Nuclear data uncertainty quantification for the FREYA fast critical experiments

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7th International Serpent User Group Meeting
Gainesville, FL November 2017

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Outline

- Overview of the FREYA project
- VENUS facility and critical VENUS-F cores
- Modeling of critical VENUS-F cores
- Calculations vs. Experiment
- Uncertainty analysis
- Summary

Overview of the FREYA project

- FREYA - **F**ast **R**eactor **E**xperiments for h**Y**brid **A**pplications
  - FP7 EU project
  - Running period: 2011 – 2016

- Experiments to support design & licensing of ADS and LFR
  - ADS = Accelerator Driven System (*sub-critica*l)
  - LFR = Lead-cooled Fast Reactor (*critical*)

- Supported system #1: **MYRRHA**
  - **M**ulti-purpose h**Y**brid **R**esearch **R**eactor for **H**igh-tech **A**pplications
  - Dual mode of operation: sub-critical and critical

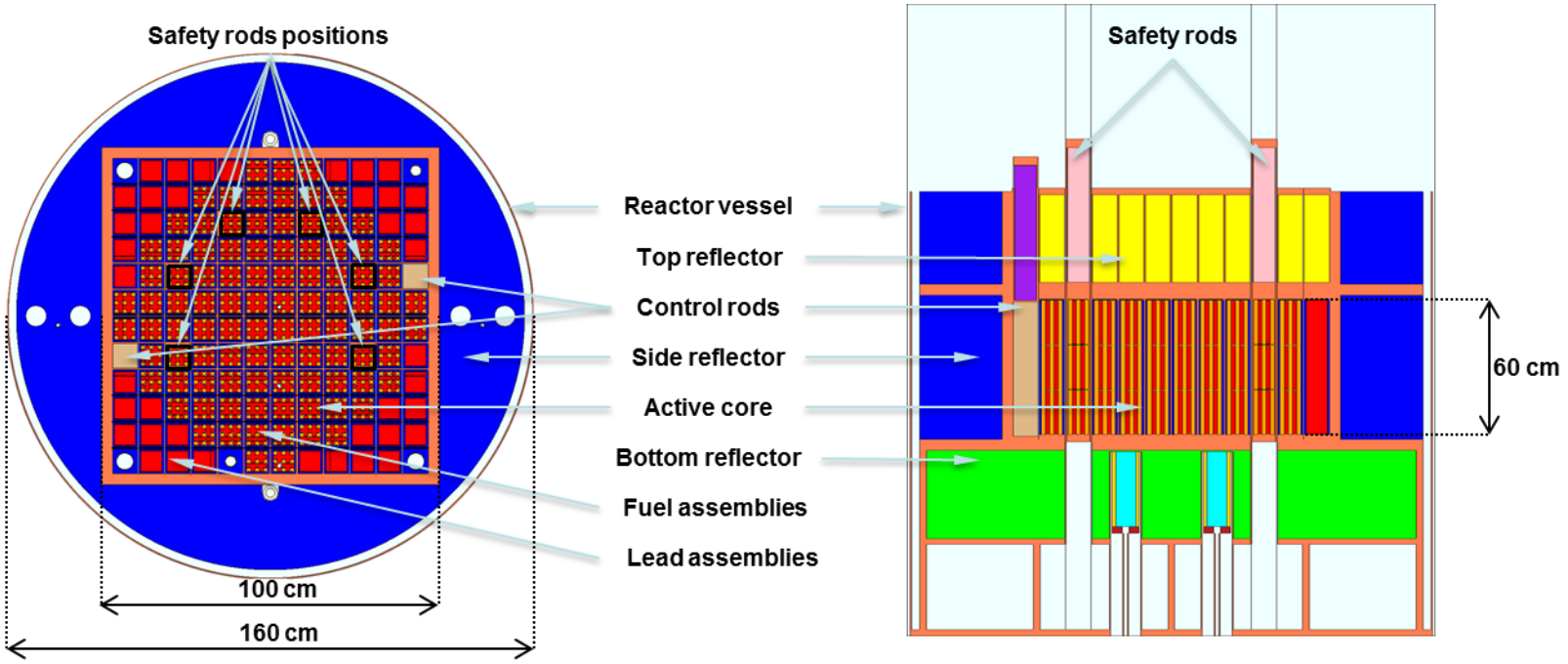
- Supported system #2: **ALFRED**
  - **A**dvanced **LFR** **E**uropean **D**emonstrator

