PAUL SCHERRER INSTITUT

Wir schaffen Wissen – heute für morgen

Paul Scherrer Institut

G. Perret

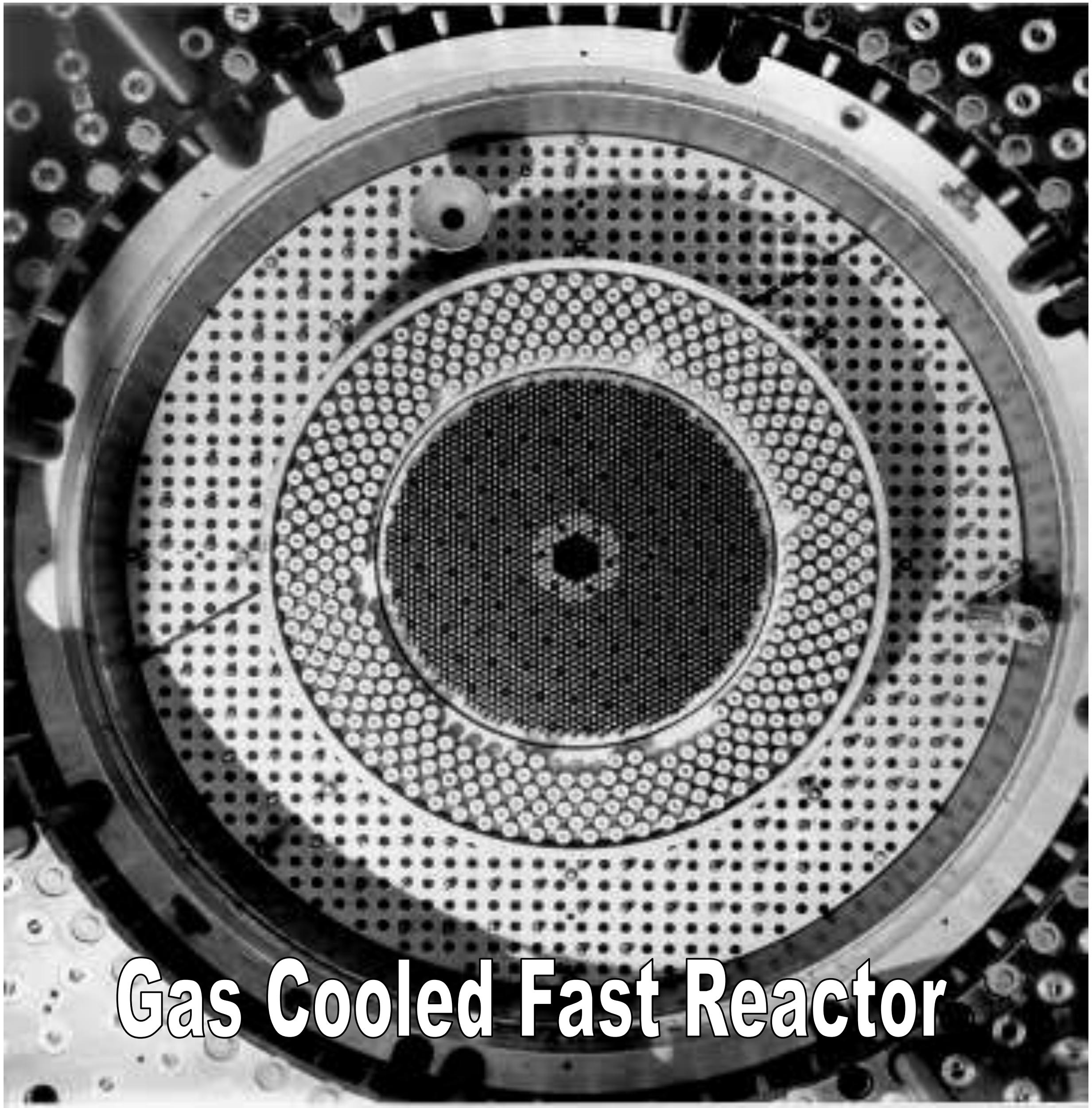
PROTEUS Experimental data

PROTEUS programmes overview

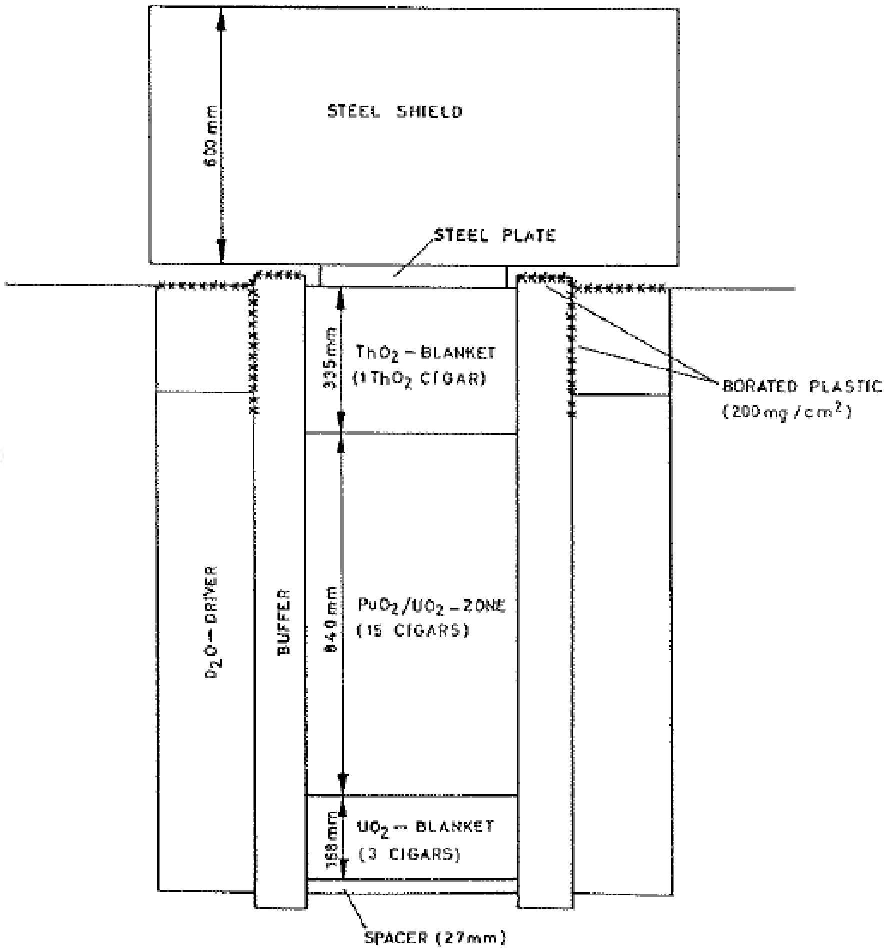
- Gas-Cooled Fast Reactor (1972-79)
  - UO_2-PuO_2 cores w/ and w/o blankets
  - Thorium oxide and metal cores
  - Shielding studies

- High Conversion Light Water Reactor (1980-1990)
  - Tight and large pitch, different moderation conditions
  - Absorbers worth, void coefficients

- LWR-PROTEUS (2000-2006)
  - Phase I: SVEA-96+ BWR assembly
  - Phase II: PWR mock-up with burnt fuel samples
  - Phase III:SVEA-96 Optima-2 assembly


Gas Cooled Fast Reactor

GCFR Program (1970's)



- Investigate GCFR with PuO_2/UO_2 (15% Pu, air cooled, E≈180keV)
- Investigate Thorium cross sections in fast spectra
- Radial and axial blankets
  - U depleted
  - ThO_2 / Th metallic
- Shielding benchmark with large steel reflector

