Integral experiments for Bi nuclear data validation at the fast VENUS-F reactor

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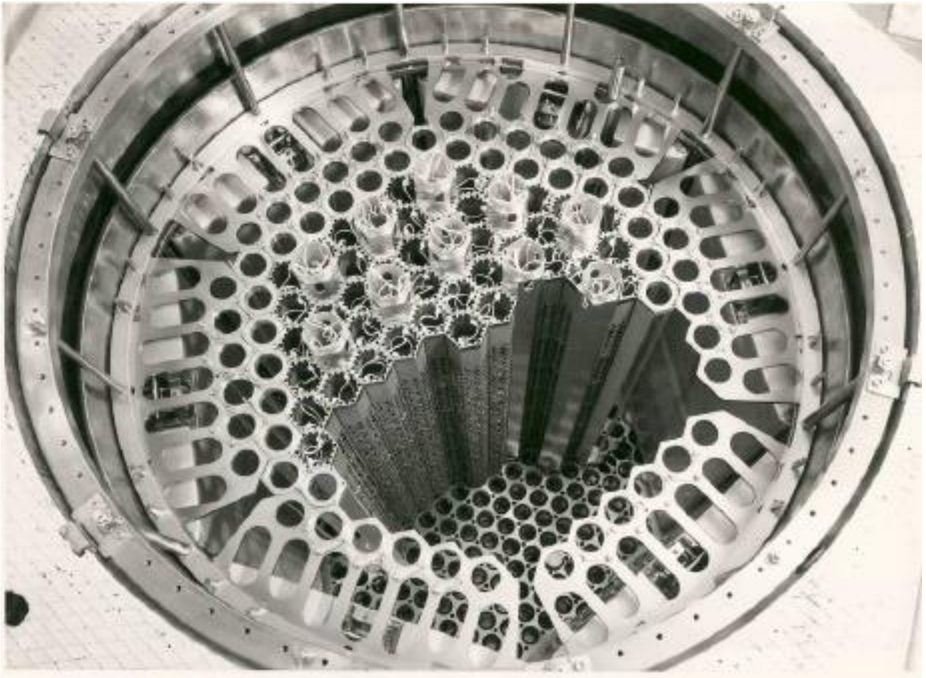
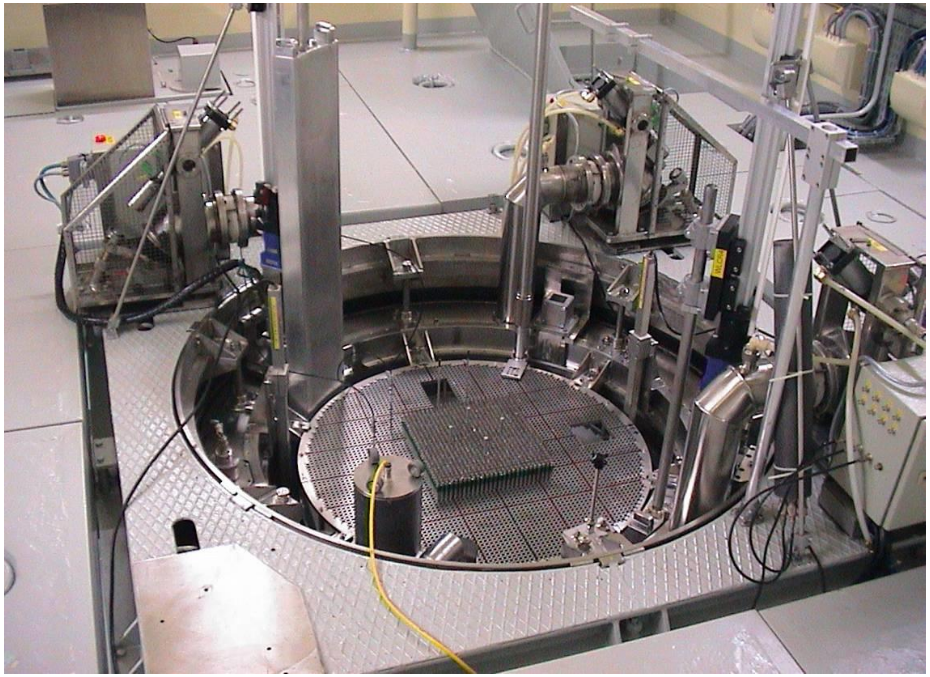
VENUS (1964-2007)

- zero-power nuclear reactor
- thermal (water moderated)
- at SCK•CEN in Mol, Belgium





VENUS (1964-2007)

- Integral experiments for nuclear data validation
- mock-up for PWR and BWR reactors

NEA NUCLEAR SCIENCE COMMITTEE
TASK FORCE ON COMPUTING RADIATION DOSE AND MODELLING
OF RADIATION-INDUCED DEGRADATION OF REACTOR COMPONETS

PREDICTION OF NEUTRON EMBRITTLEMENT IN THE REACTOR PRESSURE VESSEL:

VENUS-1 AND VENUS-3 BENCHMARKS

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Nuclear Science
NEA/NSC/DOC(2003)5
ISBN 92-64-02160-4

Benchmark on the Three-dimensional VENUS-2 MOX Core Measurements

Final Report

January 2004

NEA No. 4438

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

VENUS-F (since 2011)

- **VENUS-F**
  - zero-power **f**ast reactor
  - solid Pb, Bi as coolant simulator and reflector
  - can be operated critical and subcritical
  - serves as a mockup of MYRRHA reactor core
- **MYRRHA**
  - fast reactor/ADS demonstrator
  - LBE as coolant and spallation target

- validation of online reactivity monitoring
- validation of nuclear data and neutronic codes