VENUS reactor and critical VENUS-F cores

VENUS reactor

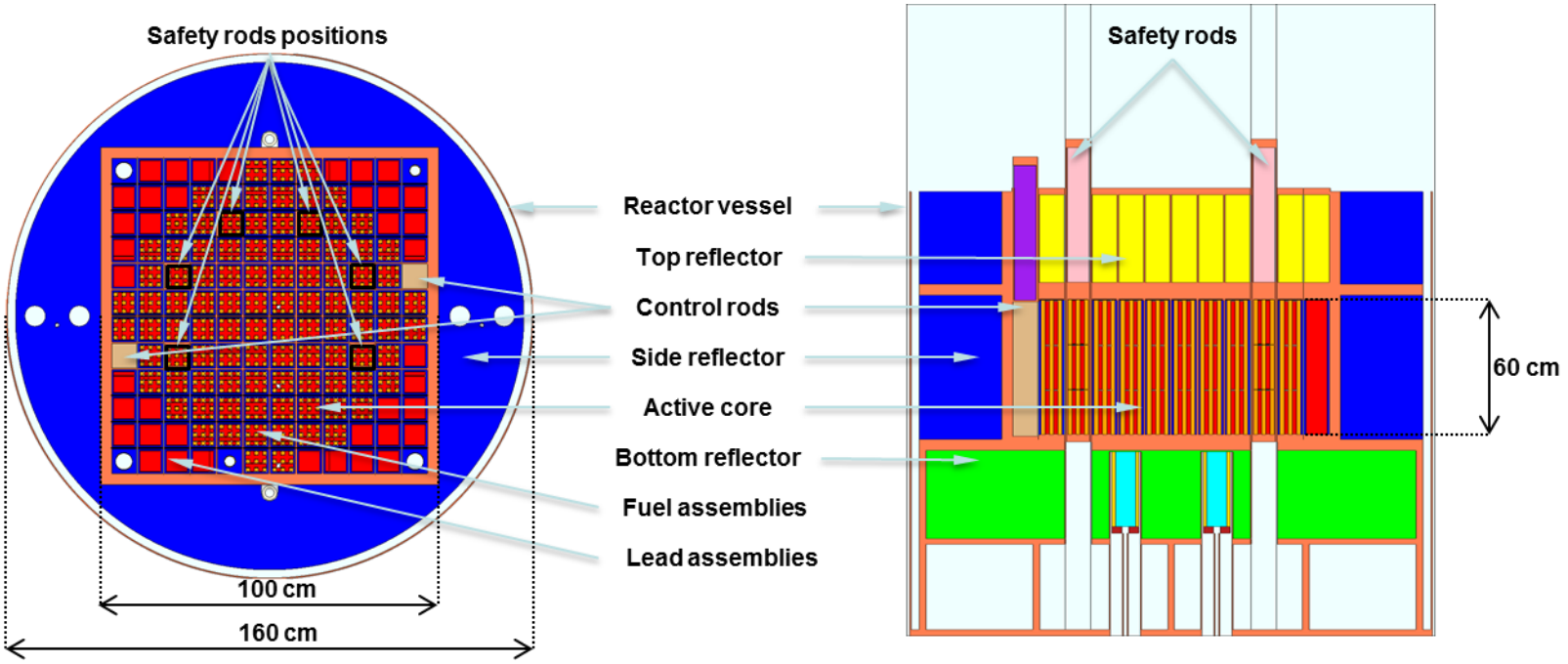
- Water-moderated zero power reactor
- Located at SCK•CEN, Mol, Belgium
- Dedicated to LWR-related experiments
- Experimental data for international benchmarks (OECD)
  - VENUS-1 and VENUS-3 RPV neutron embrittlement test
  - VENUS-2 MOX benchmark

VENUS-F reactor



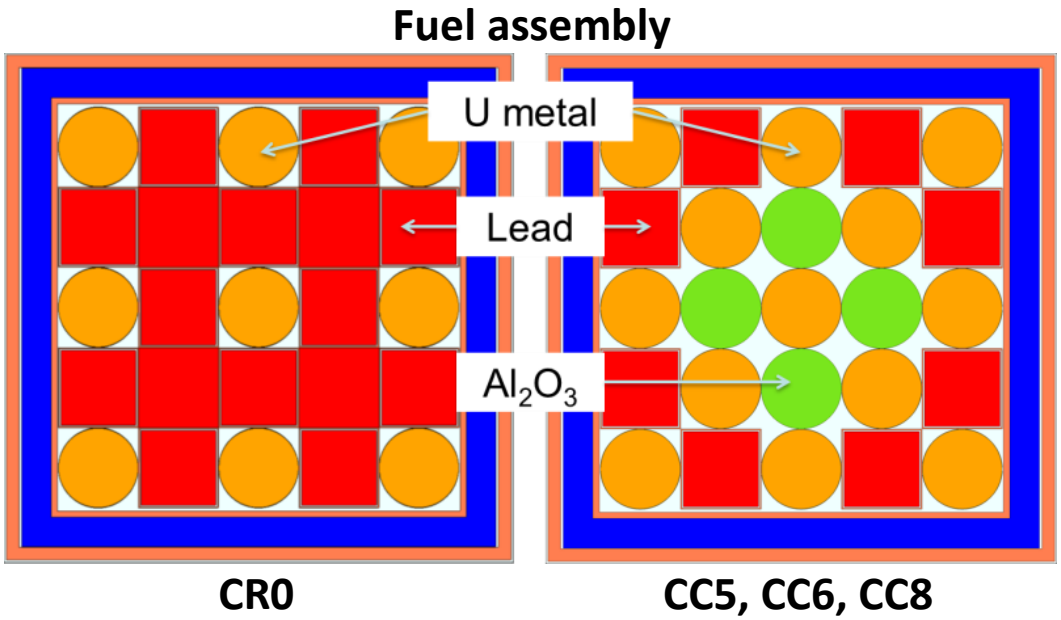
- Increasing interest in lead fast reactor systems in Europe
- Demand for integral experiments
- In 2011 VENUS converted in VENUS-F fast lead reactor
  - FP7 EU project GUINEVERE (2007-2010)

