# An in-depth analysis of Minor Actinide Fission Chambers Measurements in the FCA IX Experimental Programme.

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**Abstract.** 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. This has been achieved through the use of different moderators and different Uranium enrichments (93% for most of them except FCA-IX-7 where it is 20%). 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. Mass quantitative determinations of the electrodeposited nuclides were carried out through spectral analysis using a surface barrier silicon detector and a pulse height analyzer. The quantitative determination errors for electrodeposited nuclides were 3% for $^{244}$Cm and 1.5% for the other.

Uncertainties are calculated with COMAC V1 covariances associated for the JEFF32 library, with their own covariances for ENDF-BVII.1 and for JENDL4.0 libraries. The critical mass uncertainties are dominated by $^{235}$U capture contribution for JEFF3.1.1, JEFF3.2 and ENDF-BVII.1. However, uncertainties with JENDL4.0 are much lower due to a much reduced $^{235}$U capture contribution.

Calculated Uncertainty is mainly due to Nuclear Data Uncertainties and can be split into direct effect (Minor Actinide cross section) and indirect effect (through flux shape). The indirect effect is an important contribution to the total calculated effect (except for $^{238}$Pu): This is mainly due to $^{235}$U capture and that limits the possible feedback on the cross sections of minor actinides that have been measured through fission chambers. However, the fission rates of $^{237}$Np, of $^{243}$Am and $^{244}$Cm have a direct effect on significantly higher than those of the $^{235}$U and $^{239}$Pu in contrast to the $^{238}$Pu, $^{242}$Pu and the $^{241}$Am. The use of criticality measurements of these 7 cores can help reduce the magnitude of the indirect effect of $^{235}$U and therefore allow closer access to effective fission sections of the measured actinide fission chambers. All data sets exhibit the same trends with $^{242}$Pu and $^{244}$Cm fissions too large by around 10% while $^{241}$Am seems too small by 7%.

## 1 Introduction

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 [1]. 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 [2]. This is a good opportunity for identify the correctness of Minor Actinides Fission cross sections.

## 2 FCA IX plant layout

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. This has been achieved through the use of different moderators and different Uranium enrichments (93% for most of them except FCA-IX-7 where it is 20%). In the following Figure 1, we can see the normalized fission spectra as calculated with the TRIPOLI4 Monte Carlo code [3].

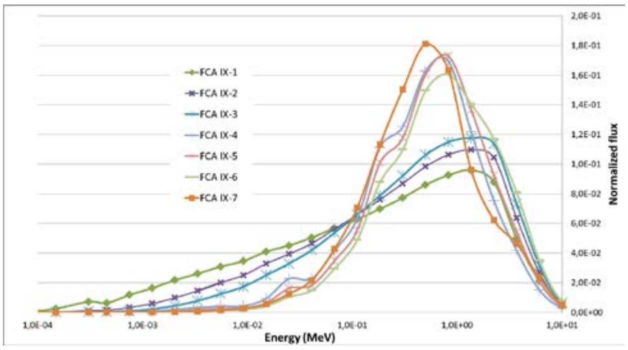


**Figure 1.** Normalised FCA-IX spectra

Given the relative similarities between most of the spectra, only FCA IX-1, FCA IX-6 and FCA IX-7 results have been reported in the following.

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## 3 Criticality

Experimental values for criticality are given by JAEA [1]. Results of the analysis using TRIPOLI4 (T4) [3] and JEFF3.2 [7] are given in the following Table 1:

**Table 1:** E-C values for FCA IX critical masses using TRIPOLI4 & JEFF3.2

| | FCA IX-1 | FCA IX-6 | FCA IX-7 |
|---|---|---|---|
| Experiment | 1.00340 | 1.00250 | 1.00220 |
| □ exp (pcm) | 240 | 60 | 70 |
| T4 JEFF32 Heterogeneous | 1.01438 | 1.01081 | 1.01122 |
| □ T4 (pcm) | 7 | 7 | 6 |
| E-C (pcm) | -1079 | -820 | -890 |
| □ (pcm) | 250 | 92 | 99 |

One can see that there is a significant bias between JEFF3.2 calculations and experiments.
E-C as well as uncertainties on Keff have been calculated for different libraries. These use COMAC V1 covariances [6] for the JEFF32 library [7] and their own covariances for ENDF-BVII.1 [8] and for JENDL4.0 [9] (Table 2).