GUINEVERE FREYA Myrte MYRRHA Research and Transmutation Endeavour

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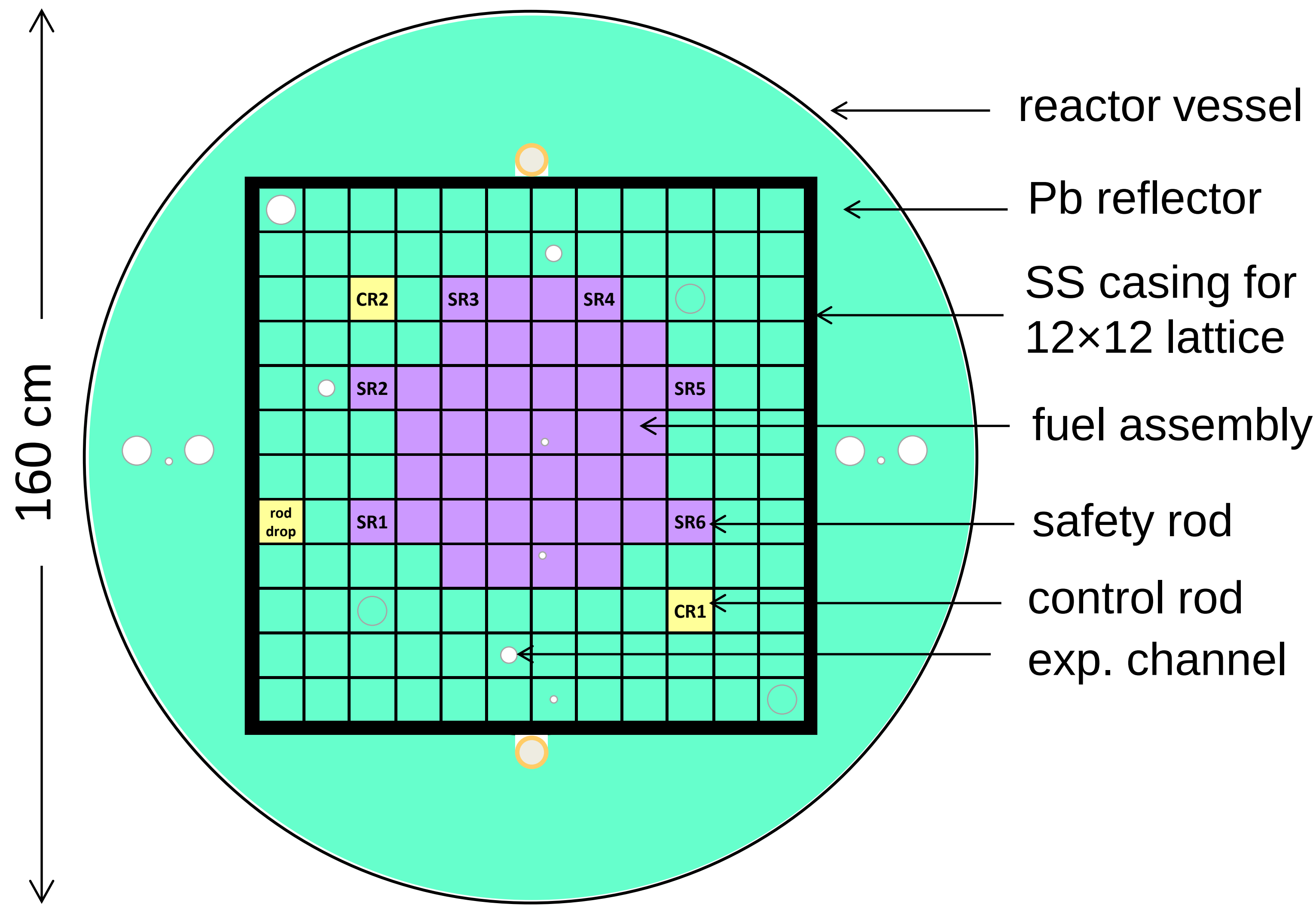
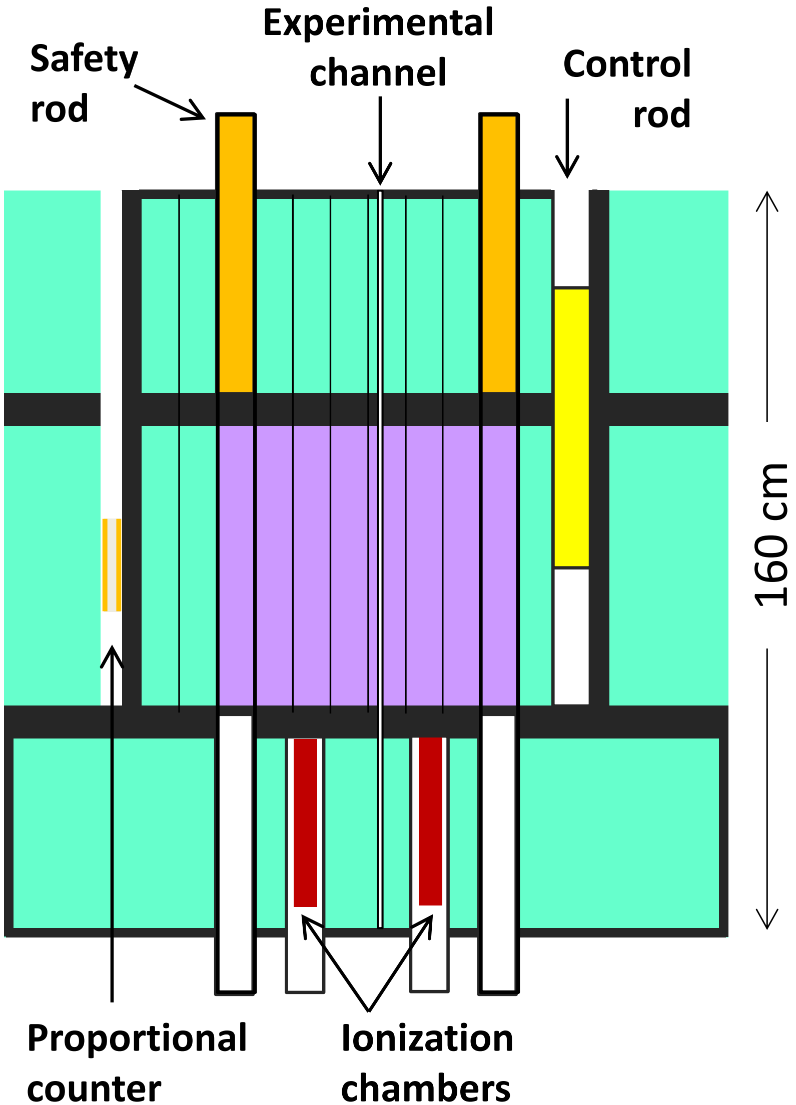
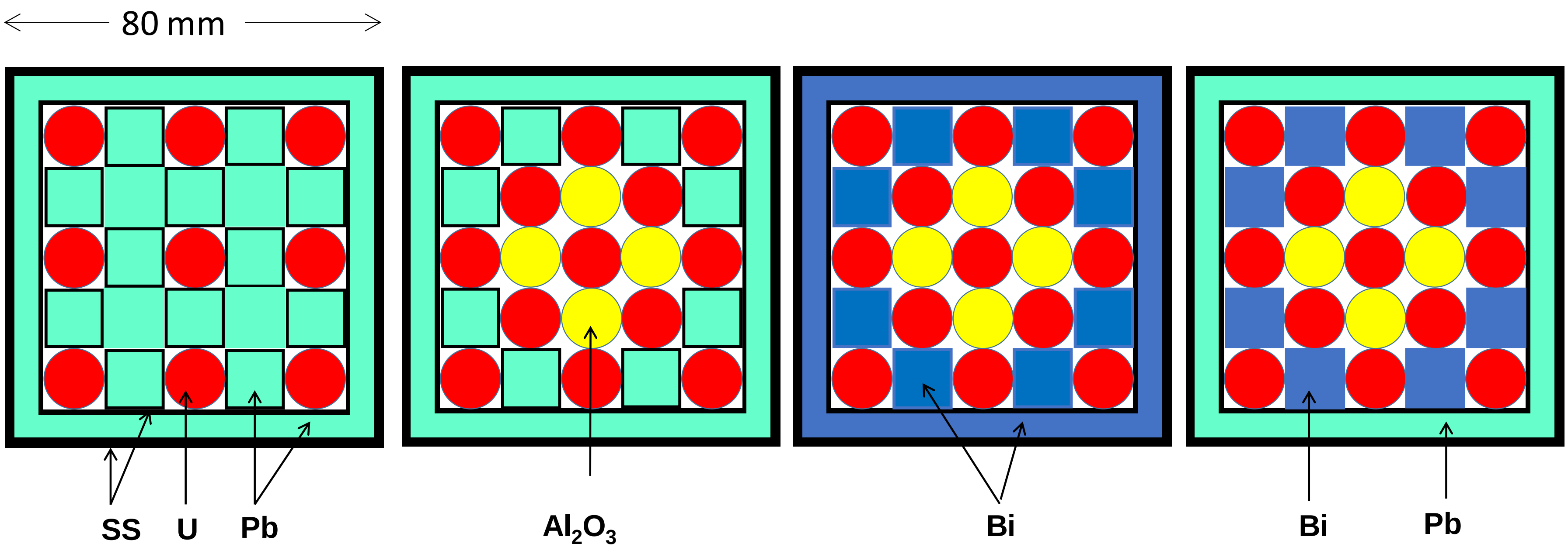
VENUS-F – a versatile reactor

