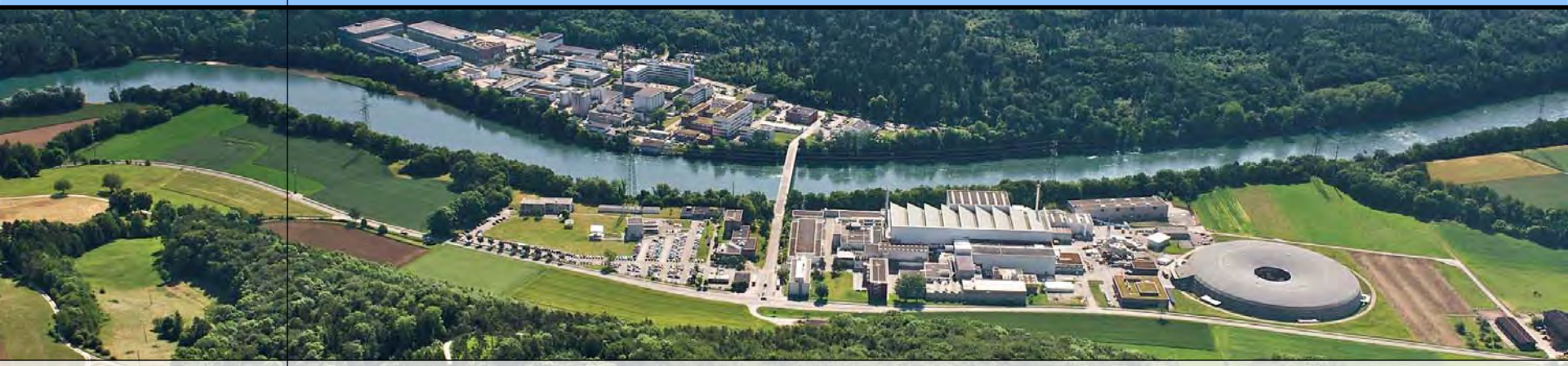
PAUL SCHERRER INSTITUT



Wir schaffen Wissen – heute für morgen

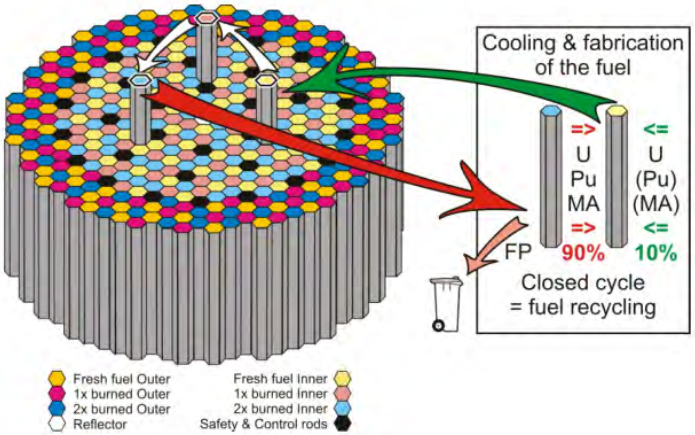
Paul Scherrer Institut

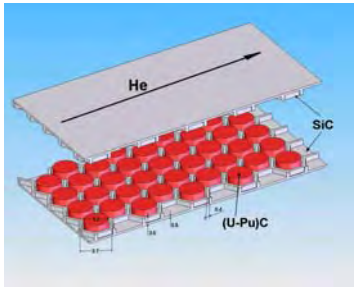
G. Perret, R. M. Pattupara, G. Girardin, R. Chawla

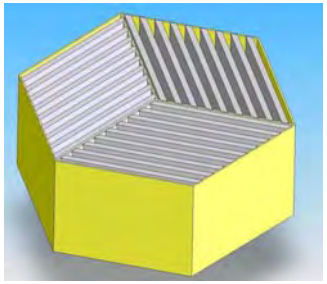
Reanalysis of the Gas-Cooled Fast Reactor Experiments at the Zero Power Facility PROTEUS – Spectral Indices

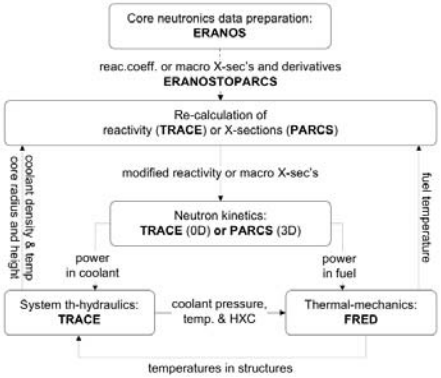
GFR Context

- GFR is a reactor concept for the GEN-IV initiative
- Integrated in the EU FP5 to 7 projects
- Challenges:
  - Heat removal
  - Core neutronics with Pu and MA
  - Materials at high temperature
  - Fuel type CERCER/CERMET, Carbide, Nitride, Oxide
- FAST Code system at Paul Scherrer Inst.
- Past efforts (70s to 00s) with evolutionary concepts – Pu oxides with metal cladding and limited temperature