Table 2: E-C values for FCA IX critical masses using different libraries and associated covariances

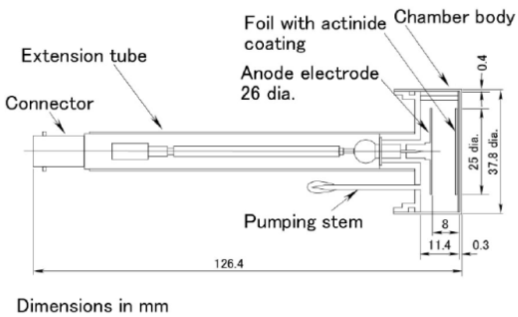
| E-C (pcm) | FCA IX-1 | FCA IX-6 | FCA IX-7 |
|---|---|---|---|
| JENDL4.0 | -1079 | -307 | -290 |
| ND Uncertainty | 724 | 606 | 811 |
| ENDF-BVII.1 | -548 | -706 | -1022 |
| ND Uncertainty | 2670 | 1789 | 1822 |
| JEFF3.2 | -1079 | -820 | -890 |
| ND Uncertainty | 2639 | 2143 | 2334 |

The critical mass uncertainties are dominated by $^{235}$U capture contribution for both JEFF3.2 and ENDF-BVII.1. However, uncertainties with JENDL4.0 are, in general, much lower due to a much reduced $^{235}$U capture contribution. Since C-E values are quite low with both JEFF3.2 and ENDF-BVII.1, a $^{235}$U capture seems the major suspect in the too high calculated reactivity level. Current trends on criticalities advocate for an increase of $^{235}$U capture for JEFF3.2 and ENDF B VII.1. An assimilation technique will help identify which energy region is concerned.

## 4 Reaction Rates

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. Mass quantitative determinations of the electrodeposited nuclides were carried out through spectral analysis using a surface barrier silicon detector and a pulse height analyzer [2]. The quantitative determination errors for electrodeposited nuclides were 3% for $^{244}$Cm and 1.5% for the other. Figure 2 shows how these fission chambers are designed.

Figure 2: FCA-IX fission chambers




The detailed analyses of the Minor Actinide fission chambers measurements performed during the FCA-IX programme have been done using ERANOS2.3 [4]. Associated to the C/E values are the experimental uncertainty and the calculated one. This last one is dominated by nuclear data uncertainties and has been obtained with the sandwich formula using covariance matrices associated to JEFF3.2 libraries (COMAC V1) [6], and their own ones for ENDF-BVII.1 and JENDL4.0 libraries. Sensitivities were obtained with the GPT method [5] in ERANOS [4] (Table 3).

Table 3: C/E values for FCA IX fission rate ratios using JEFF3.2

| JEFF3.2 | FCA IX-1 | FCA IX-6 | FCA IX-7 |
|---|---|---|---|
| IS_F37/F49 | 0.976 | 0.956 | 0.953 |
| Exp Unc | 0.022 | 0.019 | 0.024 |
| Calc Unc | 0.041 | 0.04 | 0.052 |
| Total Unc | 0.046 | 0.044 | 0.057 |
| IS_F48/F49 | 1.144 | 0.978 | 0.987 |
| Exp Unc | 0.035 | 0.026 | 0.026 |
| Calc Unc | 0.018 | 0.02 | 0.023 |
| Total Unc | 0.039 | 0.033 | 0.035 |
| IS_F42/F49 | 1.117 | 1.089 | 1.081 |
| Exp Unc | 0.022 | 0.019 | 0.024 |
| Calc Unc | 0.034 | 0.03 | 0.047 |
| Total Unc | 0.041 | 0.035 | 0.053 |
| IS_F51/F49 | 0.954 | 0.927 | 0.909 |
| Exp Unc | 0.022 | 0.024 | 0.024 |
| Calc Unc | 0.031 | 0.027 | 0.05 |
| Total Unc | 0.038 | 0.036 | 0.055 |
| IS_F53/F49 | 0.948 | 0.928 | 0.929 |
| Exp Unc | 0.022 | 0.024 | 0.024 |
| Calc Unc | 0.091 | 0.091 | 0.099 |
| Total Unc | 0.093 | 0.094 | 0.102 |
| IS_F64/F49 | 1.092 | 1.13 | 1.091 |
| Exp Unc | 0.036 | 0.038 | 0.037 |
| Calc Unc | 0.052 | 0.053 | 0.067 |
| Total Unc | 0.063 | 0.065 | 0.077 |

This way of doing helps tracking the origin of nuclear data uncertainty in the calculation of measured fission rate ratios.

The fact that these cores are all enriched Uranium introduce an indirect effect due to the capture cross section of $^{235}$U and that limits the possible feedback on the cross sections of minor actinides that have been measured through fission chambers. However, the fission rates of $^{237}$Np, of $^{243}$Am and $^{244}$Cm have a direct effect significantly higher than those of the $^{235}$U and $^{239}$Pu in contrast to the $^{238}$Pu, $^{242}$Pu and the $^{241}$Am for which information is diluted.

One can illustrate this with use of different covariance sets.

The use of COMAC V1 covariances for FCA IX $^{237}$Np/$^{239}$Pu reaction rate ratio using the JEFF3.2 library gives the following results (Table 4).

Table 4: Uncertainty breakdown for FCA IX-1 $^{237}$Np/$^{239}$Pu reaction rate ratio using JEFF3.2

| 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. The situation is quite different for the same reaction rate ratio $^{237}$Np/$^{239}$Pu when using JENDL4.0 library (Table 5).