PROTEUS web site

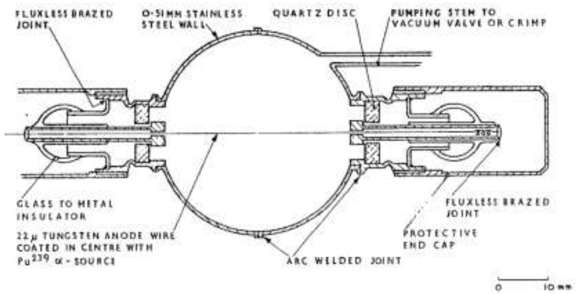
GCFR Measurements

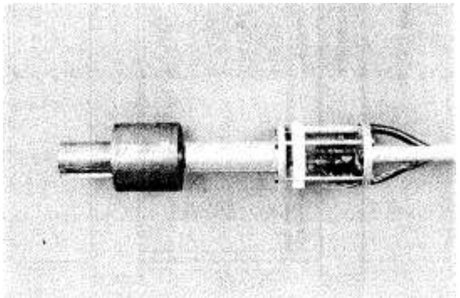
- Axial / radial reaction rate distributions (activation foils / fission ch.)
    - Capture in U-238
    - Fission in Pu-239, U-238, U-235, U-233

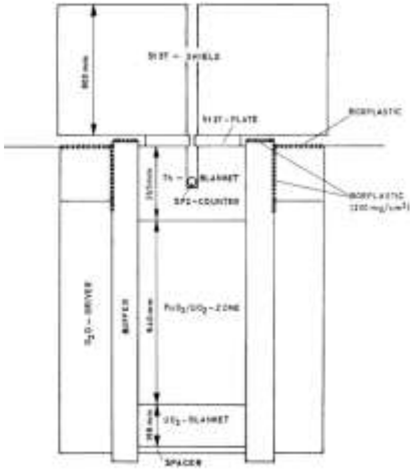
- Spectral indices
    - C8/F9 , F8/F9 , F5/F9, C2/F9, (n,2n)2/C2

- Small sample reactivity worth

- Neutron spectrum
  Fast spectra measurable via time-of-flight, proton recoil counters, Li6 detectors, threshold-reaction activation foils







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Availability of experimental data

Core Number	Central reaction rate ratios	Cor-rection factors	Radial traverse	Axial traverse	Neutron spec-trum	Reactivity Worth	K-inf
3. U-metal Buffer, REF-ERENCE	C8/F9, F8/F9, F5/F9	**Yes**	No	No	**Yes**	No	No
4.a UO_2-Column	C8/F9, F8/F9, F5/F9	No	**Yes**, C8, F8, F9 at centre (graph)	No	Yes	No	No
4.d Steam Entry	C8/F9, F8/F9, F5/F9	No	No	No	No	**Yes,** for 2 "water" levels	No
6. High-UO2	C8/F9, F8/F9	**Yes**	No	No	**Yes**	No	**Yes**

Core Number	Central reaction rate ratios	Cor-rection factors	Radial traverse	Axial traverse	Neutron spec-trum	Reactivity Worth	K-inf
7. High-Steel	C8/F9, F8/F9, F5/F9	**Yes**	No	No	**Yes**	No	**Yes**
9. Shield	No	No	**Yes**	**Yes**	**Yes**	No	No
10. High-Iron (II)	C8/F9, F8/F9, CMn/F9	**Yes**	No	No	**Yes**	No	**Yes**
11. Before Th	C8/F9, F8/F9, C2/F9, F2/F9, F3/F9, (n.2n)2/C2	**Yes**	No	No	**Yes**	No	No
13. ThO_2 Blanket	As Core 11	No	**Yes**, F9, C2, F2, C8, F8, F3	No	**Yes**	No	No
15. Th-metal Blanket	As Core 11	No	**Yes**, F9, C2, F2, C8, F8, F3	No	**Yes**	No	No

- Taken from TM-41-05-01 from G. Girardin
- Some missing configurations and some updates are required but it gives a very good overview of the performed measurements

Typical uncertainties

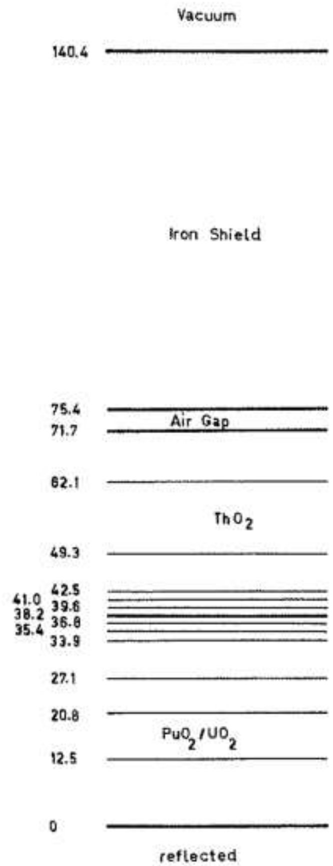
- Spectral indices
  - 1.1-1.3% for C8/F9, F8/F9, F5/F9, F3/F9 and C2/F9
  - 1.8-2% for F7/F9 and F2/F9
  - 2.3-2.5% for C7/F9 and (n,2n)2/C2.
- Reaction rate distributions
  - 0.5% for C8, 1% for F8 and F9 in core and 2% in blanket
  - 1-2% for C2 and F2
  - 2% for F3 in core and 4% in blanket
- Reactivity worth
  - higher than normal because of Boron-plastic

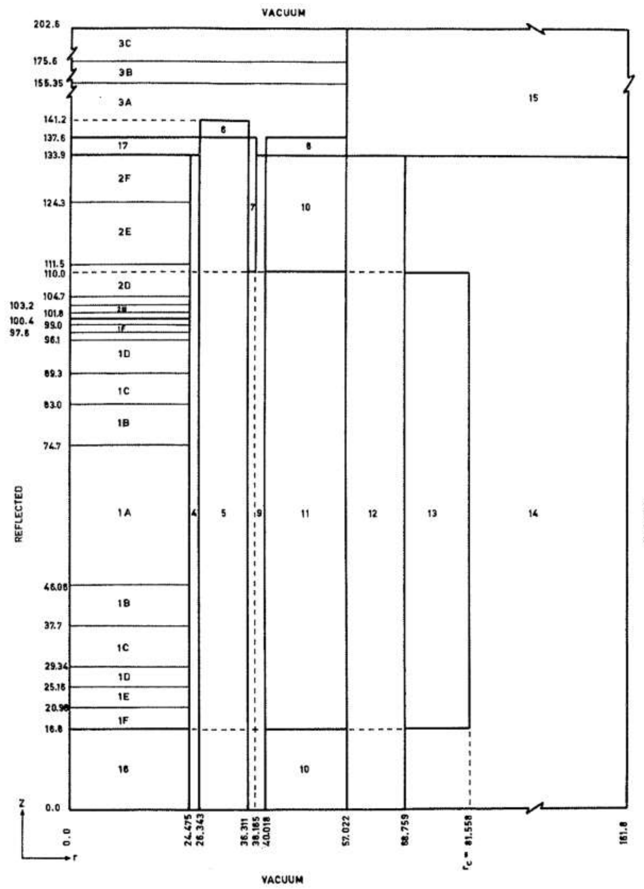
GCFR Past Calculations

- Deterministic Calculations
  - SN 1-D, DIFF-1D
  - DIFF-2D

- Cross-Section Libraries
  - ENDF/B-IV
  - FGL5

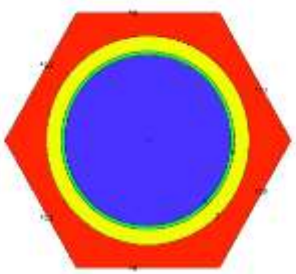
- Cross-Sections prepared with GGC-4 and MURLAB cell codes