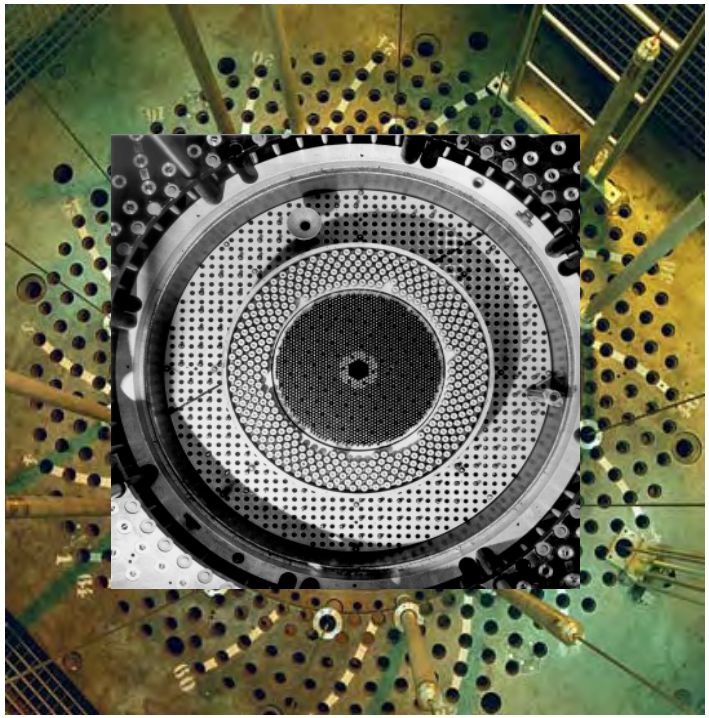






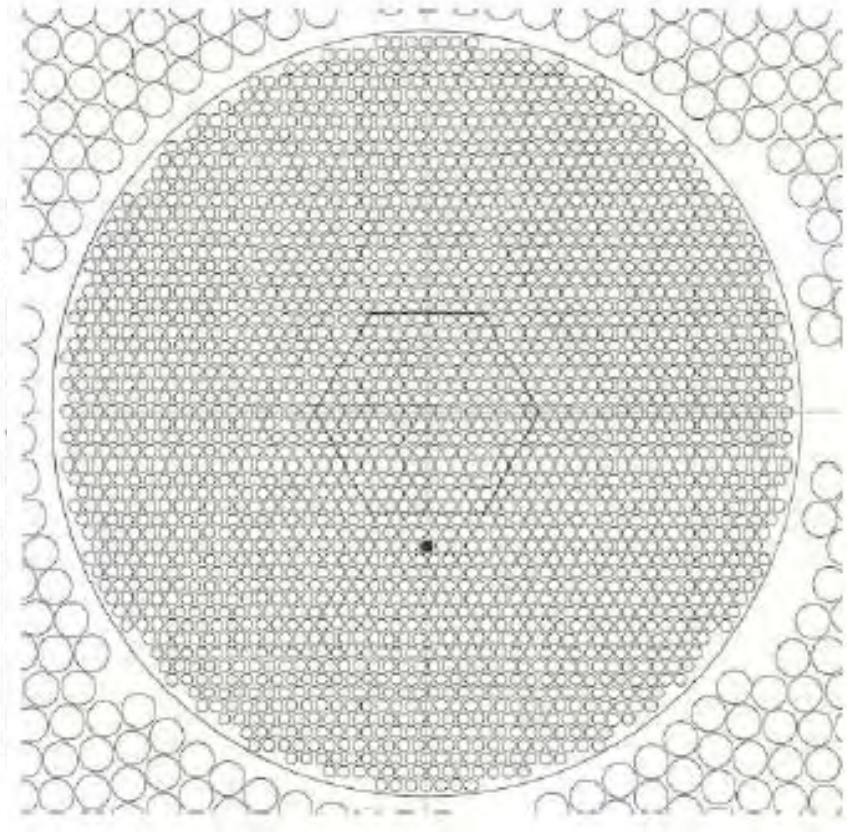


PROTEUS Reactor



- PROTEUS zero power research reactor (1968-2011)
- Power ~ 1kW
- Driven system
- Large test zone at the center
- Buffer region to adjust spectrum
- Driver regions
  - D_2O and graphite regions
  - Safety and control rods
  - Instrumentation

GCFR Program (1970's)



- Investigate GCFR with PuO_2/UO_2 (15% Pu, air cooled, E≈185keV)
- Investigate Thorium cross sections in fast spectra
- Radial and axial blankets
  - U depleted
  - ThO_2 / Th metal

http://proteus.web.psi.ch/GCFR-PROTEUS/index.html

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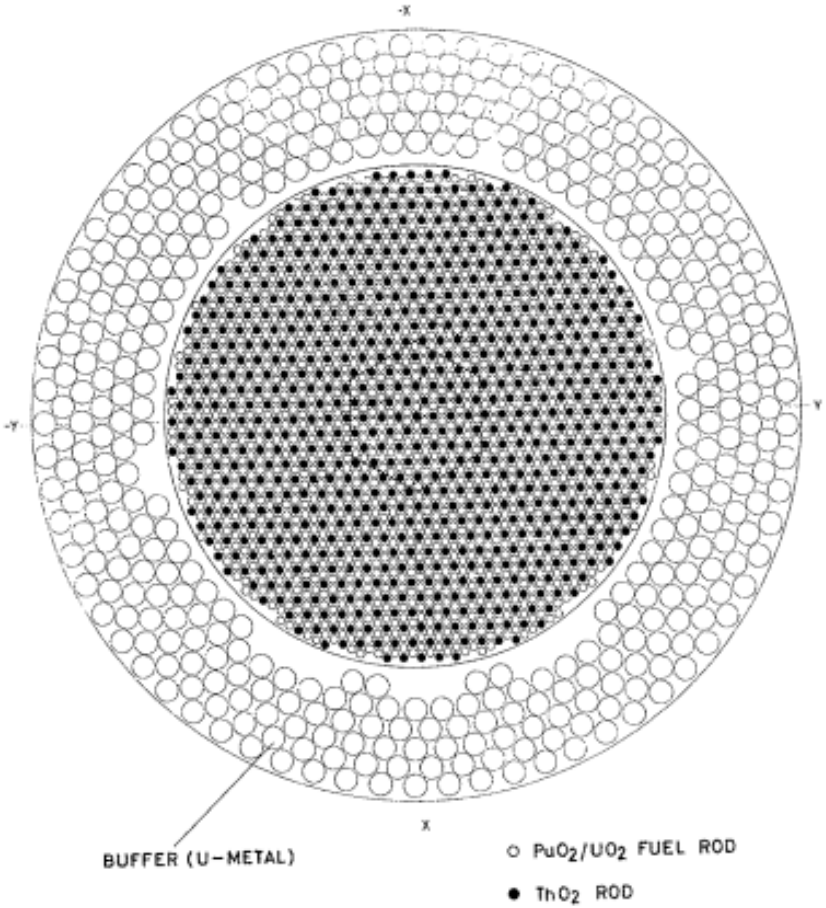

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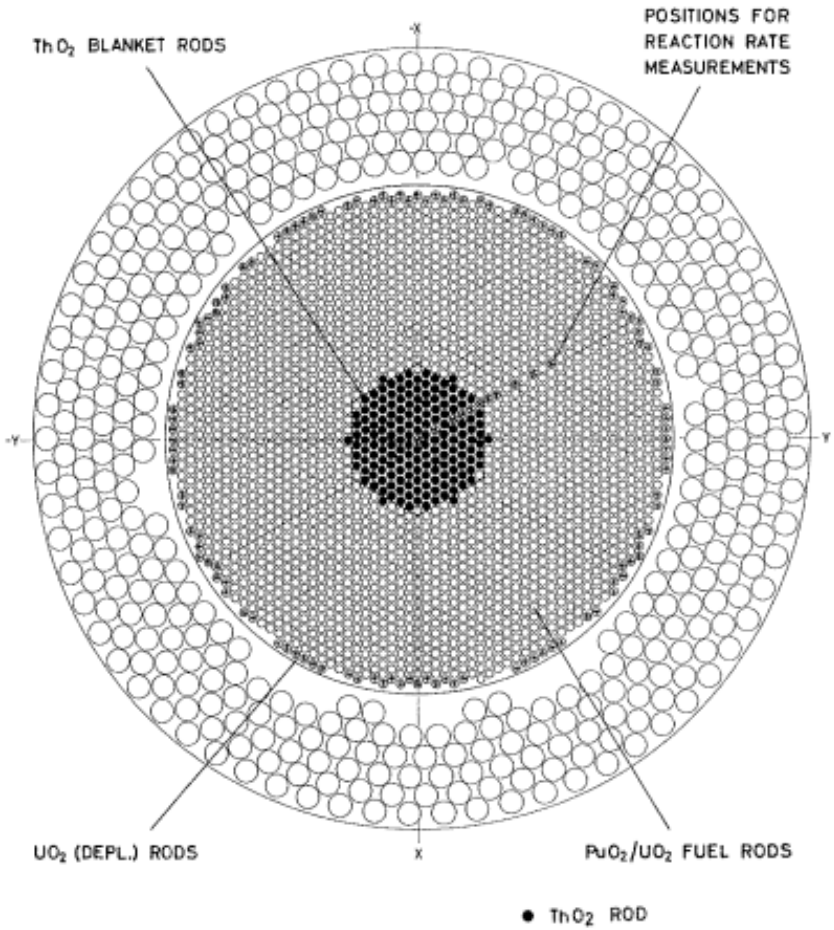