Table 5: Uncertainty breakdown for FCA IX-1 $^{237}$Np/$^{239}$Pu reaction rate using JENDL4.0

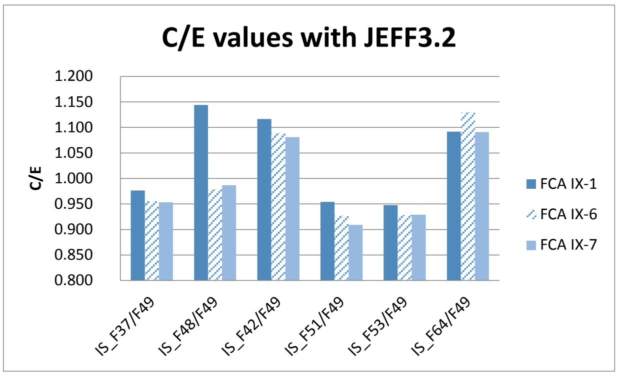
| JENDL4.0 | CAPTURE | ELASTIC | INELASTIC | NU | FISSION | N,XN | TOTAL |
|---|---|---|---|---|---|---|---|
| Fe56 | 0.047 | 0.085 | 0.490 | - | - | 0.000 | 0.500 |
| Cr52 | 0.001 | 0.012 | 0.029 | - | - | 0.000 | 0.031 |
| Ni58 | 0.005 | 0.008 | 0.016 | - | - | 0.000 | 0.019 |
| Ni60 | 0.001 | 0.002 | 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 |

One can notice that in this case, $^{235}$U contribution to the total uncertainty is much reduced and that one can now derive clear trends on $^{237}$Np fission cross-sections.

Given this, one can derive trends on cross sections being measured.

The C/E values for FCA IX fission rate ratios using JEFF3.2 are presented in the following Figure 3.

Figure 3: C/E values on FCA-IX fission rate ratios using JEFF3.2




Similarly, the C/E values for FCA IX fission rate ratios using JENDL4.0 and ENDF-BVII.1 are presented respectively in Figures 4 and 5.

Figure 4: C/E values on FCA-IX fission rate ratios using JENDL4.0

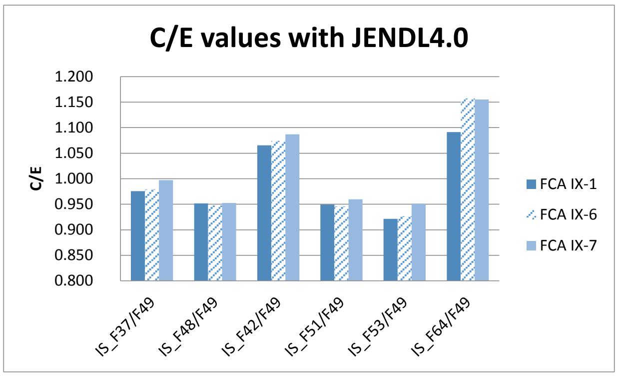
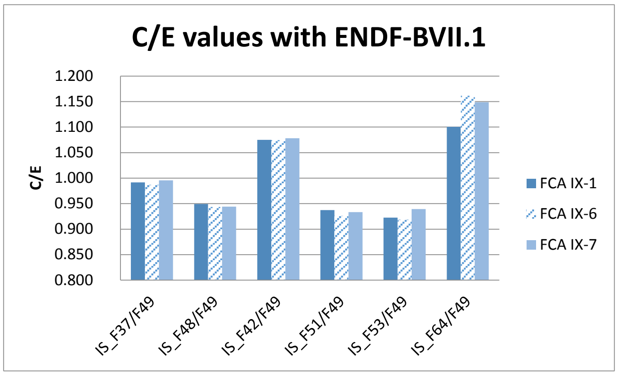



Figure 5: C/E values on FCA-IX fission rate ratios using ENDF-BVII.1




All data sets exhibit the same trends with $^{242}$Pu and $^{244}$Cm fission cross sections too large by around 10% while $^{241}$Am fission cross section seems too small by 7%. Fission cross sections of $^{237}$Np and $^{243}$Am seems correct, while statements on $^{238}$Pu fission cross section has to wait an integral data assimilation work before drawing any conclusion.

## 5 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% $^{235}$U 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.

The JEFF3.2 dominant uncertainty contributions are for each individual fission ratios from the nuclide itself (direct effect), $^{239}$Pu (direct effect as used at the denominator) and $^{235}$U (indirect effect mostly capture but also inelastic and fission). 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.

All data sets exhibit the same trends with $^{242}$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.

Acknowledgements go to JAEA who provided the detailed description of the benchmark and corrections to the raw experiments, to NEA who did provide the secretariat of the Expert Group on Improvement of Integral Experiments for Minor Actinide Management (EGIEMAM-II) under which this work has been conducted and EDF for providing funds to support Virginie Huy PhD work. I would like to thank the CEA fast reactor R&D project for supporting these activities.

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