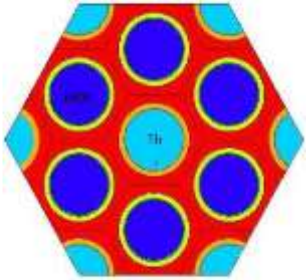


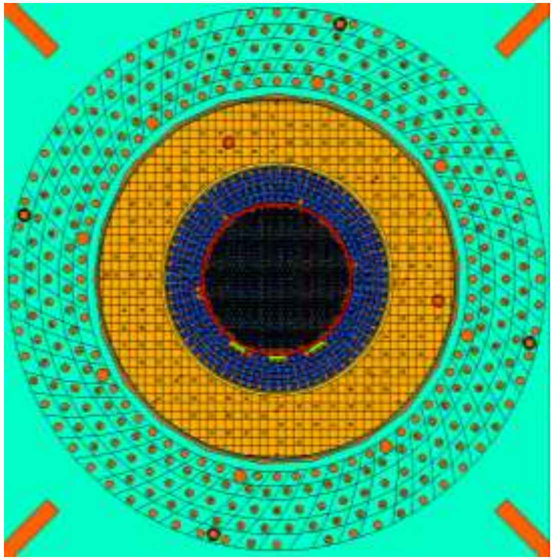


GCFR New Calculation Models

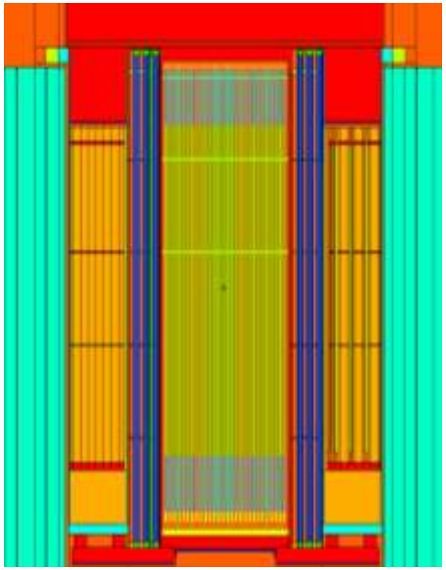
- Monte Carlo Calculations (MCNPX)
  - 2D lattice equivalent cell model
  - 3D whole-reactor core model







- 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

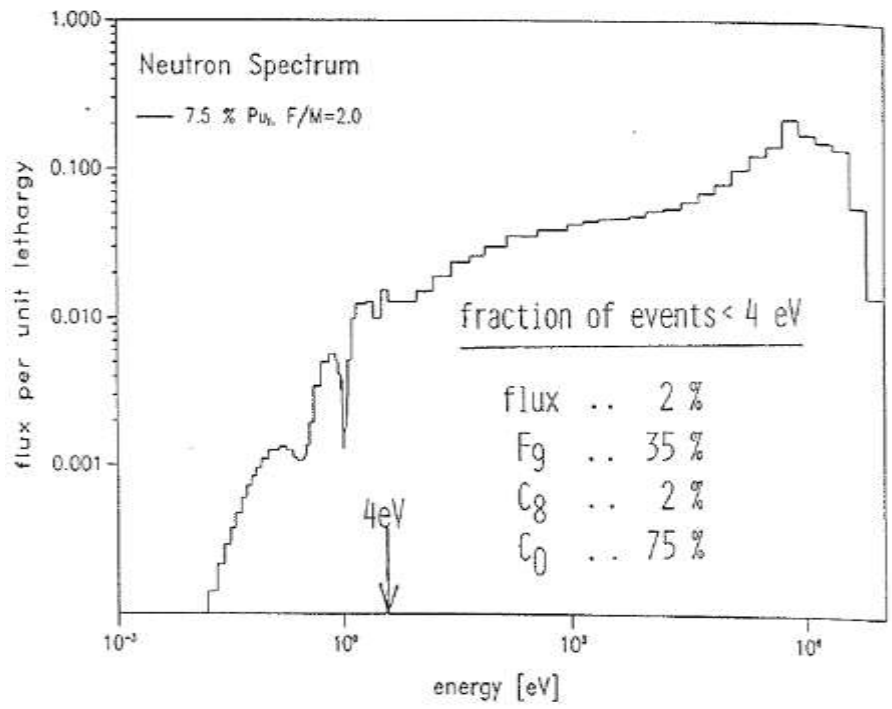

High Conversion LWR

HCLWR Program (1980's) - Motivations

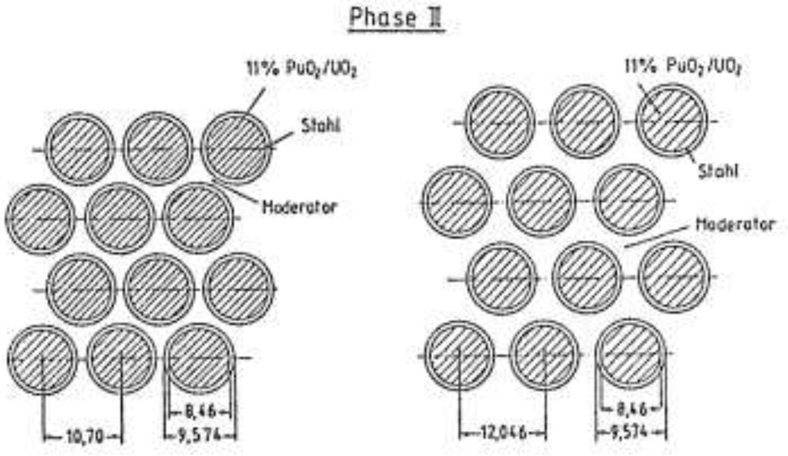
- Physics characteristics
  - •F/M ≈ 2, Fissile Pu content ≈ 7.5%
  - •Only "tail" of thermal neutrons
  - •Low-energy resonances (0.3 eV for ^{239}Pu, 1 eV for ^{240}Pu) are important

- No experimental data

- Large calculation discrepancies in particular for void coefficient, due to strong changes in individual neutron balance components

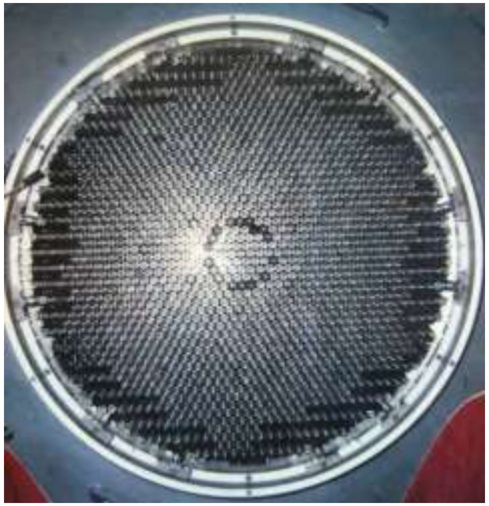


HCLWR Program (1980's)



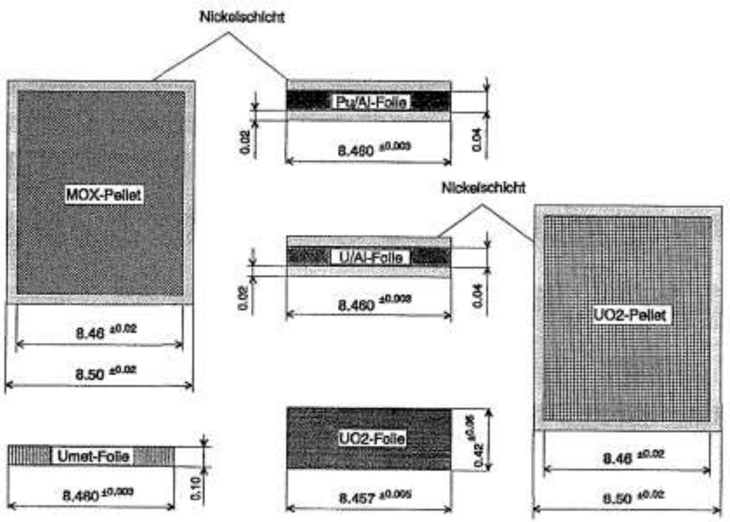
- UO_2/PuO_2 pellets with 11% PuO2
- Pu(8/9/0/1/2): 1%, 64%, 23%, 8%, 4%
- Fuel: Ø 8.46 mm, H 84 cm
- 2 axial blankets:
  - Udep. 0.224w% ^{235}U
  - 28-cm high each