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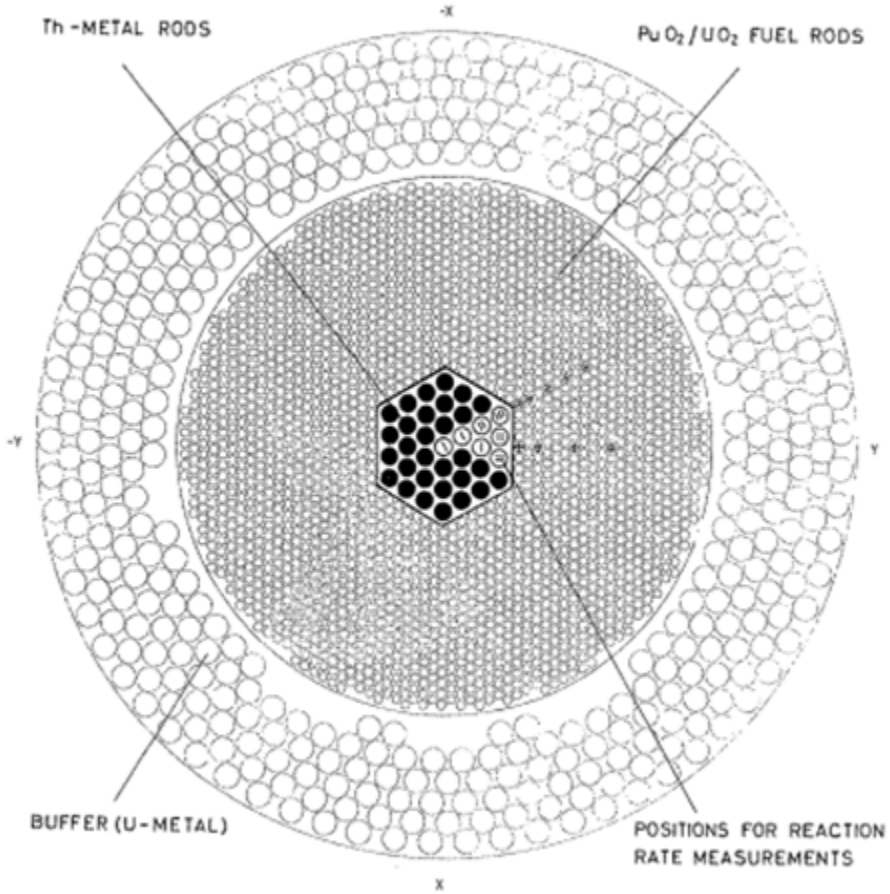

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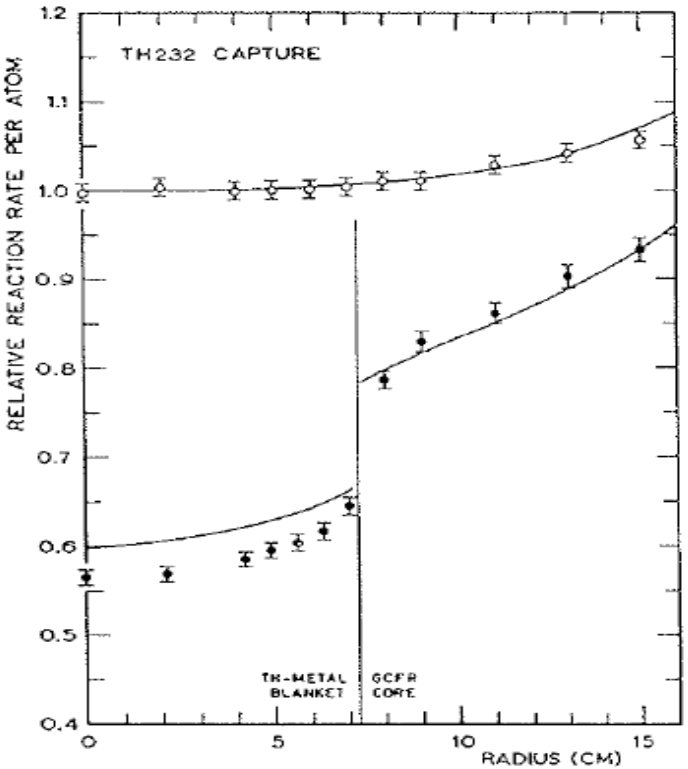
GCFR Measurements

- Axial / radial reaction rate distributions (activation foils / fission ch.)
  - Capture in ^{238}U, ^{232}Th
  - Fission in ^{239}Pu, ^{238}U, ^{235}U, ^{233}U, ^{232}Th
- Spectral indices
  - C8/F9 , F8/F9 , F5/F9,
  - C2/F9, (n,2n)2/C2, F3/F9
  - C7/F9, F7/F9
- Small sample reactivity worth
- Neutron spectrum measurements



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- Small sample reactivity worth