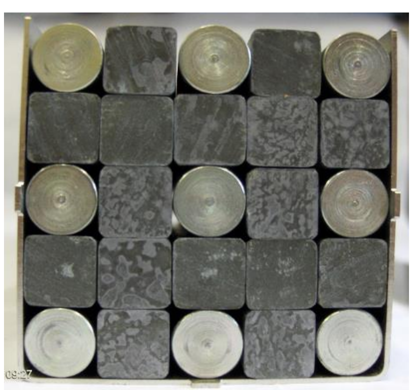


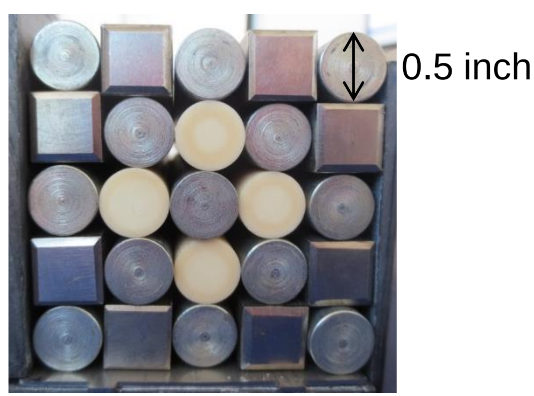
VENUS-F - axial view

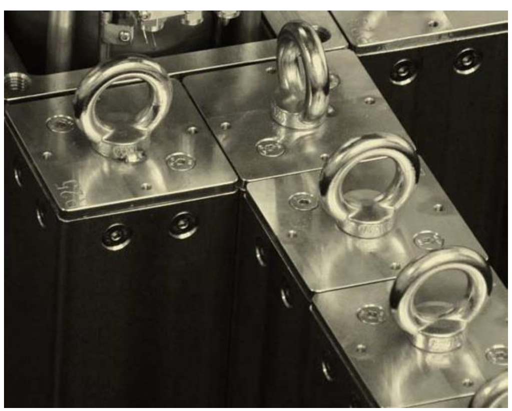


VENUS-F fuel assembly

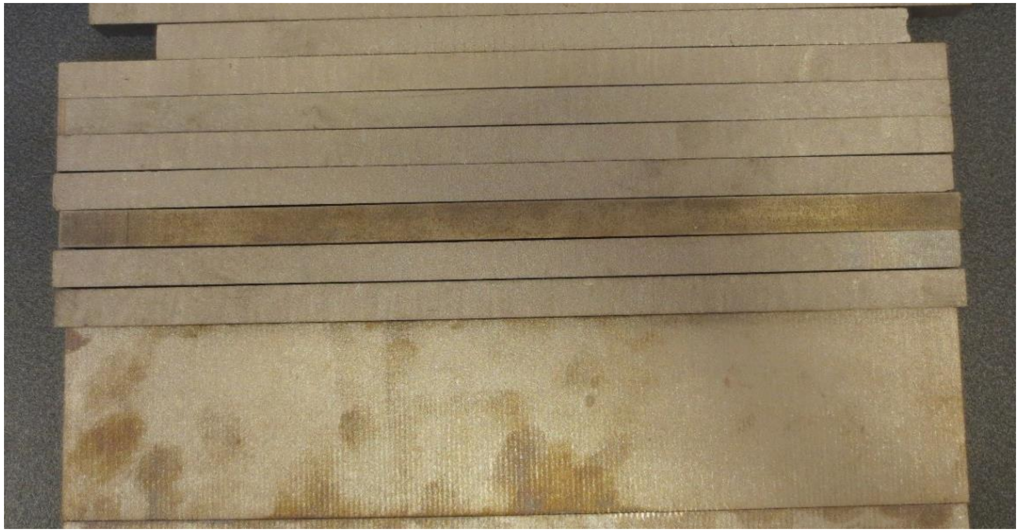


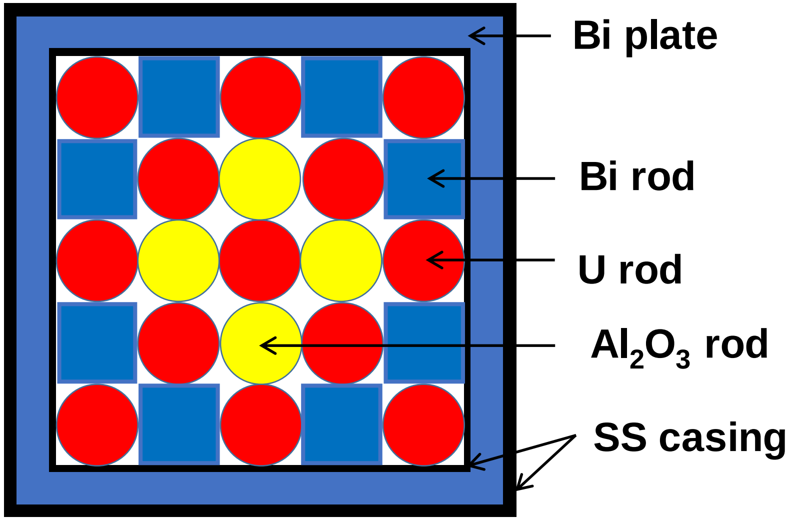


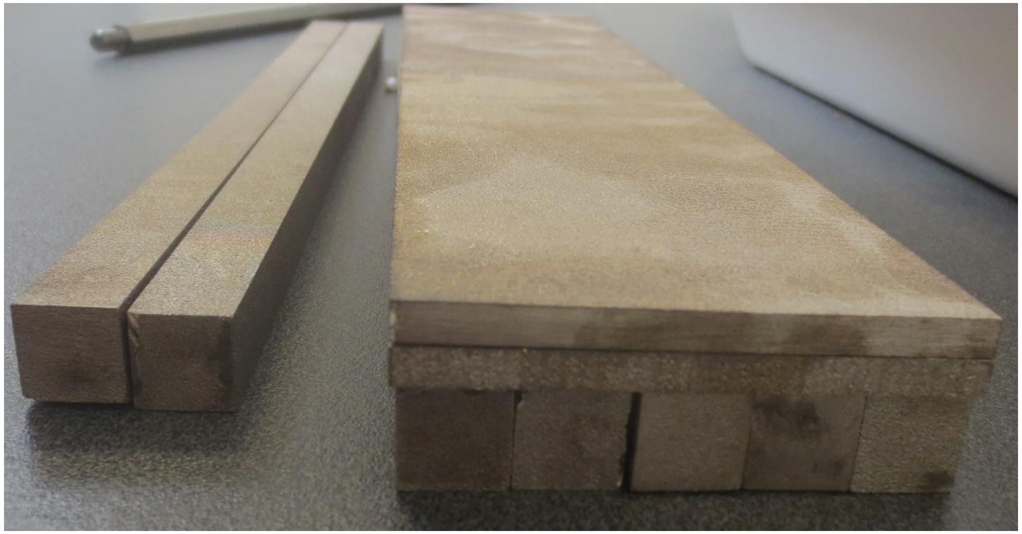


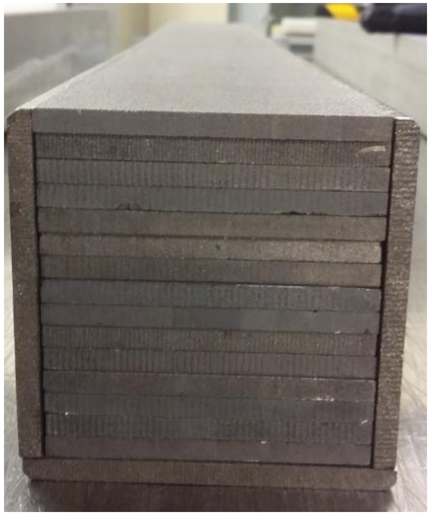


Bi rods and plates



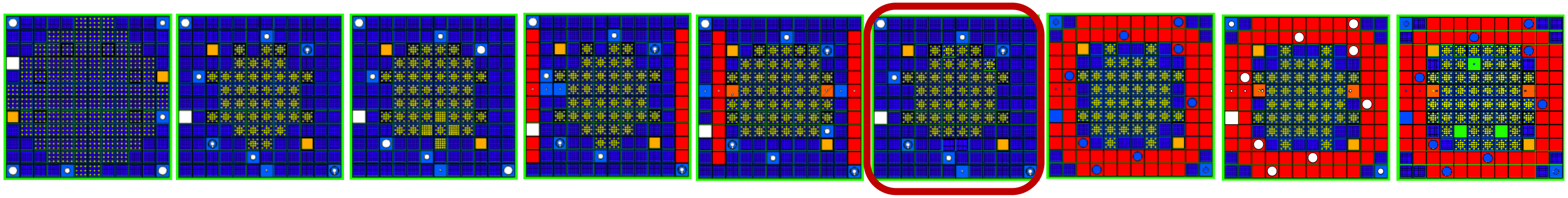






VENUS-F reactor cores

- So far 9 core configurations reached criticality

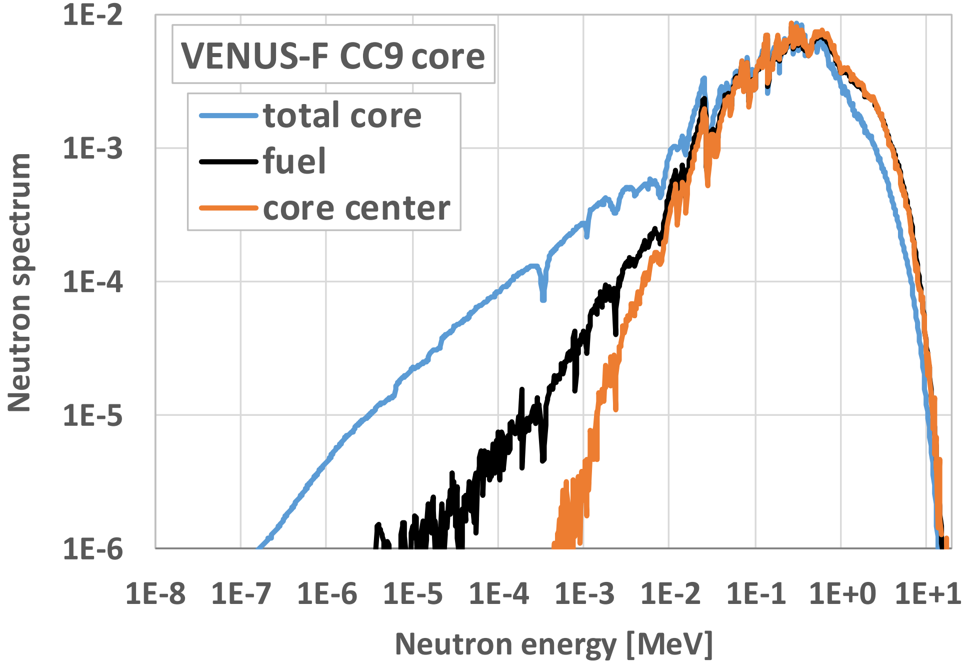


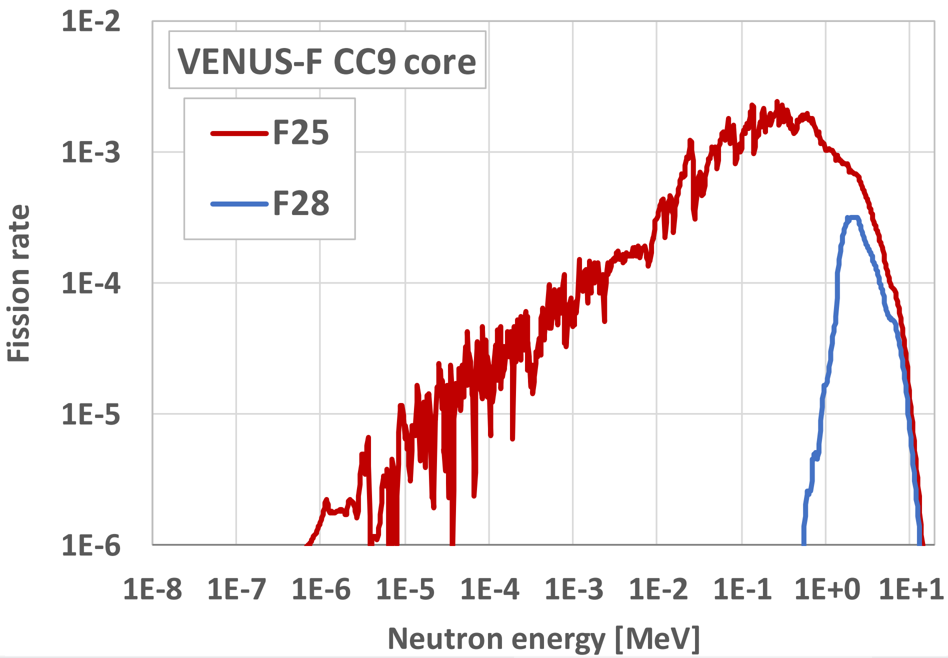
Critical configuration	#FAs	FA composition	Reflector	IPS
CR0	97	U+Pb	Pb	-
CC5	41	U+Pb+Al_2O_3	Pb	-
CC6	41	U+Pb+Al_2O_3	Pb	-
CC7	41	U+Pb+Al_2O_3	Pb+C	-
CC8	47	U+Pb+Al_2O_3	Pb+C	thermal spectrum
CC9	41	U+Bi+Al_2O_3	Pb	-