- Several moderation conditions



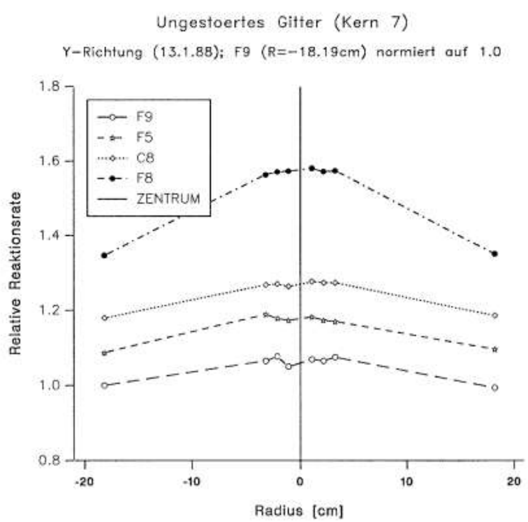
Kern	p/d	V_M/V_F	Moderator	Eff. Moderation	Hauptmerkmal
7	1.12	0.48	H_2O	0.48	'Enges Gitter'
8	1.12	0.48	ohne	0.00	} Voidsimulation
9	1.12	0.48	Dowtherm	0.28	
10	1.12	0.48	Dowtherm	0.28	} vergiftet, Einfluss von B_4C
11	1.12	0.48	ohne	0.00	
12	1.12	0.48	H_2O	0.48	
13	1.26	0.95	H_2O	0.95	'Weites Gitter'
14	1.26	0.95	ohne	0.00	} Voidsimulation
15	1.26	0.95	Dowtherm	0.55	
16	1.26	0.95	H_2O	0.95	} vergiftet, Einfluss von B_4C
17	1.26	0.95	ohne	0.00	
18	[a]	2.07	H_2O	2.07	Thermisches Spektrum
19	1.26	0.95	H_2O	0.95	5% spaltbares Plutonium (effektiv) [b]
20	1.26	0.95	D_2O	-	D_2O statt H_2O

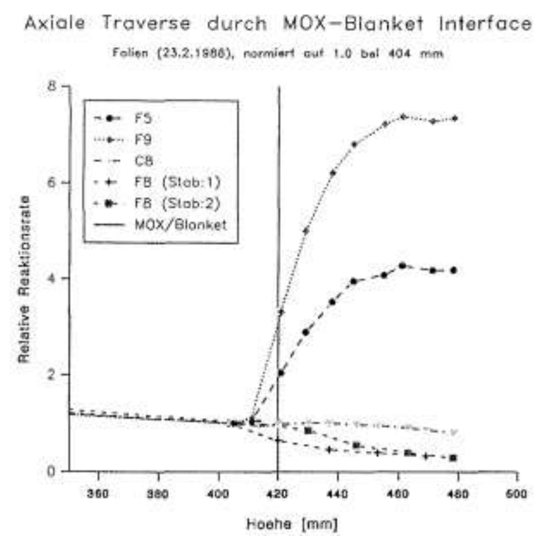
HCLWR Measurement types (1/2)



- Reaction rate ratios
  - F5/F9, F8/F9, C8/F9, F1/F9, C2/F9
  - Uncertainties: F5:1.4%, F8:2.0%, F9:1.4%, C8:1.8%, F1:5%

- Reaction rate traverses
  - Axial and Radial
  - MOX zone and MOX/Blanket

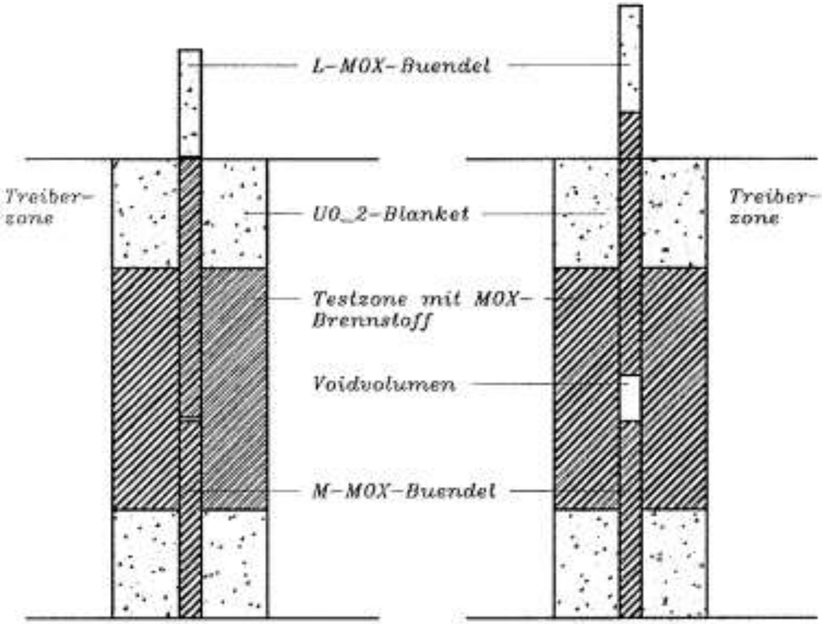




HCLWR Measurement types (2/2)

$$k_\infty = 1 + B^2 \cdot M^2$$

$$\frac{\rho_Z}{\rho_S}\frac{S}{R_f} = \bar{\nu}\frac{\overline{\Phi^+}^X}{\overline{\Phi^+}^S}\left(1 - \frac{1}{k^+}\right)$$



- K∞ measurements
  - Buckling method (σ~2.0%)
  - Cell worth method (σ~0.5-0.8%)
- Reactivity effects of
  - Void volume
  - Moderator volume

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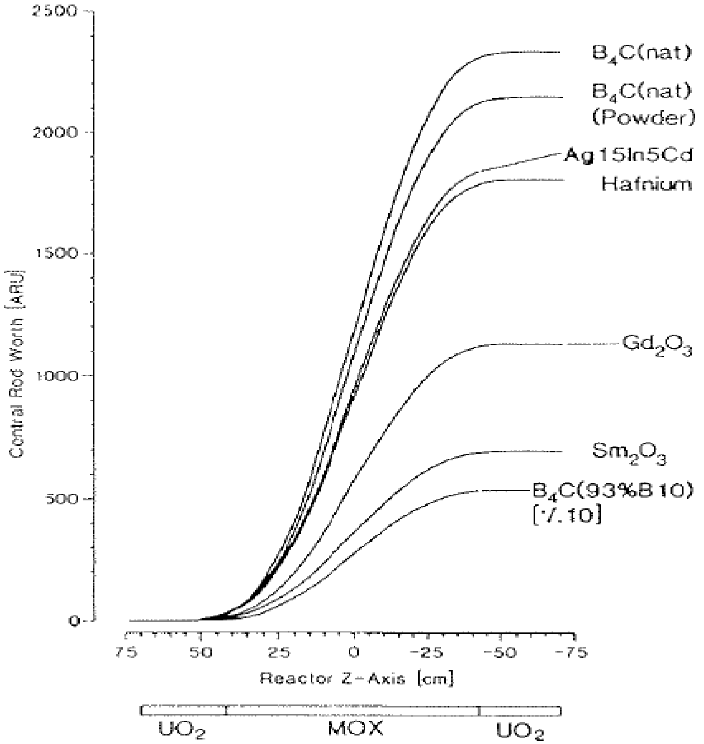


- K∞ measurements
  - Buckling method (σ~2.0%)
  - Cell worth method (σ~0.5-0.8%)
- Reactivity effects of
  - Void volume
  - Moderator volume
  - Absorber rods