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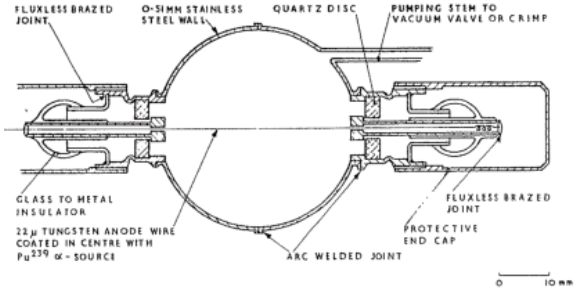
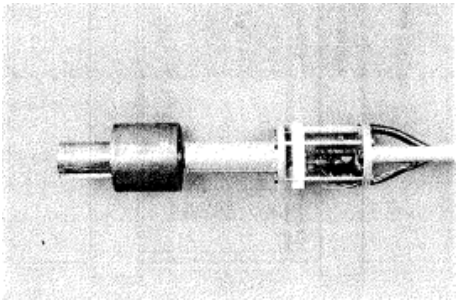
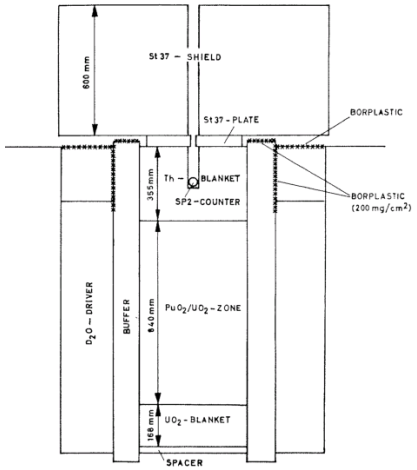
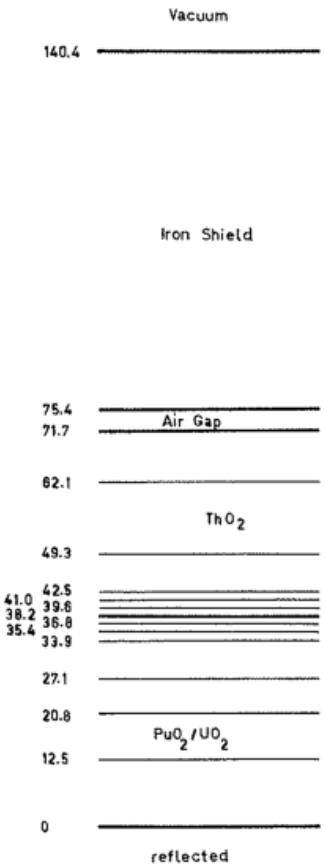


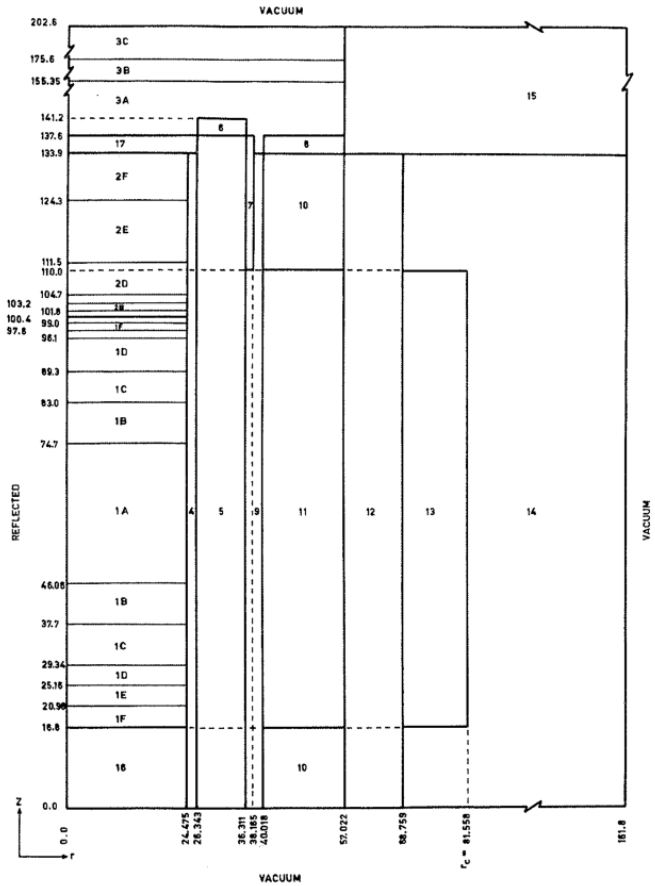




GCFR Calculations

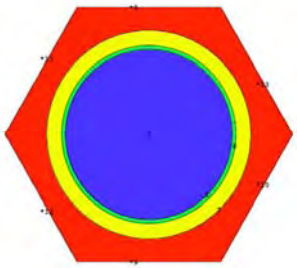
- Deterministic Calculations
  - SN 1-D, DIFF-1D
  - DIFF-2D
- Cross-Section Libraries
  - ENDF/B-IV
  - FGL5
- Cross-Sections prepared with GGC-4 and MURLAB cell codes

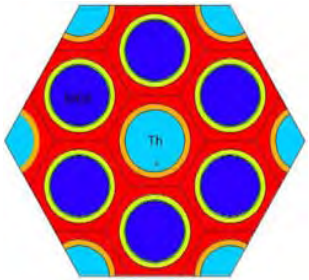


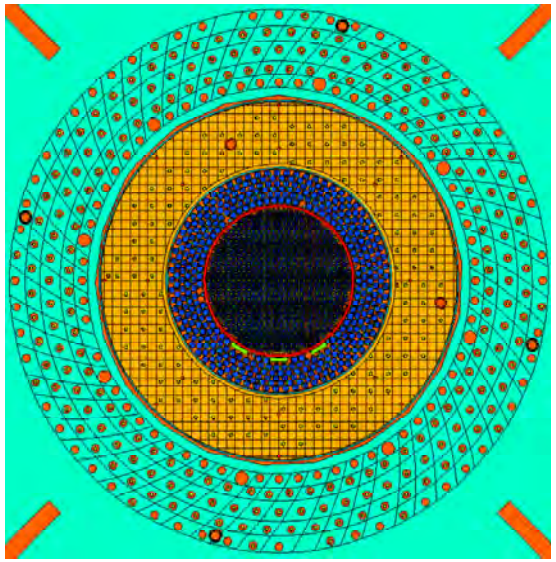


GCFR New Calculation Models

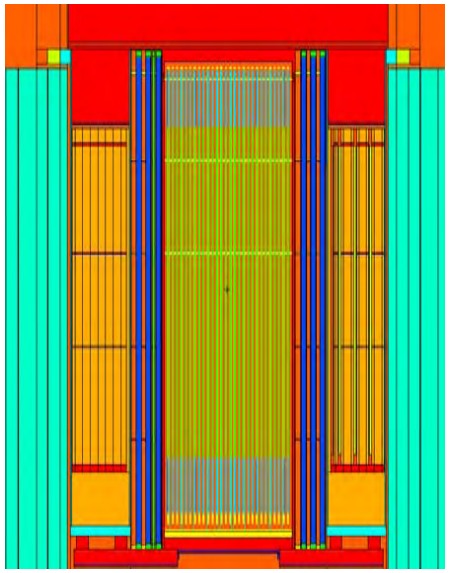
- Monte Carlo Calculations (MCNPX)
  - 2D lattice equivalent cell model
  - 3D whole-reactor core model