CC10	41	U+Pb+Bi+Al_2O_3	Pb+C	-
CC10b	47	U+Pb+Bi+Al_2O_3	Pb+C	thermal spectrum
CC11	50	U+Pb+Bi+Al_2O_3	Pb+C	thermal and fast spectrum

Performed experiments

Core	Criticality	Kinetic parameters	CR curve	SR, FA, RA, IPS worth	Spectral indices	Axial traverse	Radial traverse	Pb/Bi void	Fuel Doppler
CR0	×	×	×	×	×	×	×		×
CC5	×	×	×	×	×	×	×		×
CC6	×				×	×			
CC7	×	×	×		×	×	×	×	×
CC8	×		×	×	×	×	×		
CC9	×	×	×	×	×	×		×	×
CC10	×	×	×	×	×				
CC10b	×			×					
CC11	×		×		×		×	×	

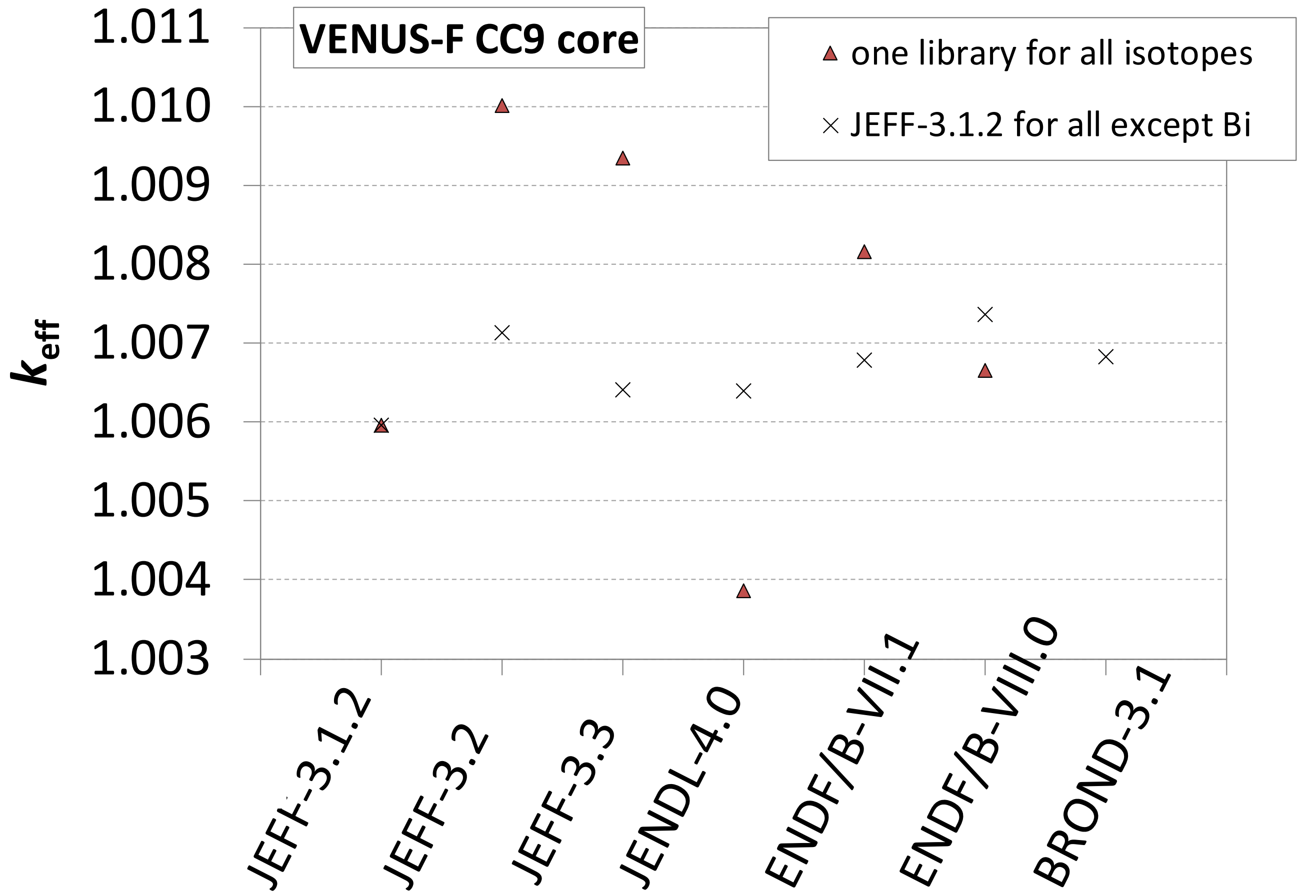
Neutron spectra and fission rates





- MCNP calculations with JEFF-3.1.2

MCNP calculation of the CC9 core criticality



- up to 600 pcm variation in k_{eff} when σ for all isotopes changed
- up to 140 pcm variation in k_{eff} due to change of Bi cross section