VENUS-F reactor



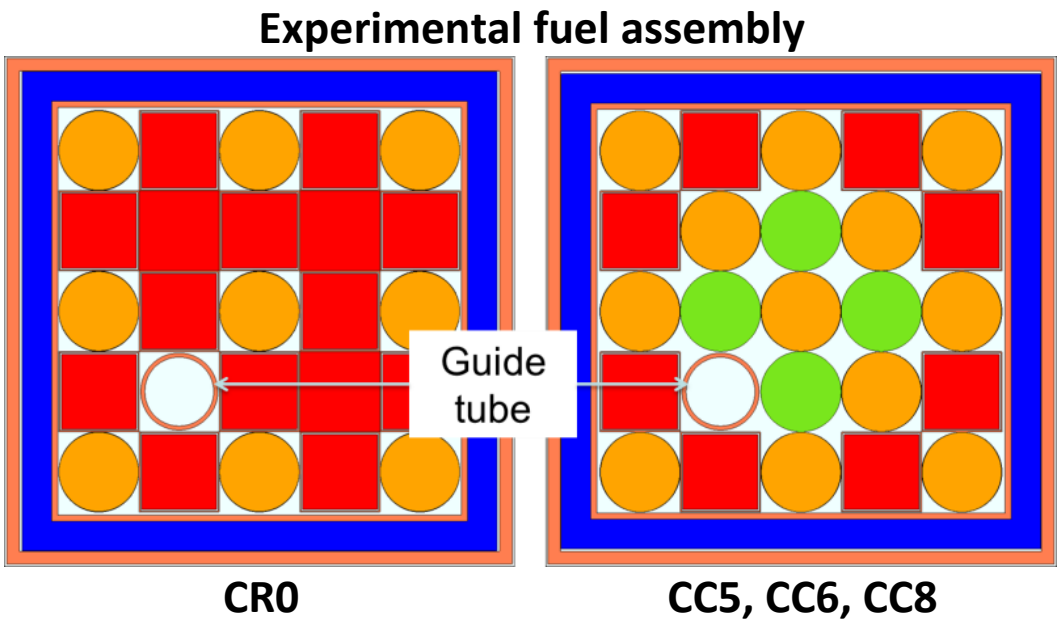
- Some reactor features
  - 12×12 square lattice (pitch = 8 cm)
  - Stainless steel casing
  - Lead reflector (radial and axial)
  - 6 safety + 2 control rods

Fuel assembly designs



- 5×5 lattice (pin pitch = 1.26 cm)
- 30 w% enriched metallic U fuel rods
- CR0 core: **16 lead blocks** + **9 U rods**
- CC cores: **8 lead blocks** + **13 U rods** + **4 Al_2O_3** rods
  - Al_2O_3 to mimic the behavior of oxide fuel

Fuel assembly designs



- Experimental fuel assemblies (EFA) with guide tube
- Dedicated to in-core measurements

Critical VENUS-F cores

- Several **critical** VENUS-F cores have been investigated
  - Reflect some basic features of MYRRHA and ALFRED

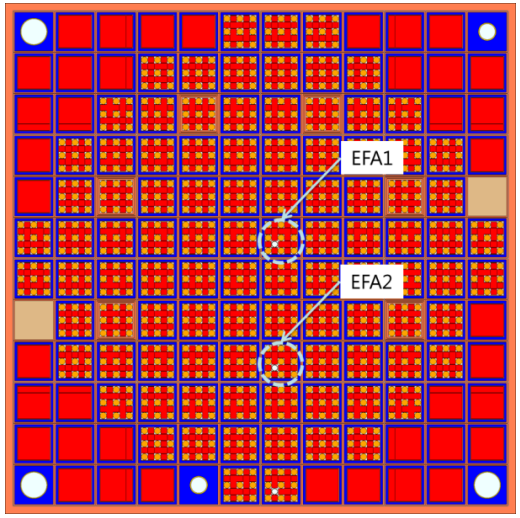
- CR0 – reference critical core
  - 97 fuel assemblies (U+Pb)

- CC5 – “clean” MYRRHA core mock-up
  - 41 fuel assemblies (U+Pb+Al)

- CC8 – “full” MYRRHA core mock-up
  - 47 fuel assemblies (U+Pb+Al)

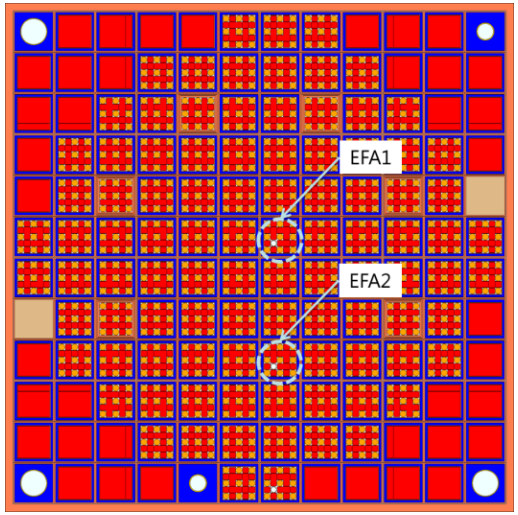
- CC6 = CC5 core + ALFRED island
  - 41 fuel assemblies (U+Pb+Al)

Critical VENUS-F cores



CR0 – Reference critical core

Critical VENUS-F cores



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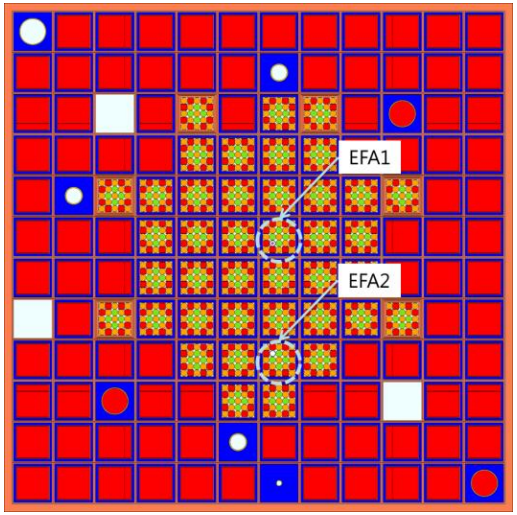

CC5 – clean MYRRHA mock-up

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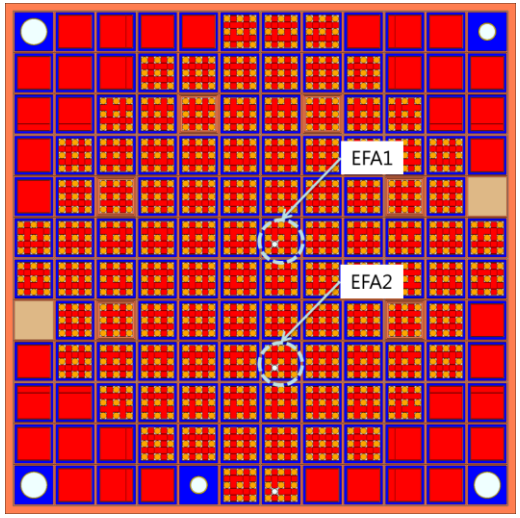