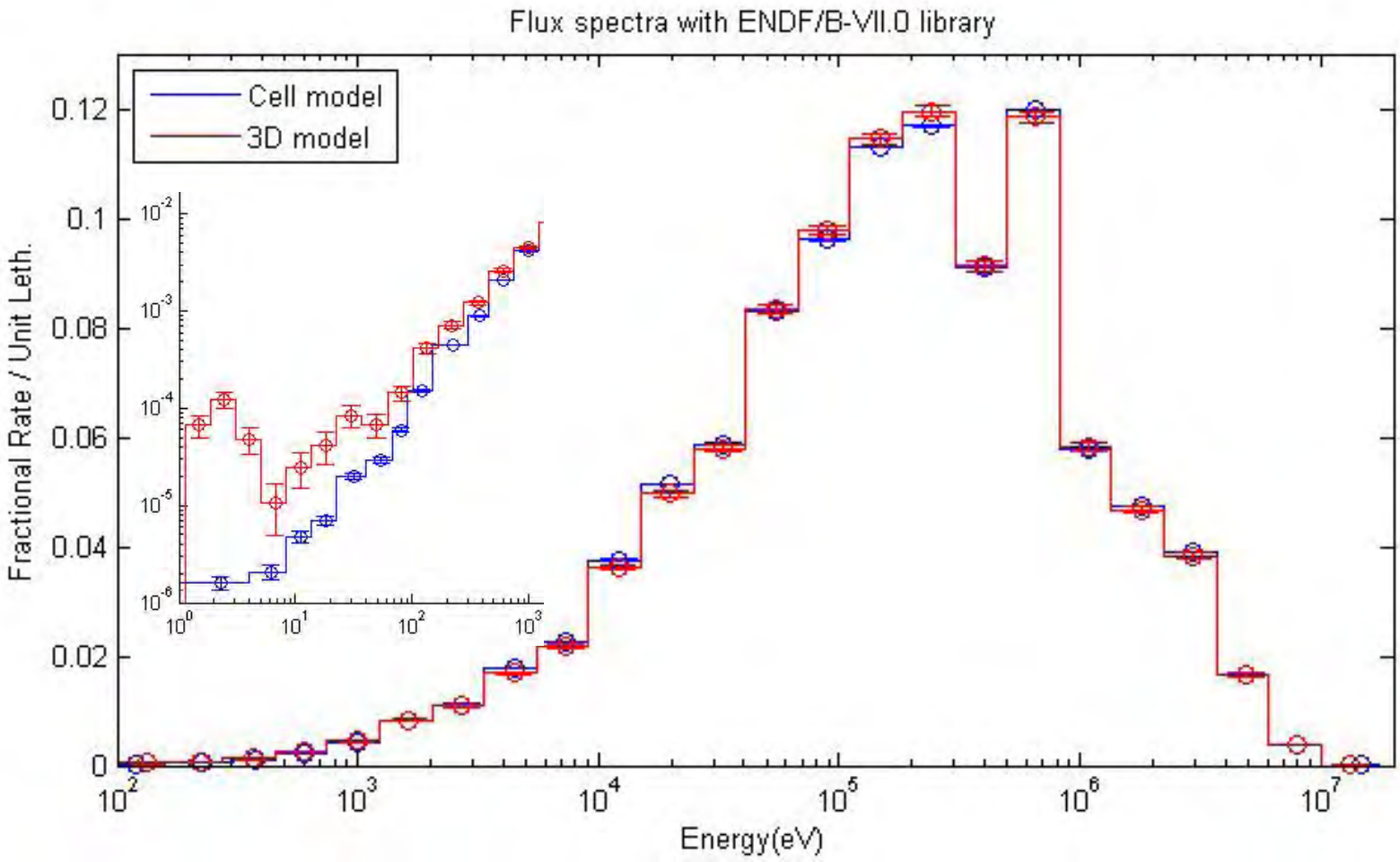


- Cross Section Libraries
  - JEFF-3.1 and 3.1.1,
  - ENDF/B-VII.0 and VII.1
  - JENDL-3.3 and 4.0



- Configurations
  - Homogeneous PuO_2/UO_2 lattice
  - Mixed PuO_2/UO_2-ThO_2 lattice

Representativity of the PROTEUS Lattice



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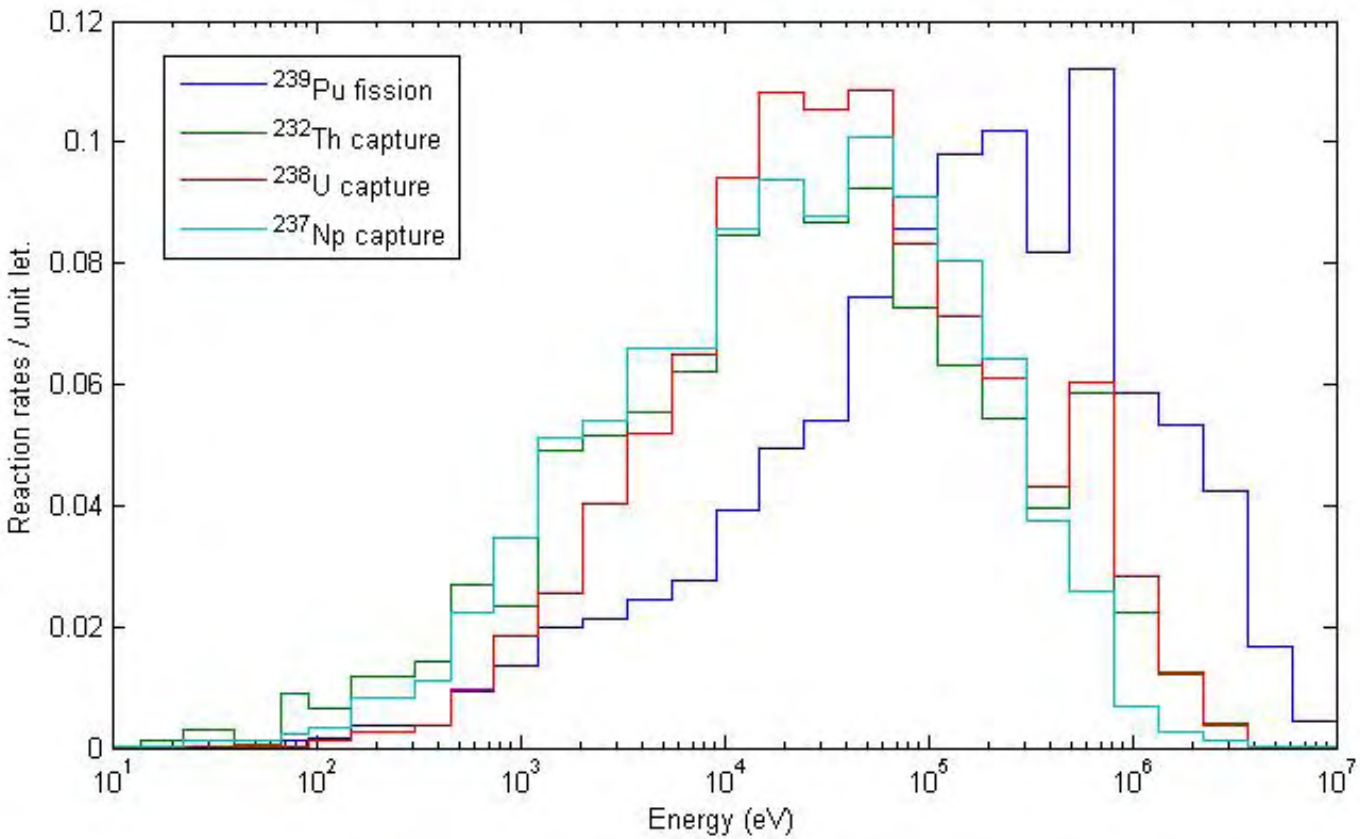