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DN parameters in analysis of experimental data

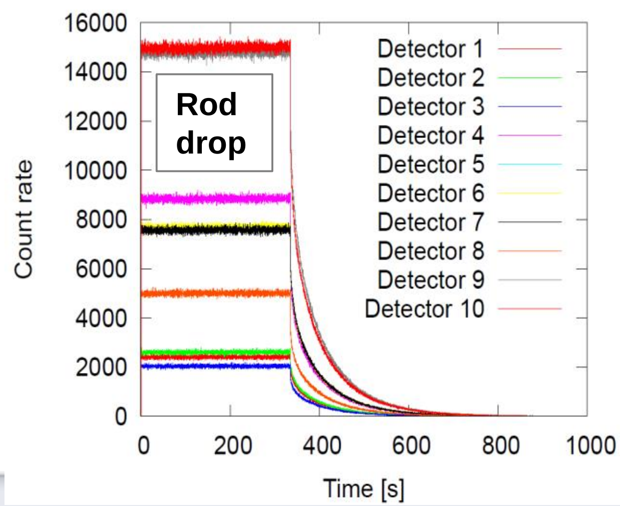
- Core averaged DN data are used as input into analysis of exp. data
- For each core configuration, averaged group half-lives and corresponding group delayed neutron fractions are calculated (MCNP)

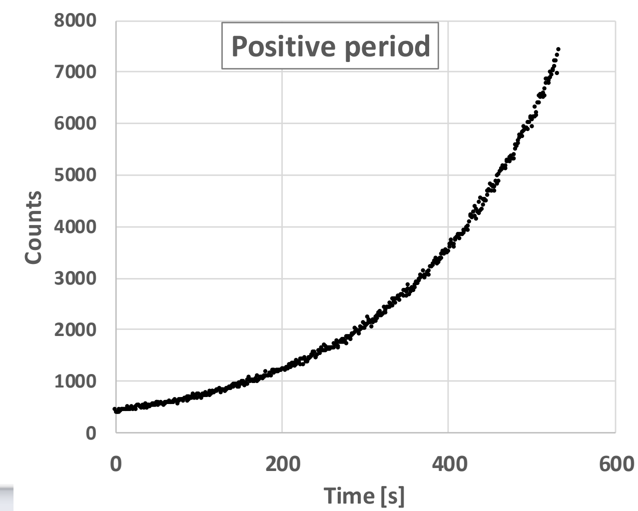
integral counting method: $$-\frac{\rho}{\beta_{eff}} = \frac{n_0 \sum_{i=1}^{G} \frac{\alpha_i}{\lambda_i}}{\int_0^\infty n(t)dt}$$

inhour equation: $$\frac{\rho}{\beta_{eff}} = \sum_{i=1}^{G} \frac{\alpha_i}{1+\lambda_i T}$$

inverse point kinetics: $$\frac{\rho(t)}{\beta_{eff}} = 1 + \frac{1}{n(t)}\left(\frac{\Lambda_{eff}}{\beta_{eff}}\frac{dn}{dt} - n_0\sum_{i=1}^{G}\alpha_i \exp(-\lambda_i t) - \sum_{i=1}^{G}\alpha_i\lambda_i\int_0^t n(t')\exp(-\lambda_i(t'-t))dt'\right)$$

$\alpha_i = \beta_i / \beta_{eff}$





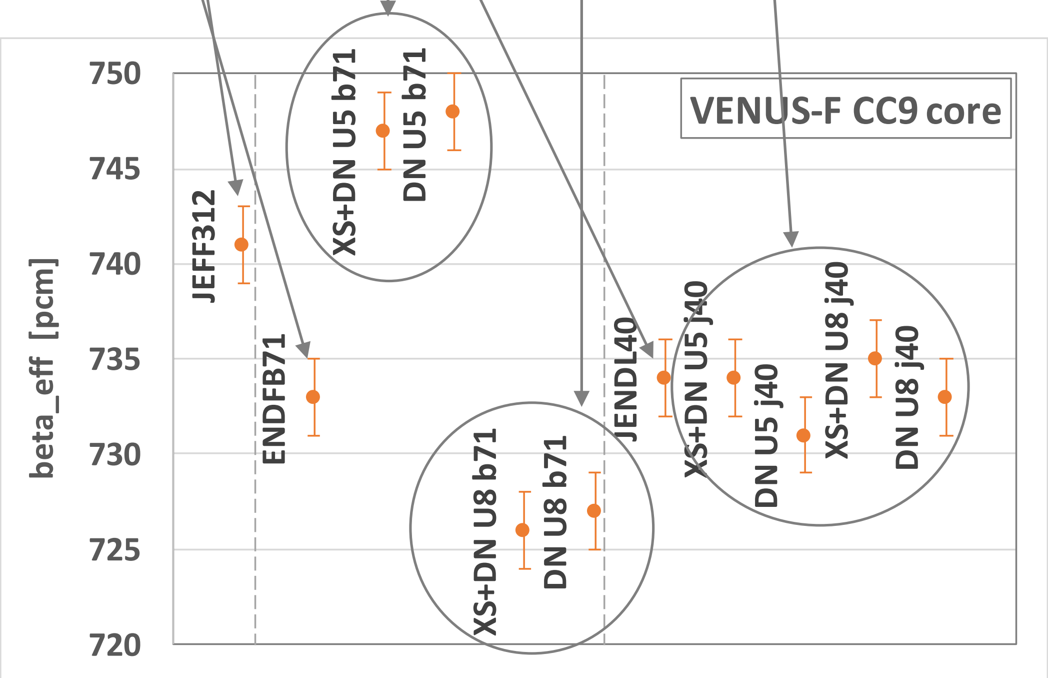
Delayed neutron data of ^{235}U and ^{238}U

- JEFF (since v.3): 8-group time structure of DN data (by Spriggs)
- JENDL (since 3.3): 6-group DN data
  - Least square method based on experimental and evaluated data
- ENDF/B (since v.VII): 6-group DN data (different group half-lives than JENDL)
  - CINDER'90 summation calculations based on evaluated exp. data file NuBase2003 (if not available, then calculated - quasi-particle random-phase approximation and the statistical gross theory)

Group structure	**8-g**	**6-g**			
Isotopes	**all**	**235U**		**238U**	
Group	**JEFF (Spriggs)**	**JENDL (Keepin)**	**ENDF**	**JENDL (Keepin)**	**ENDF**
1	55.6	55.7	52.0	52.4	50.9
2	24.5	22.7	21.2	21.6	22.1
3	16.3	6.22	5.74	5.00	5.62
4	5.21	2.3	2.29	1.93	2.14
5	2.37	0.61	0.82	0.49	0.77
6	1.04	0.23	0.24	0.17	0.23
7	0.424				
8	0.195				