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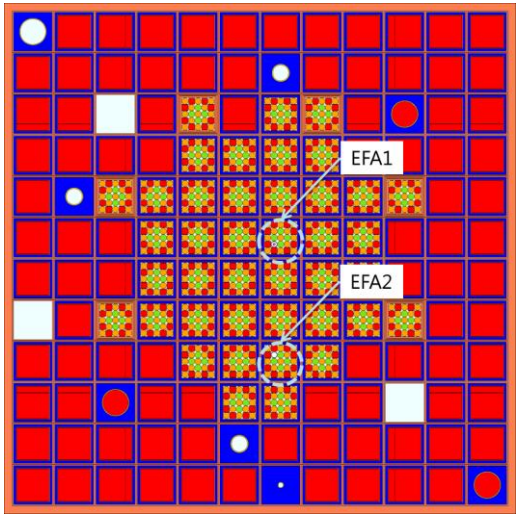

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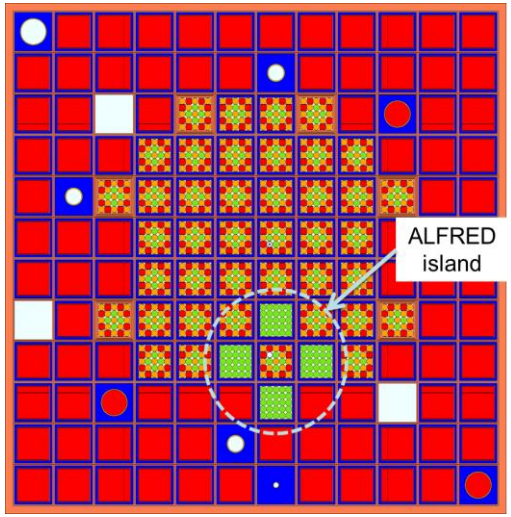

CC6 – CC5 + ALFRED island

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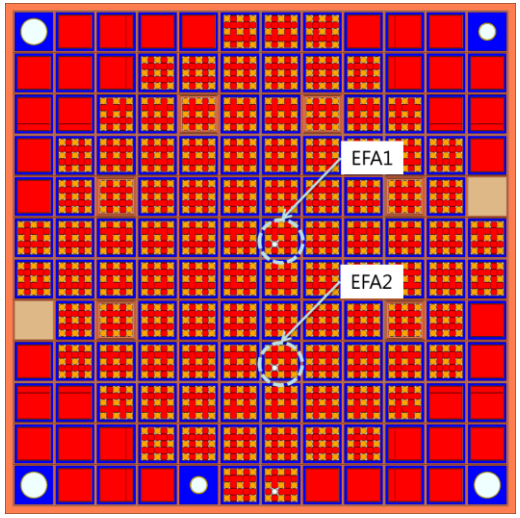

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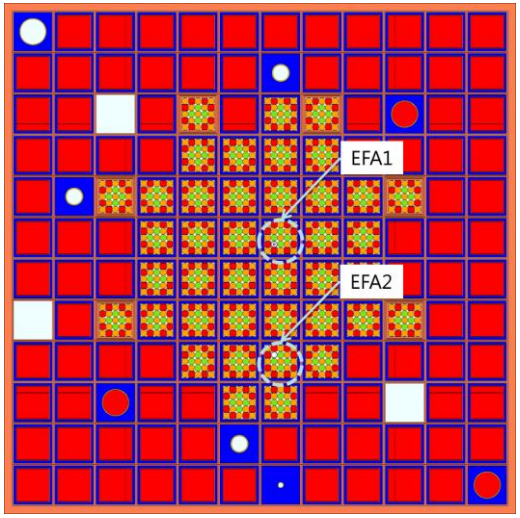
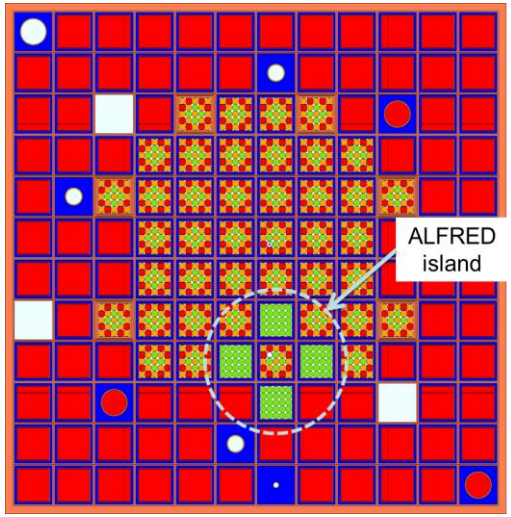


CC5 – clean MYRRHA mock-up



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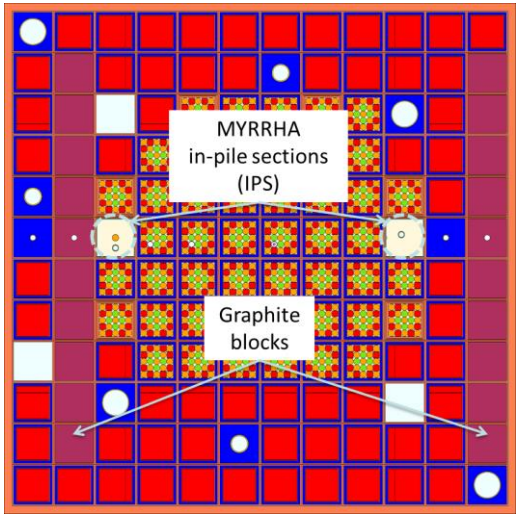