- Spectral indices correction factors (ENDF/B-VII.0)

  C8/F9: 0.988 (0.2%), F8/F9: 0.978 (0.2%), C2/F9: 1.028 (0.5%)

  F2/F9: 0.978 (0.3%), C7/F9: 1.033 (0.2%), (n,2n)2/C2: 0.965 (1.5%)

Calculated Reaction Rate Comparisons

Reaction	B70/B71	J31/B71	JN33/B71	J311/B71	JN40/B71
F5	1.000	1.002	0.999	1.002	0.990
F8	1.000	0.996	1.004	0.996	0.999
F9	1.000	0.997	1.002	0.997	1.005
(n,2n)2	1.002	1.020	**0.851**	1.020	0.987
F2	**0.976**	**1.046**	**1.042**	**1.046**	**1.059**
C8	0.999	1.003	1.028	1.003	1.002
C2	0.994	**0.976**	**0.916**	**0.976**	**0.983**
F3	1.000	1.005	1.005	1.005	1.006
F7	1.000	1.001	1.001	**0.963**	0.992
C7	1.002	**0.960**	**0.960**	**0.972**	**0.974**

- ^{235}U, ^{238}U, ^{239}Pu, ^{233}U fissions and ^{238}U captures are consistent
- ^{237}Np captures 3-4% higher for B71 than other libraries
- ^{232}Th reaction rates larger differences between libraries

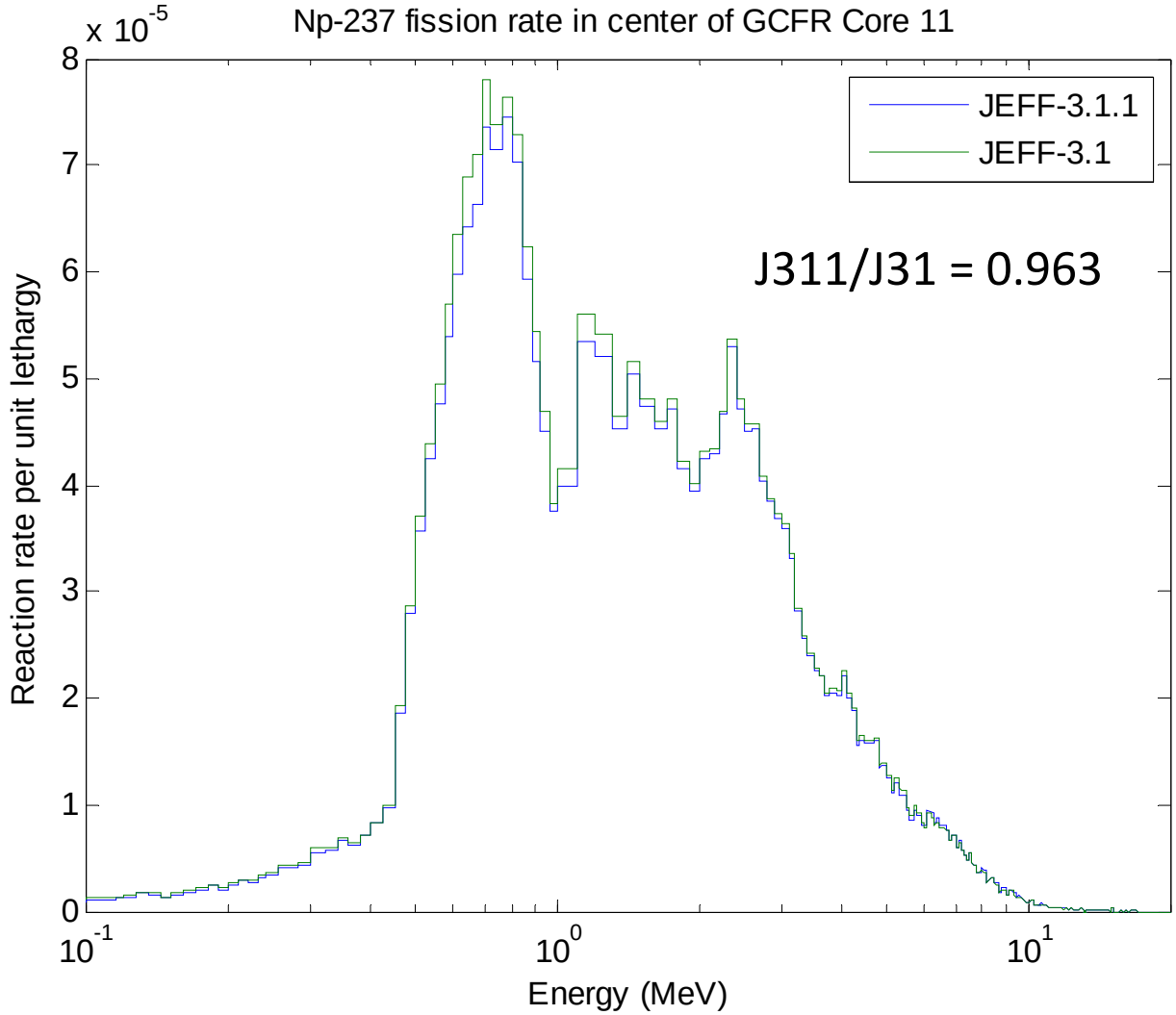
From JEFF-3.1 to JEFF-3.1.1

- Cross section changes
  - Np-237 (n,γ) value was underestimated by 10% at thermal energy in JEFF-3.1 and has been corrected in JEFF-3.1.1
  - Pu-239 cross sections revised to account for the overestimation of the Plutonium-solution-thermal criticality experiments