Impact of DN data on β_{eff} in VENUS-F

- Reference: JEFF-3.1.2 (cross-sections and DN data of all isotopes)
- ENDF/B-VII.1 or JENDL-4.0 give 1% less than JEFF-3.1.2 (3-4 σ)
- 1% smaller value if (in the reference calculation) any of the ^{235}U or ^{238}U cross-sections or DN data are replaced with JENDL-4.0 (while keeping everything else from JEFF-3.1.2)
- 2% smaller value if ENDF/B-VII.1 DNs data are used for ^{238}U
- 1% bigger value if ENDF/B-VII.1 DNs data are used for ^{235}U



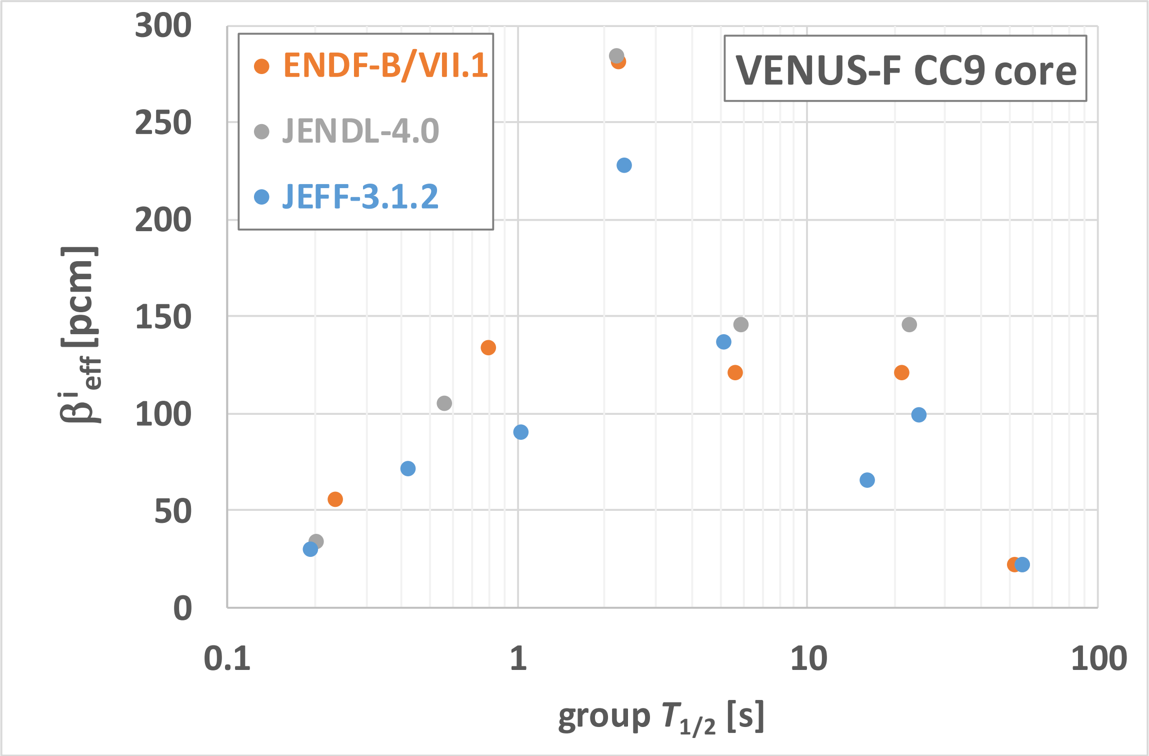
Impact of DN data on λ^i in VENUS-F

- Reference: JEFF-3.1.2– the same half-lives of 8 groups for ^{235}U and ^{238}U
- if 6-g DN data (of ENDF or JENDL) are applied for one of the isotopes, half-lives of 1st-6th group of a certain reactor configuration change
- By mixing 6-g and 8-g DN data for ^{235}U and ^{238}U can lead to absurd core averaged results: the 6th group can have shorter half-life than the 7th group

VENUS-F CC9 core		DN group							
DN data library		1st	2nd	3rd	4th	5th	6th	7th	8th
235U	238U	**T 1/2 [s]**							
JEFF-3.1.2	JEFF-3.1.2	55.6	24.5	16.3	5.21	2.37	1.04	0.424	0.195
ENDF/B-VII.1	JEFF-3.1.2	52.2	21.6	5.96	2.41	1.05	0.374	0.424	0.195

Impact of DN data on β^i_{eff} in VENUS-F

- Core averaged delayed neutron fractions calculated using different libraries difficult to compare because of different group half-lives



=> impact is best visible on reactivity effects

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Impact of DN data on experimental results (I.)

- Example – rod worth

$$-\frac{\rho}{\beta_{\text{eff}}} = \frac{n_0 \sum_{i=1}^{G} \frac{\alpha_i}{\lambda_i}}{\int_0^\infty n(t)dt}$$

$\alpha_i = \beta_i / \beta_{\text{eff}}$

measured count rates

delayed neutron parameters

- JEFF-3.1.2 and JENDL-4.0 (also tested for JEFF-3.2)
  - always lead to almost the same exp. results
  - calculations usually underestimate such exp. results (up to ~10%)
- ENDF/B-VII.1 (also JEFF-3.3T2)
  - leads to about 15% smaller experimental value than when JEFF-3.1.2 is applied
  - calculations usually overestimate such exp. results (~10%, may be up to 25%)

XS+DN library	EXP	MCNP	C/E
JEFF-3.1.2	194 ± 6	178 ± 2	0.92 ± 0.03
JENDL-4.0	192 ± 6	181 ± 2	0.94 ± 0.03
ENDF-B/VII.1	164 ± 5	174 ± 2	1.06 ± 0.03

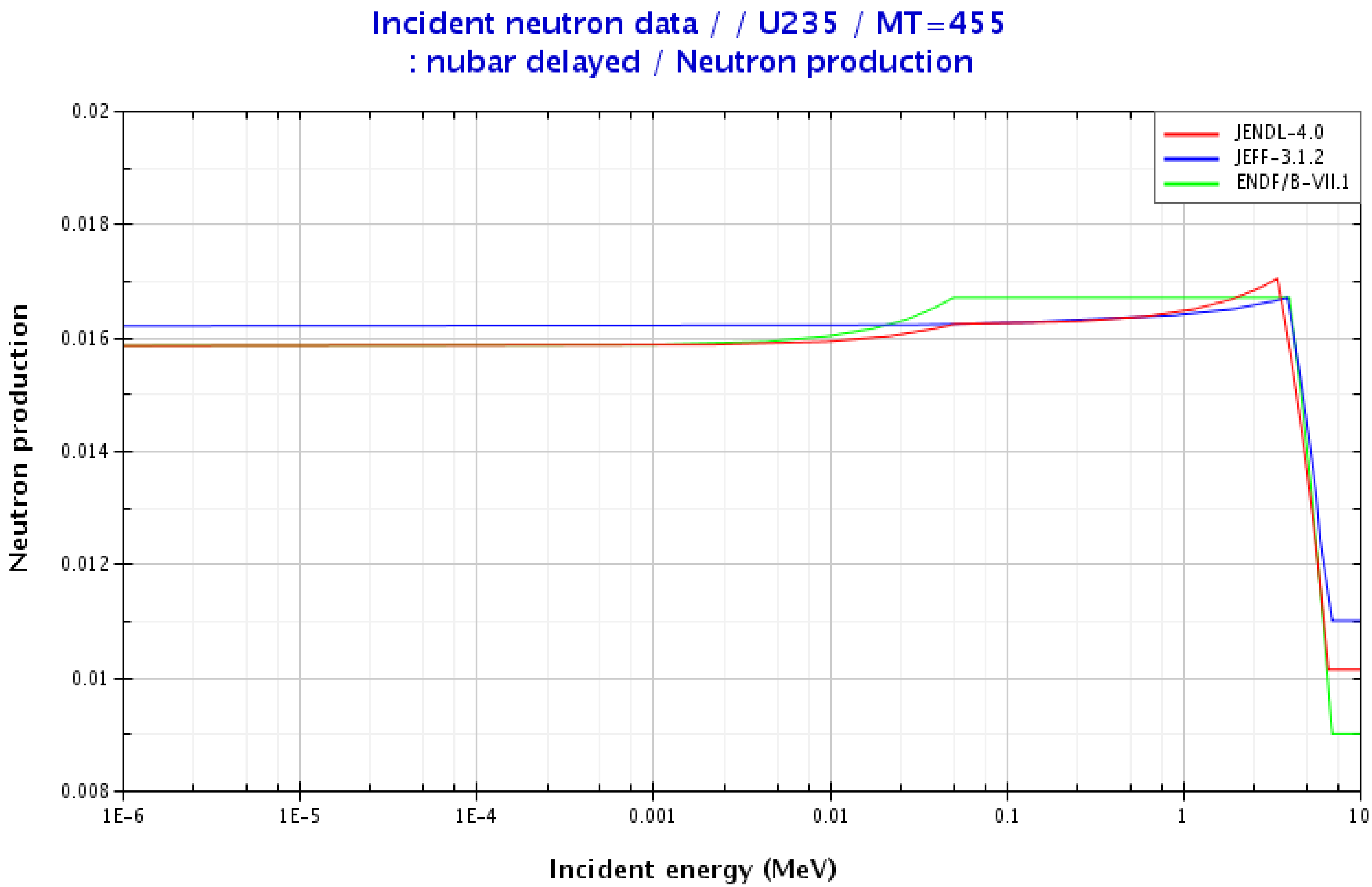
Impact of DN data on experimental results (II.)