CC8 – full MYRRHA mock-up

Modeling of critical VENUS-F cores

General approach

- Serpent Monte Carlo code
- Very detailed core models
  - Fully resolved fuel assemblies, control rods, and peripheral structures
  - Based on MCNP input provided by SCK·CEN
- Neutron histories
  - 4×10^9 active neutron histories
  - 1σ uncertainty on k-eff is about 2-3 pcm.
- Parallel execution
  - 4 MPI tasks with 16 OpenMP threads

Compared experimental and calculated data

- Integral parameters
  - Reactivity (ρ), delayed neutron fraction (β_{eff}), neutron generation time (Λ_{eff})
- Spectral indices (SI)
  - Fission rate ratios
- Axial and radial traverses
  - Spatial distribution of fission rates
- Lead void reactivity effect (LVRE)

Parameter \ Core	CR0	CC5	CC6	CC8
Reactivity	+	+	+	+
β_{eff} and Λ_{eff}	+			
Spectral indices	+	+	+	+
Axial traverses	+	+		
Radial traverses		+		+
LVRE			+	

Spectral indices

Fission rate ratios of important actinides to that of U235

$$F28/F25 = \frac{\int \sigma_{fiss}^{U238}(E)\phi(E)dE}{\int \sigma_{fiss}^{U235}(E)\phi(E)dE}$$

$$F49/F25 = \frac{\int \sigma_{fiss}^{Pu239}(E)\phi(E)dE}{\int \sigma_{fiss}^{U235}(E)\phi(E)dE}$$

$$F40/F25 = \frac{\int \sigma_{fiss}^{Pu240}(E)\phi(E)dE}{\int \sigma_{fiss}^{U235}(E)\phi(E)dE}$$

$$F37/F25 = \frac{\int \sigma_{fiss}^{Np237}(E)\phi(E)dE}{\int \sigma_{fiss}^{U235}(E)\phi(E)dE}$$

$$F42/F25 = \frac{\int \sigma_{fiss}^{Pu242}(E)\phi(E)dE}{\int \sigma_{fiss}^{U235}(E)\phi(E)dE}$$

$$F51/F25 = \frac{\int \sigma_{fiss}^{Am241}(E)\phi(E)dE}{\int \sigma_{fiss}^{U235}(E)\phi(E)dE}$$

Serpent results vs. experimental data

Reactivity

Core	ρ, pcm
CR0	496±2
CC5	763±3
CC6	812±2
CC8	186±1

- Systematic overestimation of reactivity
  - But consistent with other codes (e.g. MCNP)
- Alternative nuclear data libraries retain the difference
  - ENDF/B-VII.0, JEFF-3.2, and JENDL-4.0
- Uncertainties in nuclear data as a possible reason

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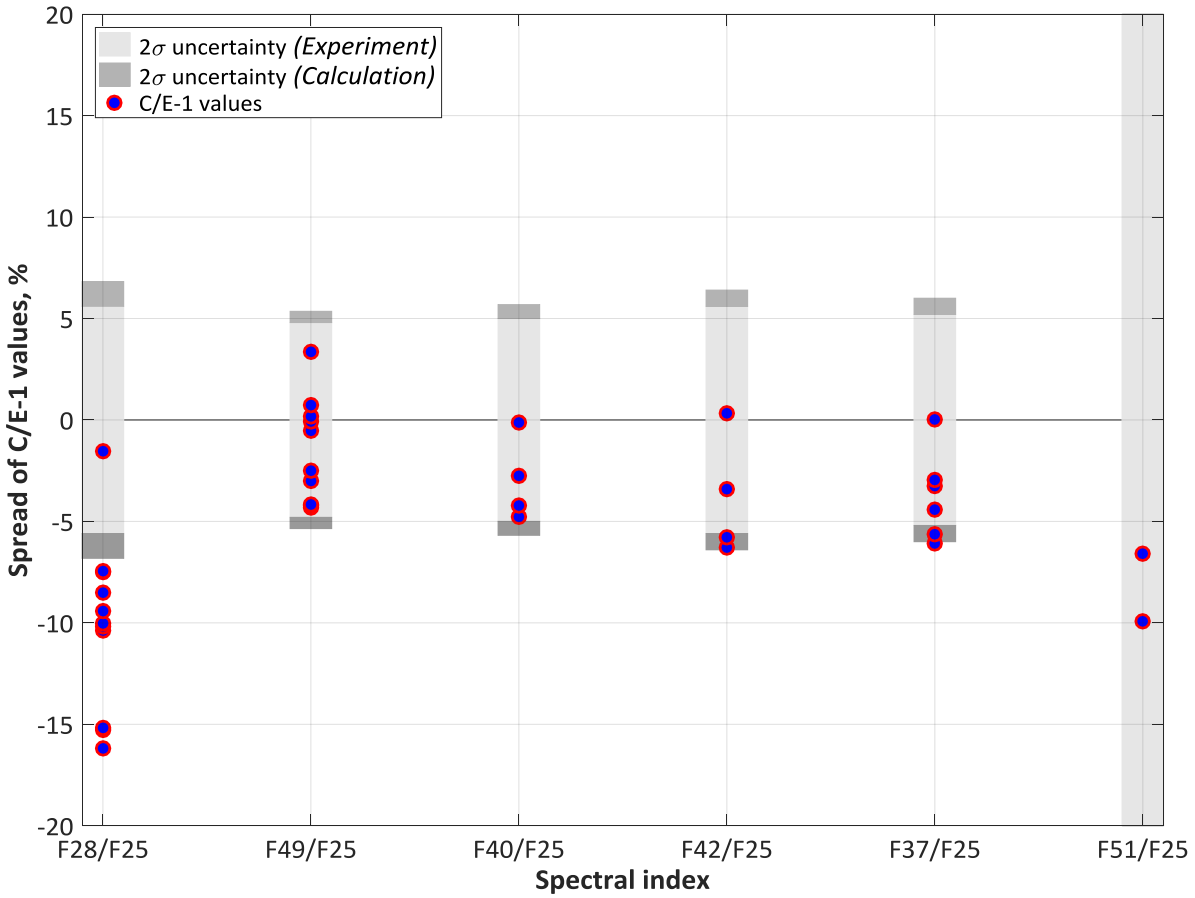
C/E for spectral indices (spread for all cores)