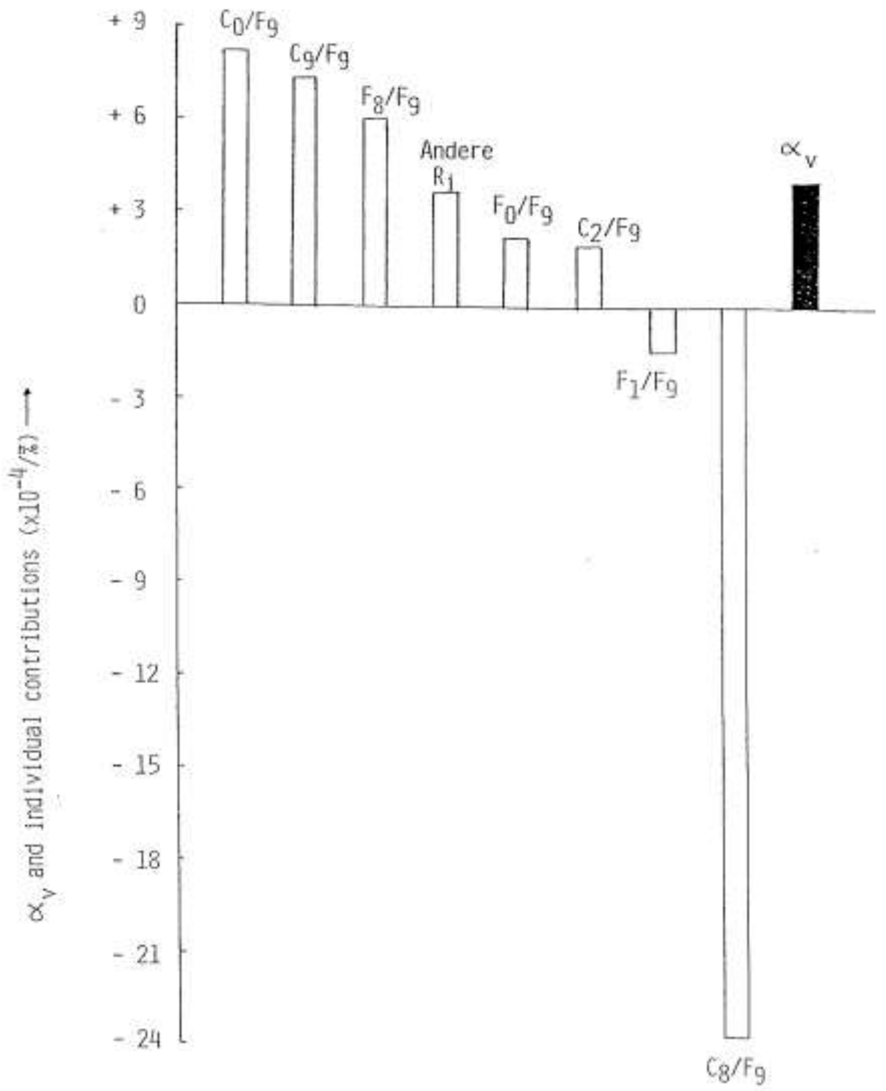
Absorber	Form	Durchmesser	Cladding	Bemerkung
B_4C(nat)	Pellet	7.473	ja	Referenzabsorber
B_4C(nat)	Pulver	7.430	ja	
B_4C(93%) ^{10}B	Pellet	7.430	ja	
Ag15In5Cd	Legierung	8.830	nein	
Hafnium	Metall	8.350	ja	(σ<1%)
Gd_2O_3	Pellet	8.310	ja	
Sm_2O_3	Pellet	7.000	ja	
Tantal	Metall	8.290	ja	
Eu_2O_3	Pellet	8.243	ja	
Zircaloy-2	Legierung	8.300	nein	Strukturmaterial
Stahl	Metall	8.240	nein	Strukturmaterial

Void coefficient in tight HCLWR lattice

$$\alpha_V = \frac{\Delta k_\infty}{\bar{k}_\infty \Delta V}$$

$$\underset{i}{\mathrm{Sum}}\left[\frac{\Delta k_\infty}{\bar{k}_\infty}\right]_i = \frac{\Delta k_\infty}{\bar{k}_\infty}$$

$$\left[\frac{\Delta k_\infty}{\bar{k}_\infty}\right]_i \cong -\frac{\Delta A_i}{\bar{A}} + \frac{\Delta P_i}{\bar{P}}$$

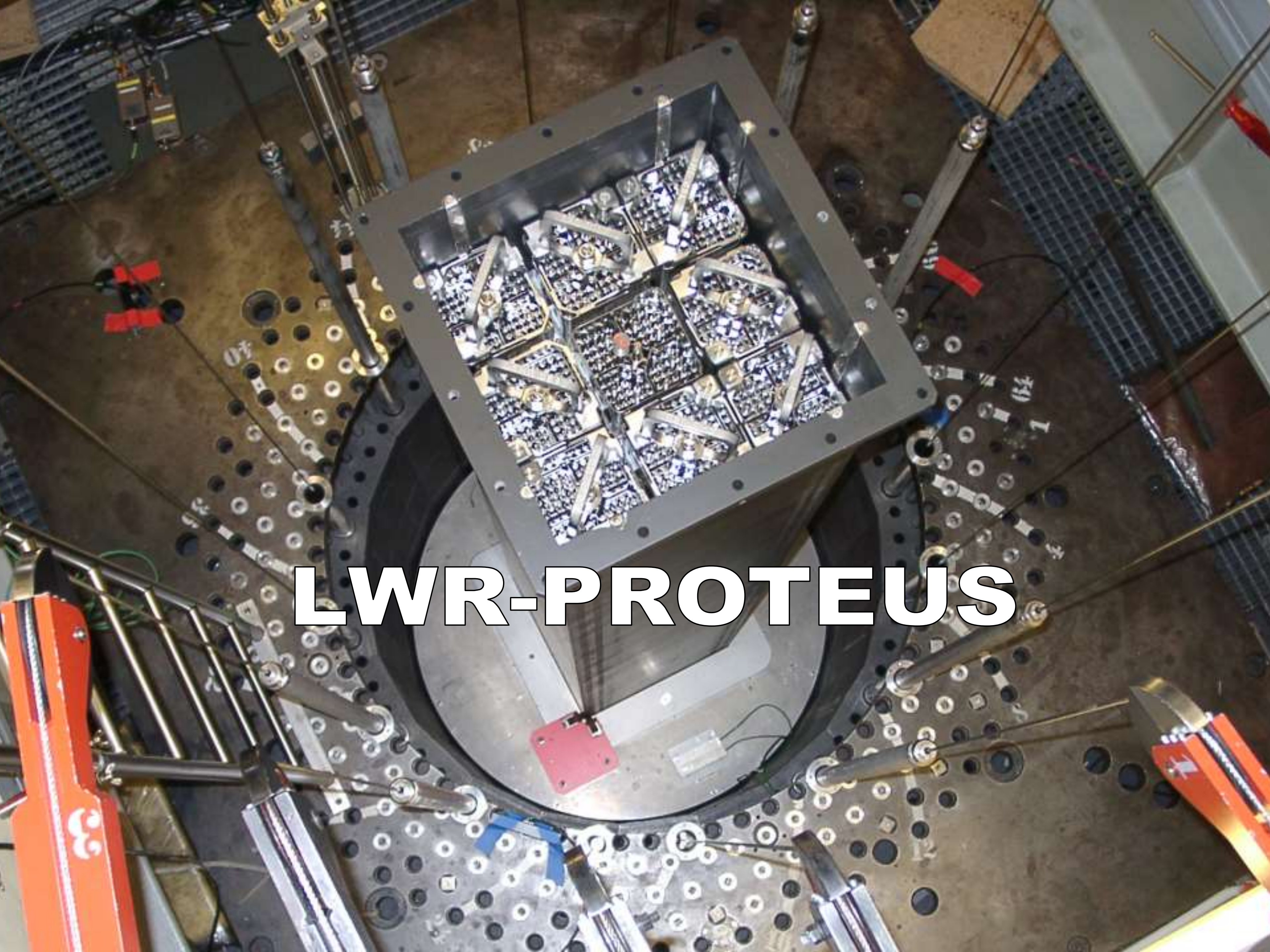


HCLWR Summary

- Provide first-of-its-kind integral data for system for which different standard codes, data libraries yield large discrepancies
  - Differences of up to 5% in k∞ , 10% in C8/F9 , even in sign of void coefficient…