- Example – rod worth, JEFF-3.1.2 - reference
- Replacement of JEFF-3.1.2 ^{235}U DN data by:
  - ENDF => exp. results significantly change
  - JENDL => exp. results slightly change
- Replacement of JEFF-3.1.2 ^{238}U DN data by:
  - ENDF => exp. results significantly change and lead to C/E ≈ 1
  - JENDL => exp. results slightly change and lead to C/E ≈ 1

XS library	DN data library		Rod worth		
	235U	238U	C/E		
JEFF-3.1.2			0.92	±	0.03
ENDF/B-VII.1			1.13	±	0.05
JEFF-3.1.2	ENDF/B-VII.1	JEFF-3.1.2	1.09	±	0.03
JEFF-3.1.2	JEFF-3.1.2	ENDF/B-VII.1	0.99	±	0.03
JENDL-4.0			0.91	±	0.04
JEFF-3.1.2	JENDL-4.0	JEFF-3.1.2	0.95	±	0.03
JEFF-3.1.2	JEFF-3.1.2	JENDL-4.0	1.00	±	0.03

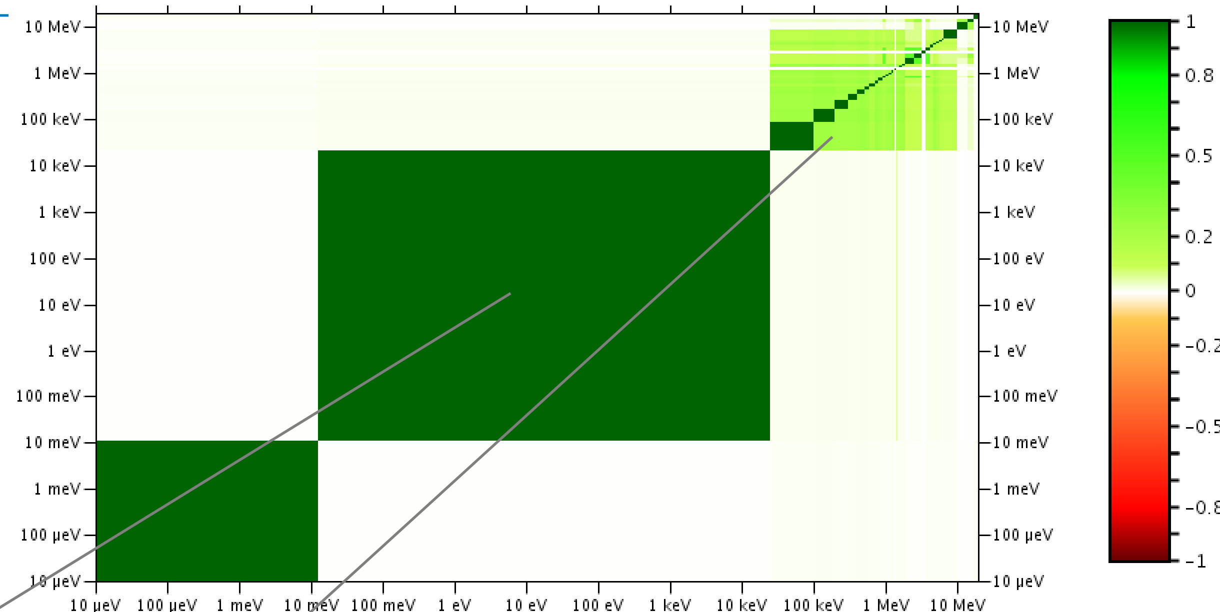
^{235}U delayed neutron multiplicity

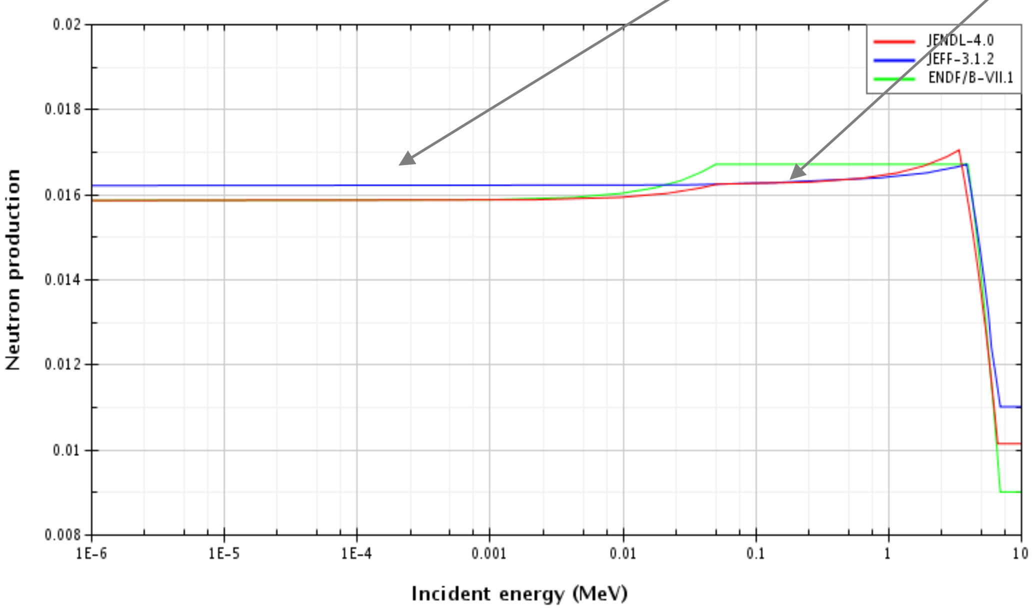
- <10 keV: JENDL and ENDF give nubar 2-3% smaller than JEFF
- 50 keV-1 MeV: ENDF gives nubar 2% bigger than JEFF and JENDL