- Systematic underestimation of F28/F25 (more than 2σ)
- More reasonable agreement for the rest
- Again, uncertainties in nuclear data as a possible reason

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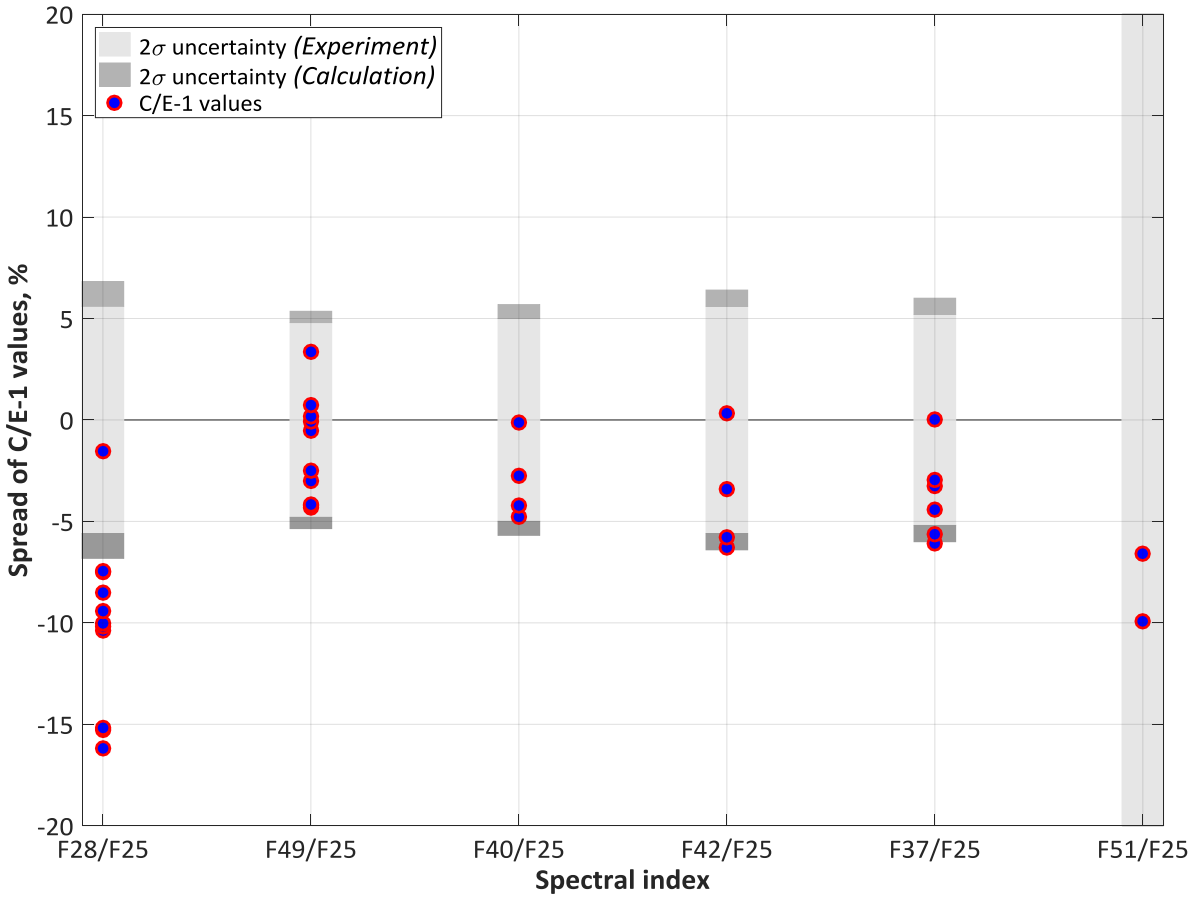