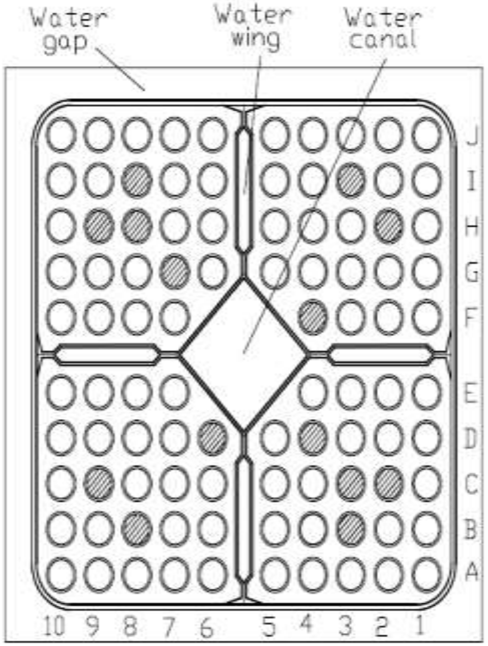
- Benchmark measurements of neutron balance in different tight lattices, with representative Pu-content
  - Simulation of voidage in each case (0%, 100%, as well intermediate)
  - “Moderators”: H_2O, air, Dowtherm (organic liquid with intermediate H-density)

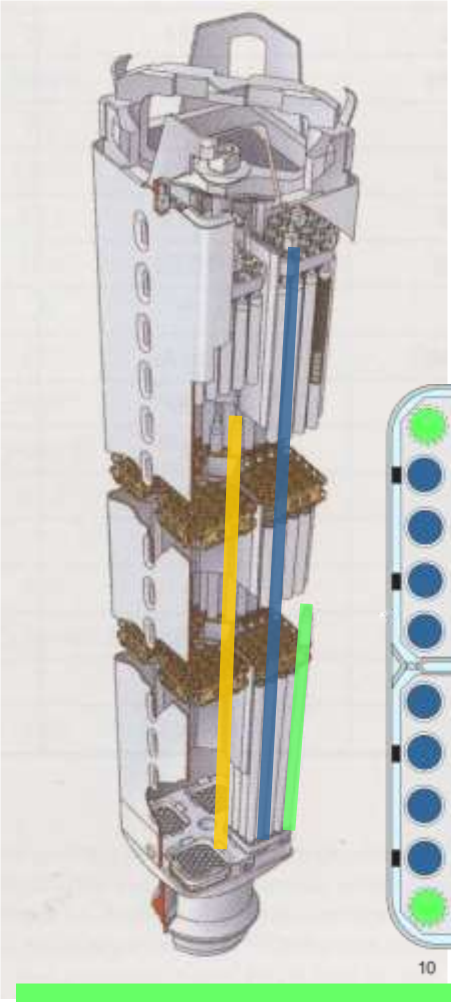
- Additional investigations:
  - Effects of change in Pu-content (mixed lattice with UO_2 rods)
  - Control rod studies, and use of new absorber materials (enr. B, Hf, etc.)
  - Effects of control absorber on void coefficient (poisoned lattice)


LWR-PROTEUS

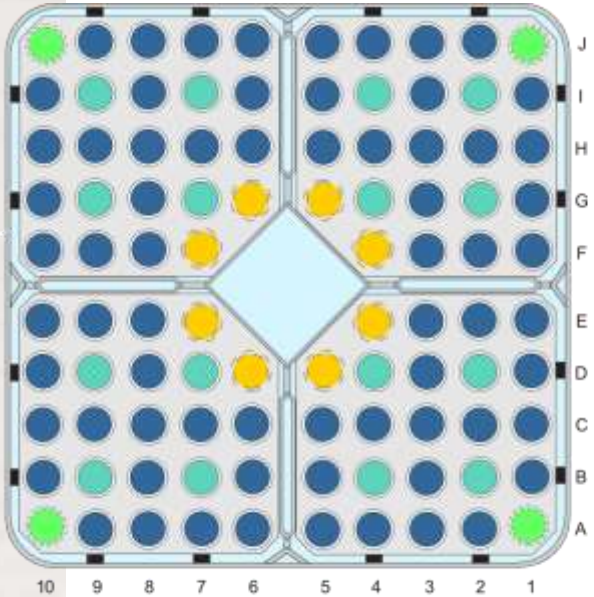
LWR Phase I and III fuel assemblies

Phase I:
SVEA-96+



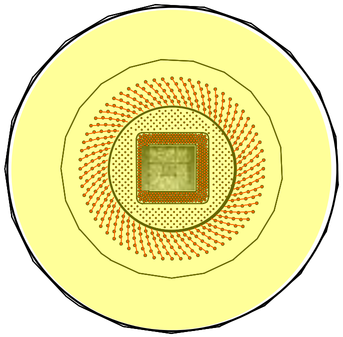


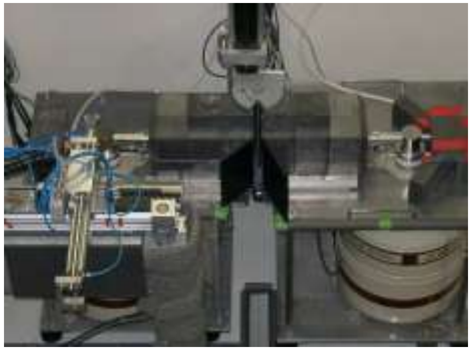
Phase III:
SVEA-96 Optima2

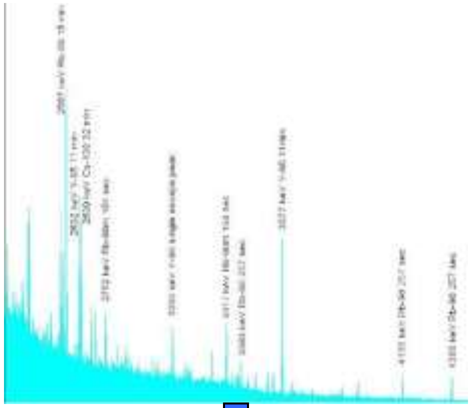


1/3 part length UO_2 pins	Full length UO_2 pins
2/3 part length UO_2 pins	Full length UO_2-Gd_2O_3 pins

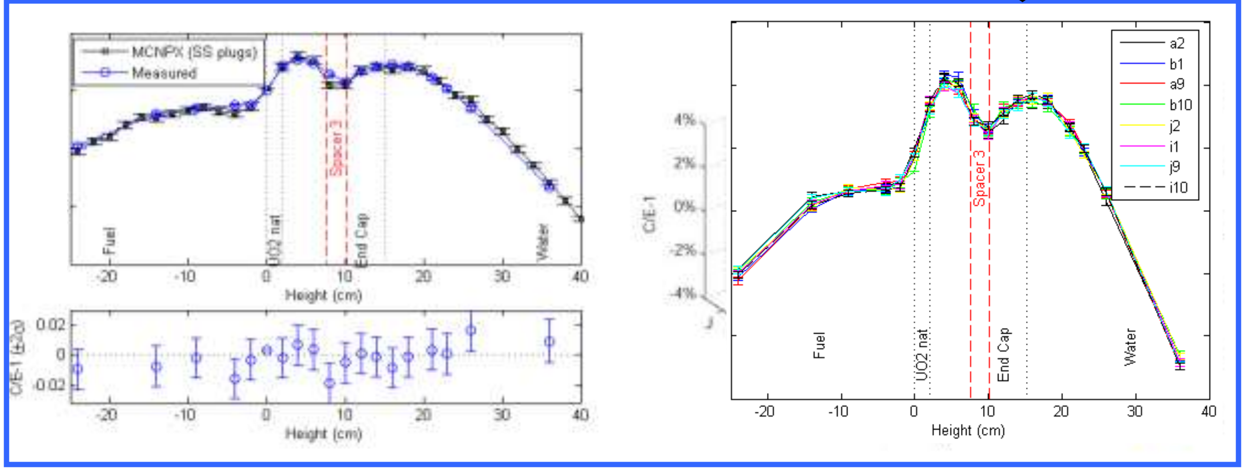
Reaction Rate Measurements per γ-scan







Calculation Tools



List of configuration in Phase I

Conf.	Axial Enrich^t Zone	Water Density (Channel/Bypass)	Absorber Blades	Assembly Layout
1B	upper	100%/100% (pure H_2O)	None	Symmetric
1A	lower			
1C	boundary			
2C	lower	100%/100% (pure H_2O)	Full length B_4C	Symmetric
2A	lower		Full length Hf	
2B	upper		Full length Hf	
3A	lower	10%/75% (CH_2 w/o H_2O)	None	Symmetric
3B	upper			
3D	boundary			
4A	lower	10%/100% (CH_2 w/ H_2O)	None	Symmetric
5A	lower	10%/75% (CH_2 w/o H_2O)	Full length Hf	Symmetric
6A	lower	100%/100% (pure H_2O)	Part length Hf	Symmetric
7A	lower	100%/100% (pure H_2O)	None	Asymmetric