^{235}U delayed neutron multiplicity – covariance data

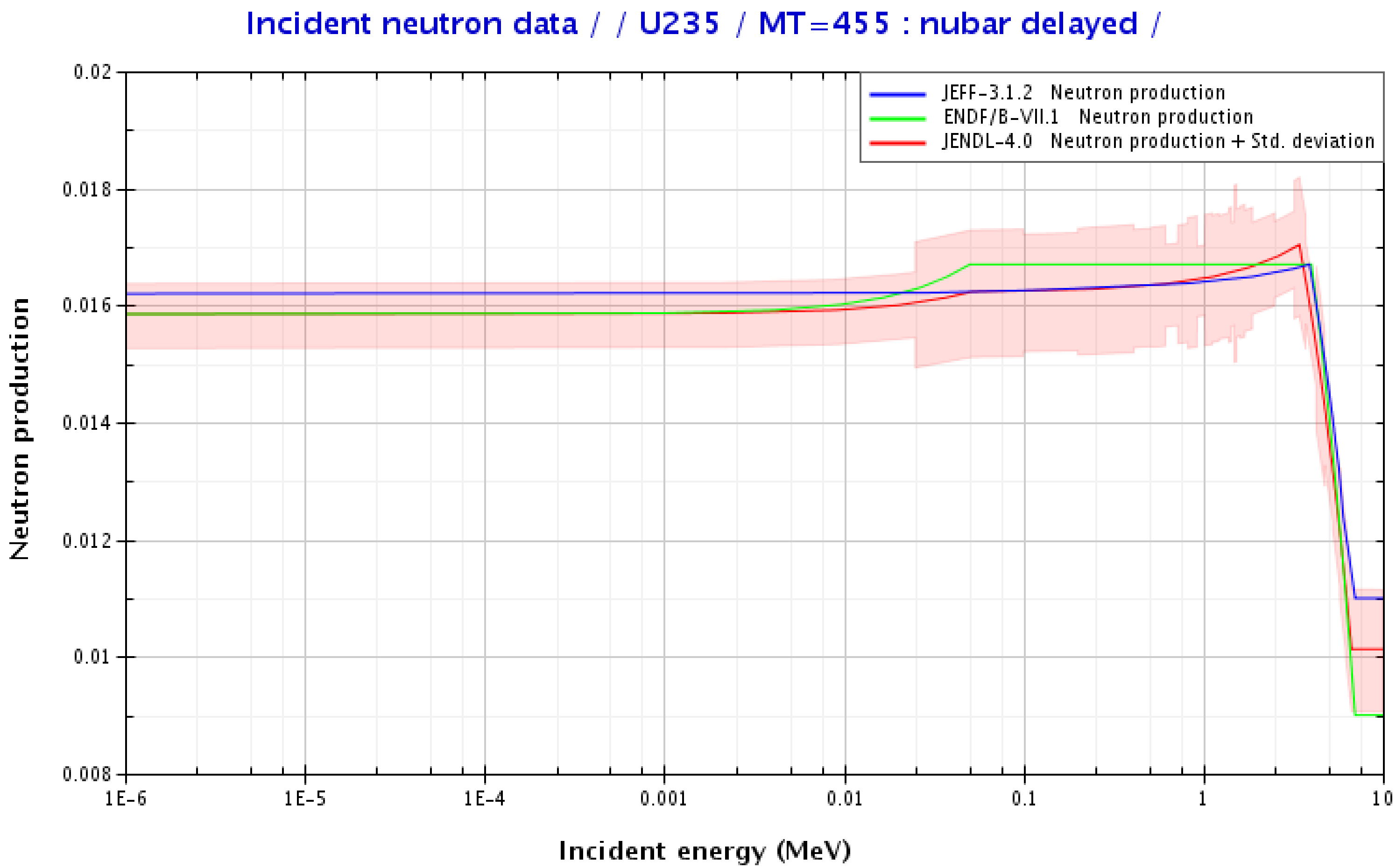
- JENDL nubar covariances:





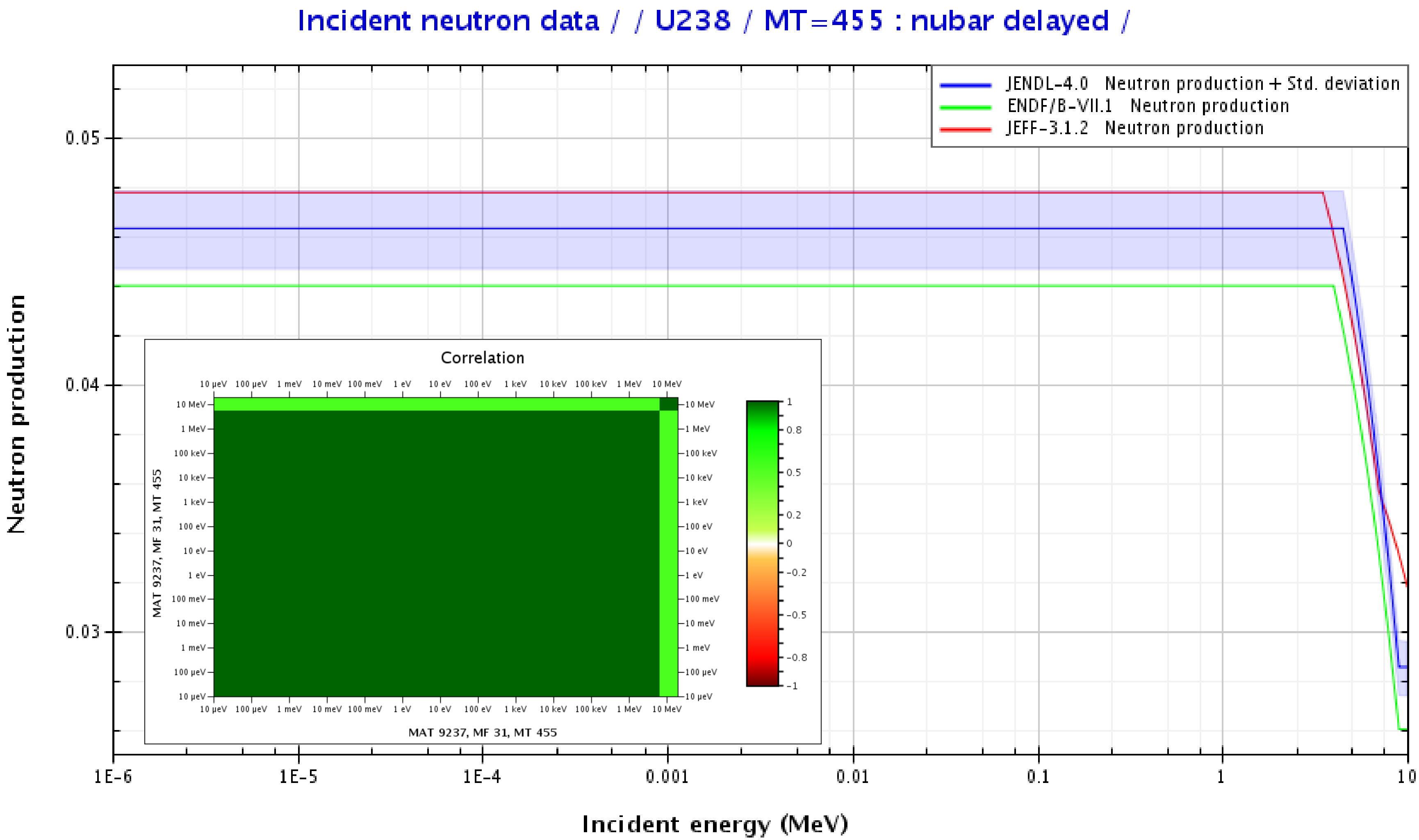
Uncertainty in ^{235}U delayed neutron multiplicity

- <20 keV: 3.5% uncertainty
- 20 keV-3 MeV: ≈ 7 % uncertainty



^{238}U delayed neutron multiplicity

- JENDL and ENDF have by 3% and 5% smaller nubar than JEFF
- 3.5% uncertainty



Summary

- Exp. campaign on Bi nuclear data validation at VENUS-F completed
- Up to 140 pcm variation in k_{eff} when various Bi σ applied
- Core averaged DN parameters (λ_i, β_i) from JEFF(8-g), ENDF (6-g), JENDL (6-g) applied in analysis of measured data lead to considerably different experimental reactivity effects
- JEFF-3.1.2 and JENDL-4.0 lead to C/E < 1
- ENDF/B-VII.1 leads to C/E > 1
- These trends observed in other VENUS-F configurations as well
- Although the best agreement of experiments and calculations with JEFF-3.1.2 ^{235}U DN data combined with either JENDL-4.0 or ENDF/B-VII.1 ^{238}U DN data, mixing 6-g and 8-g DN data can lead to strange λ_i
- Uncertainty in ^{235}U DN nubar (JENDL 3-7%) is bigger than the differences between nubar of different libraries (2-3%)

Outlook

- Publish all experimental data measured in the Bi core
- Next week: new critical core configuration loading
- Experimental campaign until beginning of 2019:
  - IPS reactivity effects
  - spectral indices
  - fuel Doppler
- Beginning of 2019: new sub-critical core
- Later in 2019: back to the thermal VENUS configuration

Backup slides

Fission yields