000 | 0.007 |
| Np237 | 0.000 | 0.000 | 0.000 | 0.000 | 1.554 | 0.000 | 1.554 |
| Pu239 | 0.000 | 0.000 | 0.000 | 0.000 | 0.538 | 0.000 | 0.538 |
| U235 | 0.395 | 0.054 | 0.626 | 0.007 | 0.642 | 0.005 | 0.981 |
| U238 | 0.080 | 0.102 | 0.066 | 0.016 | 0.010 | 0.004 | 0.147 |
| TOTAL | 0.406 | 0.146 | 0.798 | 0.017 | 1.766 | 0.006 | 1.985 |

The dominant uncertainty contributions are for each individual fission ratios from the nuclide itself (here $^{237}Np$ and direct effect), $^{239}Pu$ (direct effect as used at the denominator) and $^{235}U$ (indirect effect, mostly fission but also inelastic and capture).

# CONCLUSIONS

7 FCA-IX cores offer a variety of neutron spectrum thanks to different moderators and enrichments. FCA-IX-1 to FCA-IX-6 cores exhibit a 93% 235U enrichment while FCA-IX-7 has 20% $^{235}$U enrichment.

The fact that these cores are all Uranium enriched cores introduces an indirect effect due to $^{235}$U capture cross section which somehow limits feedbacks on Minor Actinide cross sections being measured through fission chambers at least for $^{238}$Pu, $^{242}$Pu and $^{241}$Am. This conclusion comes from $^{235}$U covariances as they are associated to JEFF3.2 (named COMAC V1) and ENDFB VII.1 files. The situation is quite different for JENDL4.0 for which $^{235}$U covariances are smaller by a factor 3. The use of experimental keff for these 7 cores can help reducing the magnitude of the $^{235}$U indirect effect of JEFF3.2 and ENDF-BVII.1 and hence will allow having a refine access to MA fission cross sections though measured fission chambers.

For JEFF3.2, $^{237}$Np, $^{243}$Am and $^{244}$Cm have a direct effect significantly larger than the other 2 which means that the measurement can be used to validate their fission cross sections.

$^{242}$Pu and $^{244}$Cm fissions too large by around 10% while $^{241}$Am seems too small by 7%. Although the 7 FCA-IX cores have different neutron spectra, this conclusion stands for all cores.

# THANKS FOR YOUR ATTENTION

Commissariat à l’énergie atomique et aux énergies alternatives
Centre de Cadarache | Gérald Rimpault DEN/DER/SPRC Bâtiment 230
13108 Saint Paul Lez Durance, tel: (33) 4 42 25 79 23

DEN
DER
SPRC
LEPh