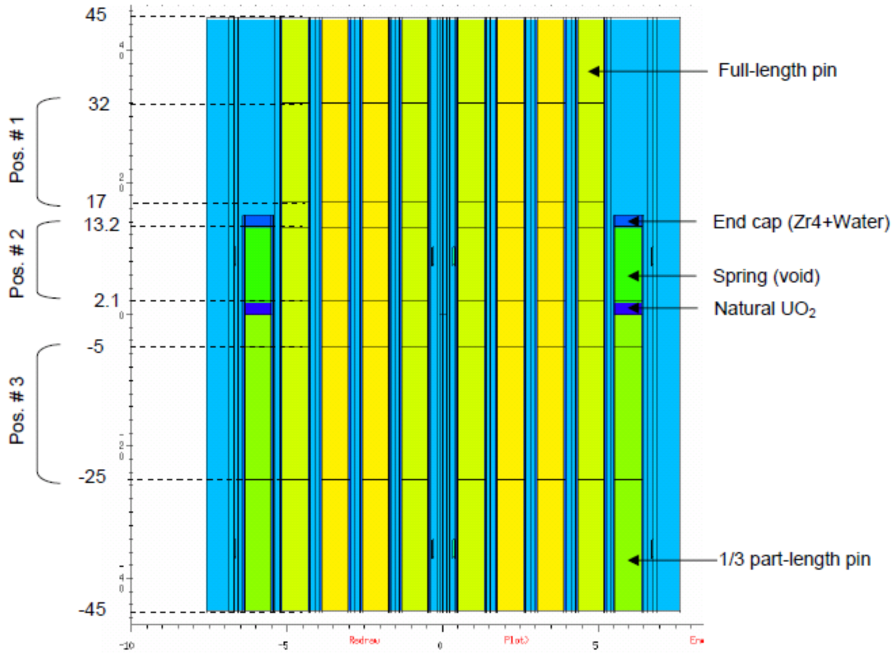
Phase I – Example of Meas. & uncert.

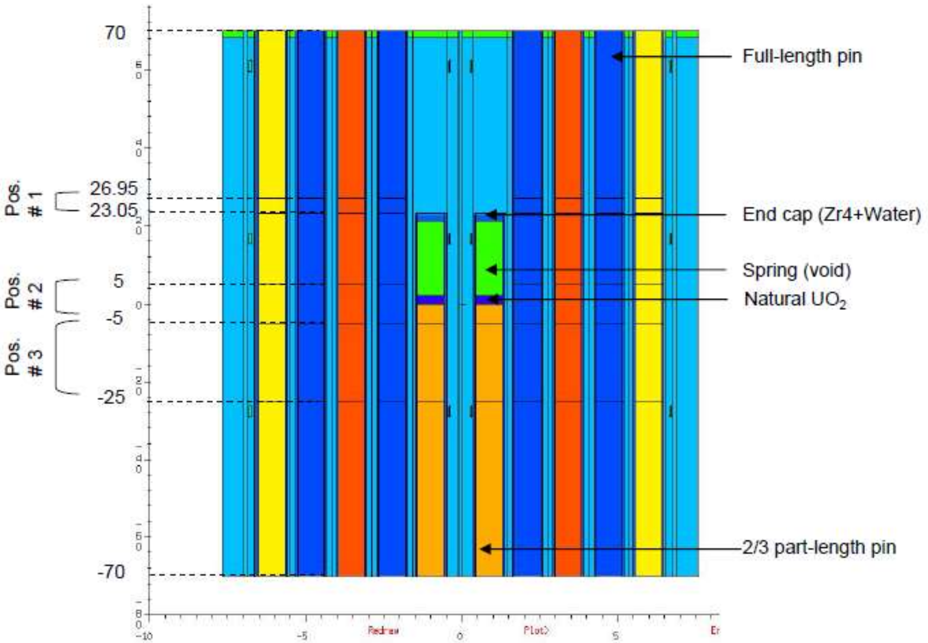
- Configuration 1C
  - Gamma-scanning for total fission rate axial distribution (σ~ 0.5-1%)
  - Axial U-235 fission chamber scan
  - U-238 metal, U-235/Al alloy foil measurements
  - Gold axial flux distributions (outside test zone)

- Configuration 2C (boron-carbide in lower part of fuel assembly)
  - Gamma-scanning fission (~1% absolute, 0.5% relative) – radial maps with 64 pins
  - Pin reactivity worths: 12 UO_2 and 2 Gd_2-O_3 pins (0.7% stat, 4% tot)
  - Foil irradiation (~2% for U8 foils, ~1% for UO_2 foils)
  - Traversing in-core probe with GM tubes (~5%)

List of configuration in Phase III

Conf.	Axial Interface	Moderator
1	1/3 part-length rods	67% H_2O, 33% D_2O
2	2/3 part-length rods	67% H_2O, 33% D_2O
3	Top section (84 pins)	Boxes with different mixtures of D_2O, H_2O





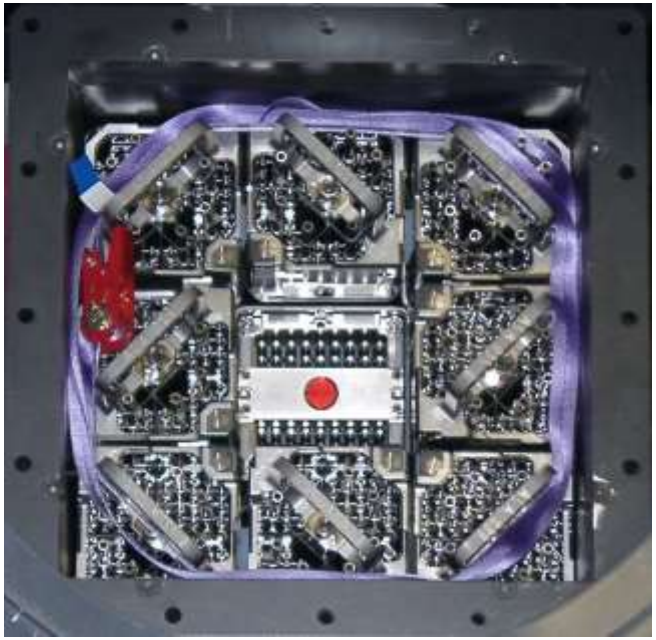
Reaction rate measurements in Phase III

- Phase III-1
  - Three radial maps of C8, Ftot and C8/Ftot
    - 72 pins measured (including 8 UO_2-Gd_2O_3 pins) + 4 PLR
  - Detailed axial maps (2cm steps) of C8, Ftot and C8/Ftot
    - 8 UO_2 pins close to PLR
    - 4 UO_2-Gd_2O_3 pins next to PLR

- Phase III-2
  - Three radial maps of C8, Ftot and C8/Ftot
    - 74 pins measured (including 7 UO_2-Gd_2O_3 pins)
  - Detailed axial maps (2cm steps) of C8, Ftot and C8/Ftot
    - 4 UO_2 pins close to PLR
    - 3 UO_2-Gd_2O_3 pins next to PLR
    - 7 UO_2 PLR

- Uncertainties
  - Ftot, C8: 0.5-0.9%, C8/Ftot: 2.5% (with nucl. data uncertainties)