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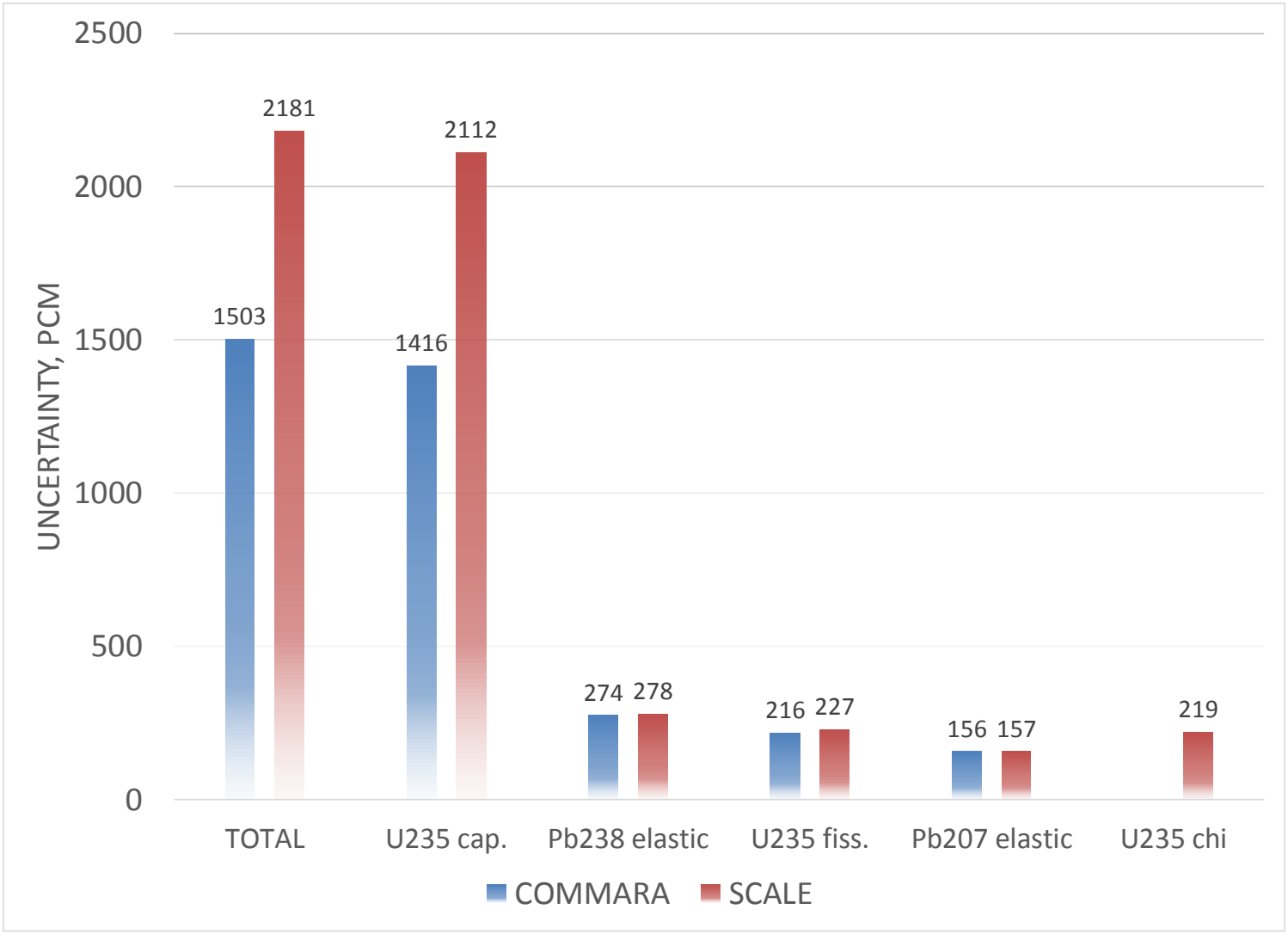
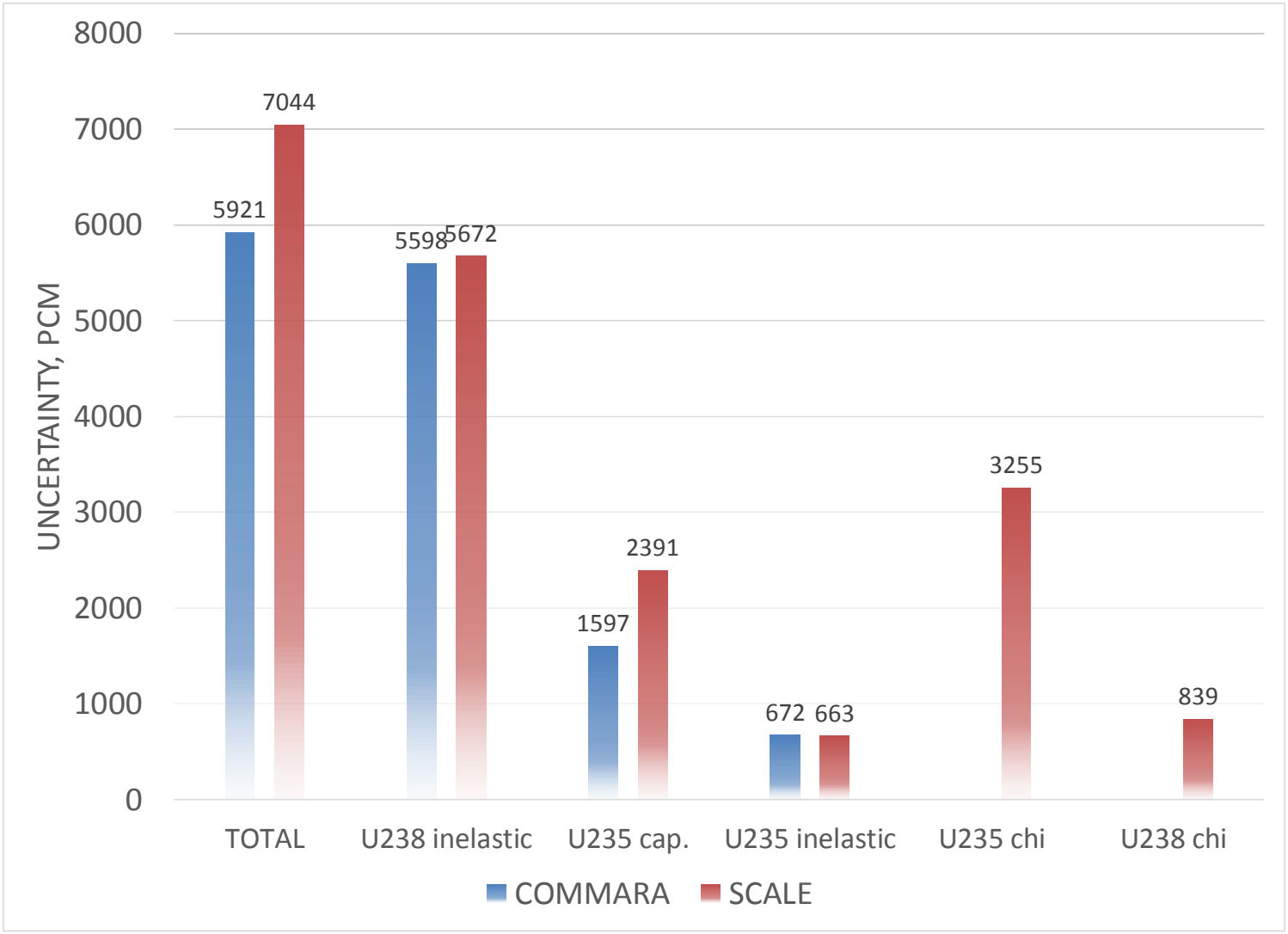
Uncertainty analysis