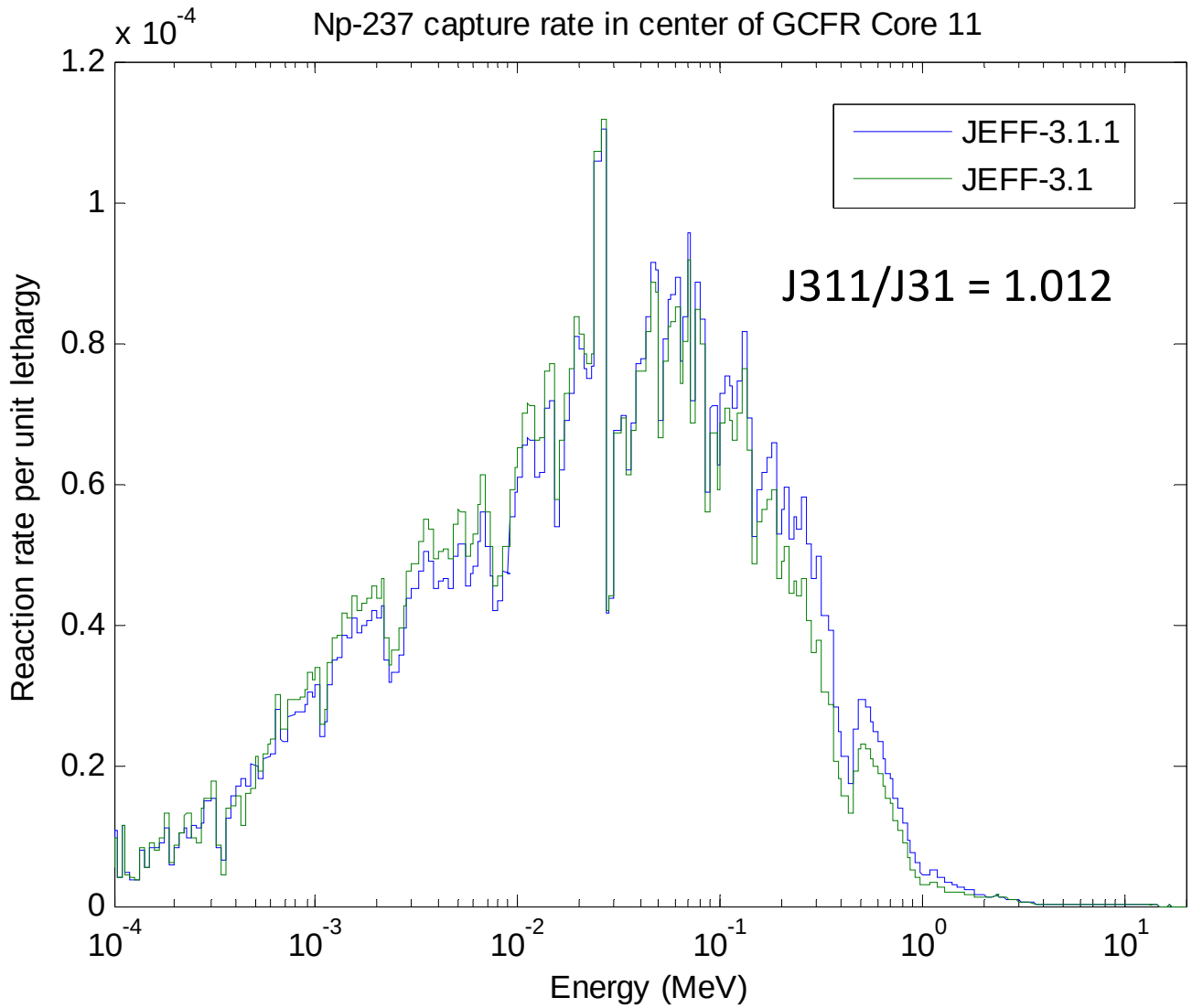
- Reaction rate changes in the GCFR spectra (using full core MCNPX model with Flux calculated with ENDF/B-VII.1)

Reaction	F7	C7	F9
Value (J311/J31)	0.963	1.012	1.000

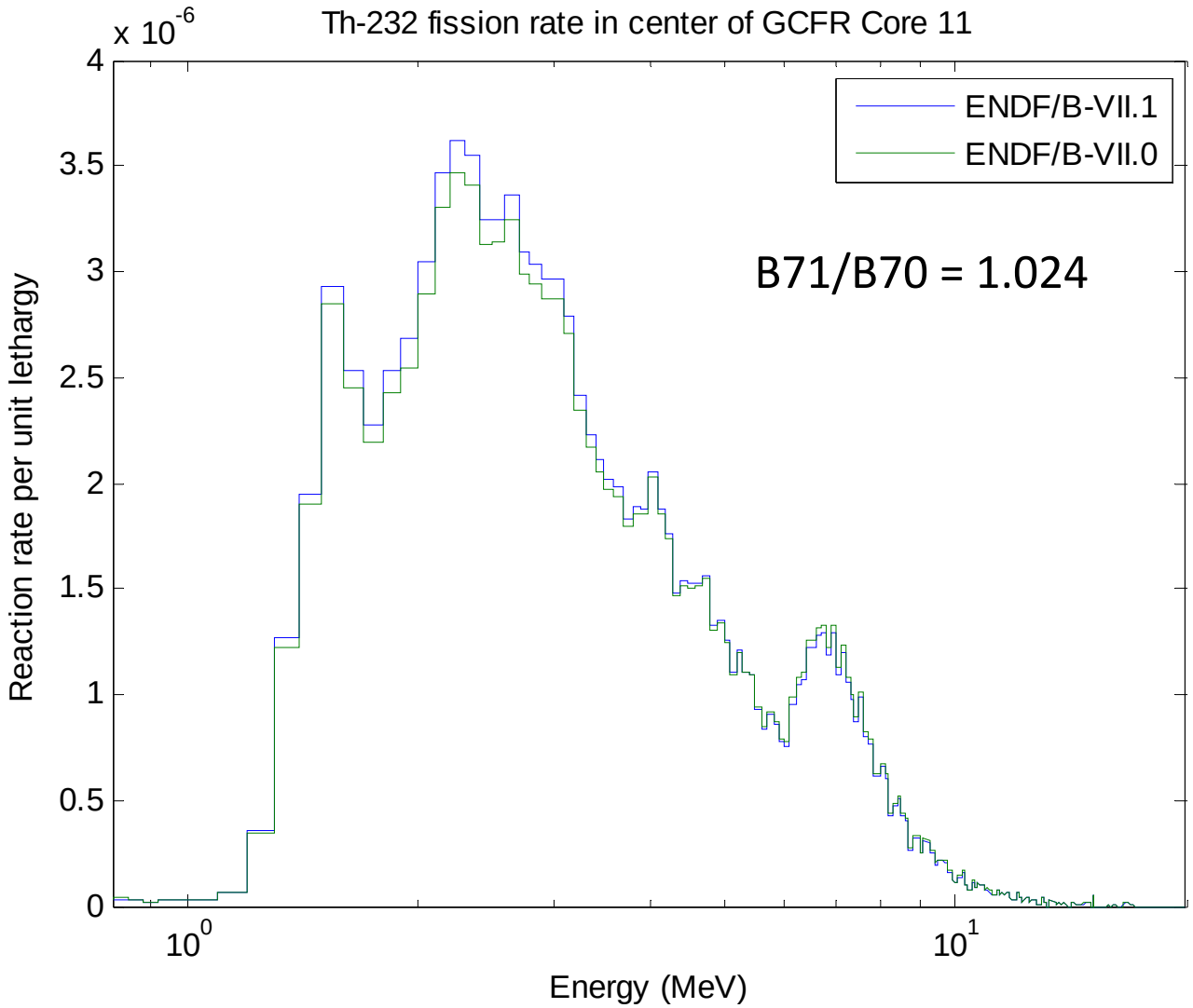
^{237}Np fissions with JEFF-3.1 and 3.1.1