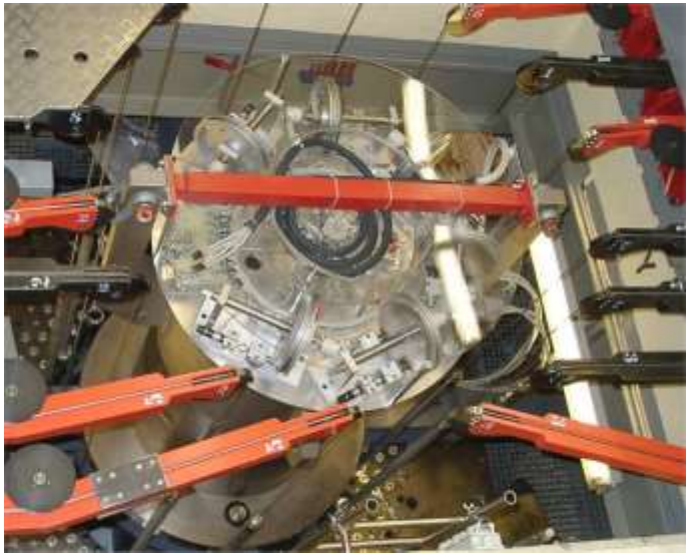
LWR Phase II set-up



- Study of burnt PWR/BWR fuel segments inserted in the middle of a lattice of fresh PWR rods

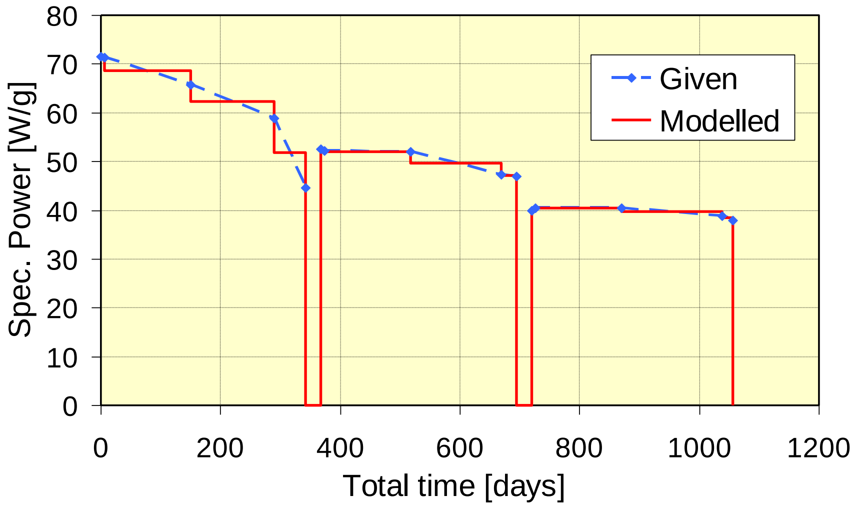
- Different moderation conditions
  - H_2O, H_2O/D_2O, borated water

- Reactivity worth measurement of
  - spent fuel
  - special samples (absorber)



Spent fuel samples

- Spent fuel segments from Swiss nuclear power plants
  - 9 UO_2 burn-ups from ~40 to ~120 GWd/t
  - 4 MOX burn-ups up to ~70 GWd/t
  - 40 cm long with overclad (Ø 1.2cm)

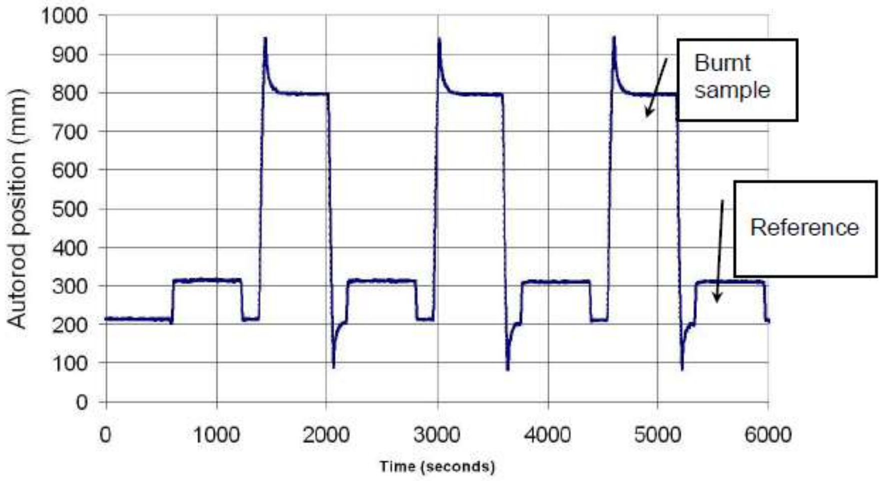


- CASMO-4/5 burn-up calculations using NPP irradiation conditions

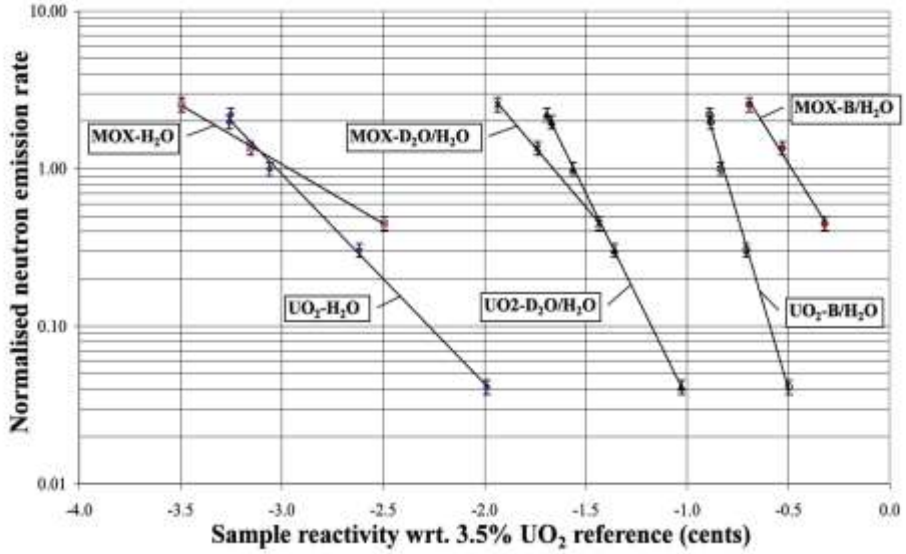
- Measurement by destructive analysis (gamma-scanning, ICP-MS and HPLC-ICP-MS, 57 isotopes)

Phase II – Measurements (1/2)

- Reactivity worth measurements (w/ respect to UO_2 3.5%)
  - Compensation and asymptotic period measurements
  - Best uncertainty ~ 0.5% (4% w/ nuclear data uncert.)



- Neutron source emission
  - Measurements by source amplification and outside reactor
  - Absolute and relative values
  - Typical uncertainty ~ 5% (absolute) and 1.5% (relative)



Summary

- GCFR
  - (U, Pu)O_2 and ThO_2 and Th metal configurations
  - Mainly reaction rate ratios and distribution measurements
  - Uncertainties <2-3% for most reactions
  - Additional measurements: shielding and steam entry effects

Applications: X-section improvements in fast spectra…

- HCLWR
  - Tight and wide pitch lattices with 0, 42.5% and 100% moderation
  - k_∞ measurements with 0.5% to 0.8% uncertainty
  - reactivity worth of absorber measurements (σ<1%)
  - reaction rate ratios and distribution measurements (1%< σ <5%)

Applications: keff for different conditions of BWR, reaction rate distribution at the interface with blanket…

Summary

- LWR-PROTEUS – Phase I and III
  - Numerous radial and axial power and C8 distributions in SVEA-96+ and SVEA-96 Optima2 assemblies (σ_{fiss}~0.5-1%, $\sigma_{C8/fiss}$~2.5%) with varying conditions: absorber-rods, moderation
  - Pin reactivity worth (σ_{rel}~0.5%, σ_{abs}~4%)
  - In-core probe measurements (σ~5%)
  - Core Criticality

  Applications: Power distributions in BWR, keff at cold conditions…

- LWR-PROTEUS – Phase II
  - Spent fuel samples 20 to 120 GWd/t (UOX, MOX)
  - Isotopic composition of 51 nuclides
  - Burn-up with Nd-148 (σ~2.5%)
  - Reactivity worth (σ~0.5%)
  - Relative and absolute neutron source strength (σ~1.5% and 4%)

  Applications: Burn-up credit, X-sections…

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Thank you for your attention, comments and questions.