- Serpent 2.1.29 with GPT option
- Obtain energy dependent sensitivities to XS data
  - k-eff + reaction rate ratios (F28/F25, F49/F25)
- Obtain uncertainties by applying XS covariance matrices
  - 33-group COMMARA-2.0 data
  - 56-group SCALE6.2 data
- Isotopes
  - Pb-204, Pb-206, Pb-207, Pb-208, U-235, U-238
- XS data
  - capture, fission, elastic scattering, inelastic scattering, n,2n, chi
- **So far CC5 core only**

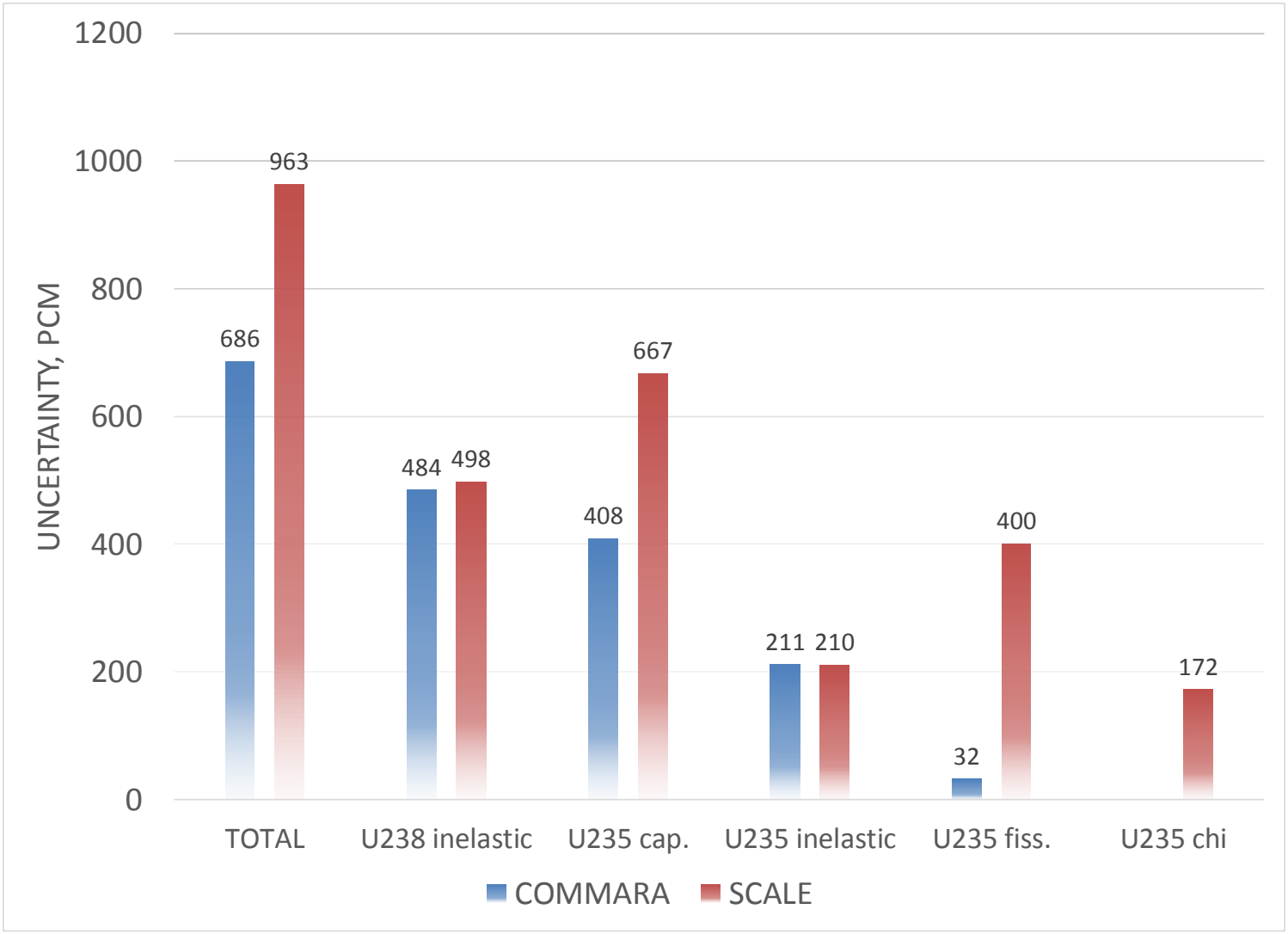
Uncertainty in k-eff



Uncertainty in F28/F25



Uncertainty in F49/F25



Summary

- K-eff:
  - Total nuclear data uncertainty of about **1500-2200 pcm**
  - Largest contributor: U-235 capture
  - C/E is within the quantified uncertainty

- F28/F25
  - Total nuclear data uncertainty of **about 6-7%**
  - Largest contributors: U-238 in. scattering and U-235 chi
  - C/E is within the quantified uncertainty

- F49/F25
  - Total nuclear data uncertainty of about 0.7-0.9%
  - Largest contributors: U-238 in. scattering and U-235 capture

Thank you!