^{237}Np captures with JEFF-3.1 and 3.1.1



^{232}Th fissions with ENDF/B-VII.0 and VII.1



Spectral Indices Agreement with Exp. (1/2)

SI / Library	B70	B71	J31	J311	JN33	JN40
C8/F9	0.995 (1.2%)	0.997 (1.2%)	0.993 (1.2%)	0.991 (1.2%)	0.993 (1.2%)	0.981 (1.2%)
F8/F9	1.009 (1.4%)	1.009 (1.4%)	0.992 (1.4%)	0.992 (1.4%)	**1.032 (1.4%)**	1.008 (1.4%)
F5/F9	1.012 (1.5%)	1.013 (1.5%)	1.012 (1.5%)	1.011 (1.5%)	1.009 (1.5%)	0.991 (1.5%)
F3/F9	0.987 (1.4%)	0.986 (1.4%)	0.992 (1.4%)	0.995 (1.4%)	0.990 (1.4%)	0.983 (1.4%)
C7/F9	1.003 (2.4%)	1.000 (2.4%)	**0.951 (2.4%)**	0.966 (2.4%)	**0.953 (2.4%)**	0.960 (2.4%)
F7/F9	1.003 (1.9%)	1.003 (1.9%)	1.006 (1.9%)	0.969 (1.9%)	1.006 (1.9%)	1.002 (1.9%)

- ^{235}U and ^{233}U fissions and ^{238}U captures are well predicted
- ^{238}U fissions is well predicted except for JN33 (corr. in JN40)
- ^{237}Np captures tend to be underestimated in all but B70 and B71
- ^{237}Np fissions are well predicted except for J311

Spectral Indices Agreement with Exp. (2/2)

SI / Library	B70	B71	J31	J311	JN33	JN40
C8/F9	0.995 (1.2%)	0.997 (1.2%)	0.993 (1.2%)	0.991 (1.2%)	0.993 (1.2%)	0.981 (1.2%)
F8/F9	1.009 (1.4%)	1.009 (1.4%)	0.992 (1.4%)	0.992 (1.4%)	**1.032 (1.4%)**	1.008 (1.4%)
F5/F9	1.012 (1.5%)	1.013 (1.5%)	1.012 (1.5%)	1.011 (1.5%)	1.009 (1.5%)	0.991 (1.5%)
F3/F9	0.987 (1.4%)	0.986 (1.4%)	0.992 (1.4%)	0.995 (1.4%)	0.990 (1.4%)	0.983 (1.4%)
C2/F9	1.015 (1.4%)	**1.032 (1.5%)**	0.985 (1.5%)	0.994 (1.6%)	**0.931 (1.6%)**	0.985 (1.5%)
F2/F9	**0.913 (2.1%)**	**0.935 (2.1%)**	0.965 (2.1%)	0.965 (2.1%)	0.996 (2.1%)	0.991 (2.1%)
(n,2n)2/C2	**1.084 (2.9%)**	1.054 (2.9%)	**1.112 (3.2%)**	1.051 (3.8%)	1.026 (3.8%)	**1.126 (3%)**

- ^{232}Th captures underestimated in JN33 but corrected in JN40
- ^{232}Th fissions underestimated in B70 and B71
- ^{232}Th (n,2n) overestimated in B70, J31 and JN40

Conclusions (1/2)

- MCNPX 3D whole reactor model of the GCFR experiments in the zero power reactor PROTEUS has been built

- PROTEUS configuration has been shown to be representative of an infinite lattice

- Spectral indices predictions with modern libraries and the 3D MCNPX model improve previous results (deterministic/old libraries)

Conclusions (2/2)

- General good agreement between predictions and experimental results is seen in the PuO_2/UO_2 lattice with the exception of:

Library	F8/F9	C7/F9	C2/F9	F2/F9	(n,2n)2/C2
ENDF/B-VII.0	-	-	-	0.913 (2.1%)	1.084 (2.9%)
JEFF-3.1	-	0.951 (2.4%)	-	-	1.112 (3.2%)
JENDL-3.3	1.032 (1.4%)	0.953 (2.4%)	0.931 (1.6%)	-	-
ENDF/B-VII.1	-	-	-	0.935 (2.1%)	-
JEFF-3.1.1	-	-	-	-	-
JENDL-4.0	-	-	-	-	1.126 (3%)

- Better agreement with the latest libraries (B71, J31 and JN40)
- All results are in good agreement with JEFF-3.1.1
- Some trends:
  - J31 -> J311: Capture in ^{237}Np improved, Fission in ^{237}Np worsen
  - B70->B71: Fission in ^{232}Th improved

Perspectives

- PROTEUS GCFR experiments are rich
  - 20 configurations with axial / radial blankets
  - Oxide and metal thorium investigations
  - Several type of measurements – SI, reaction rate dist., react. worth

- Capitalize on the effort to construct a high fidelity whole core model of the GCFR experiments

- Extend the Spectral Indices validations to heterogeneous core configurations with thorium oxide and metal

- Investigate the axial and radial reaction rate distributions at the interface between PuO_2/UO_2 and thorium oxide and metal pins

Thanks are due to:

- swiss*nuclear* for their constant support of the PROTEUS reactor and PROTEUS teams
- R. Capote and A. Trkov for their assistance with JENDL-4.0 and ENDF/B-VII.1