Experimental validation of FENDL-3 nuclear data library

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Radiation loads in fusion devices (e.g. ITER)

(e.g. ITER: 500 MW fusion power, 1.78×10^{20} n/s)

Machine operation, protection, maintenance & Safety

- Nuclear heating (e.g.: < 14 KW in TFC)
- Fast neutron fluence (e.g.: $<10^{23}$ n/m^2 Nb_3Sn, $<5 \cdot 10^{21}$ n/m^2 insulators)
  < 1(3) appm He-production thick (thin)
  < 1 dpa for re-welding
- Integrated dose (e.g. <10 MGy to insulators)
- Activation (short and long term, dust and ACP estimate, waste estimate)
- Shutdown dose rates (repair, replacement maintenance)
- Decay heat (heat removal capabilities after accident)
- Shielding properties of inner components (streaming paths)

- Tritium breeding

➔ **Calculations validated by experiments (nuclear data & codes) with assessment of uncertainties**

QA in ITER Neutronics Analyses

Neutronic calculations and analyses shall conform to the ITER Management and Quality Program.

ITER Project Management and Quality Program: Quality Assurance in Neutronic Analyses (ITER_D_23H9A4, May 2006)

- *Computer software & data must be verified and validated prior to use*
- ....
- *The FENDL-2.1 library is the reference nuclear data library for nuclear analyses for ITER*
- ......

➔ **FENDL-2.1 has been verified and validated for neutronic calculations using available fusion benchmark experiments performed during the ITER R&D activities**

➔ **Same procedure for FENDL-3**

Frascati 14-MeV Neutron Generator (FNG)

- ENEA, Frascati Research Centre (Italy)
- Accelerator based
  - ✓ T(d, n)α
  - ✓ E_d =300 keV
- European facility for fusion neutronics
  - ✓ Shielding
  - ✓ activation
  - ✓ development of detectors
- Operating since 1992

- MAIN PARAMETERS

14-MeV neutron intensity	10^{11} n/s
14-MeV neutron flux	10^{10} n/(cm^{2}s)
D+ beam energy / current	260 keV / 1 mA
Target tritium content	370 GBq

Fusion neutronics experiments at FNG

Benchmark experiments performed at FNG and used for FENDL-2.1 / MC validation :

- **Stainless steel experiment**
- **Bulk shield experiment** (inboard shield, stainless steel & water)
- **Streaming experiment** (shield with streaming channel, stainless steel & water)
- **Silicon Carbide (SiC) block**
- **Tungsten block**
- **HCPB Breeder blanket (Be / Li_2CO_3) experiment**
- HCLL Breeder blanket (LiPb) experiment in progress
- **Shutdown dose rate**

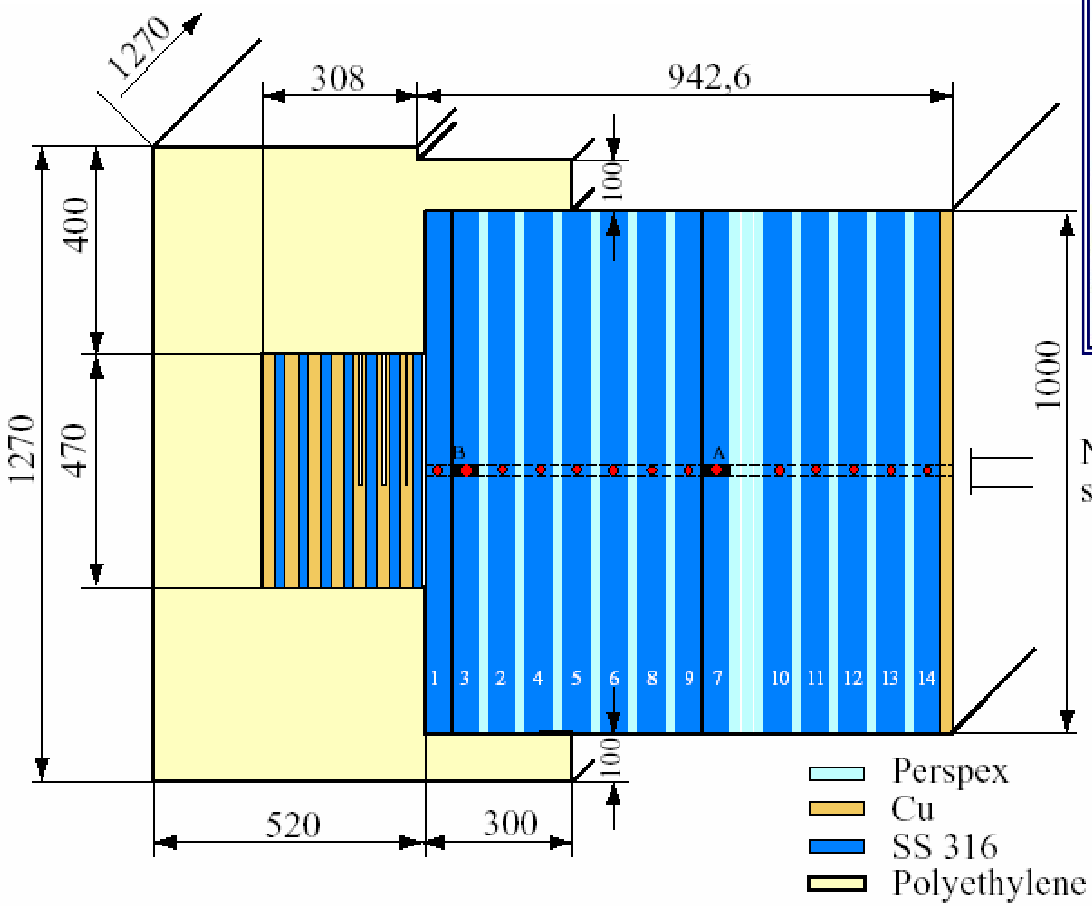
All experiments available in SINBAD Fusion benchmarks database (NEA/OECD)

Main materials in FNG experiments

Materials	FENDL-1.0	FENDL-2.0	FENDL-2.1
Fe-56	ENDF/B-VI	EFF-3.0	JEFF-3.0 (EFF-3.1)
Fe-54,57,58,59	ENDF/B-VI	ENDF/B-VI	ENDF/B-VI
Cr-50,52,53,54	ENDF/B-VI	ENDF/B-VI	ENDF/B-VI.8
Ni-58,60 Ni61,62,64	ENDF/B-VI ENDF/B-VI	ENDF/B-VI ENDF/B-VI	JEFF-3.0 (EFF-3.0) ENDF/B-VI.8
W-182,3,4,6	ENDF/B-VI	JENDL-FF (W-nat)	ENDF/B-VI.8
Li-6 Li-7	ENDF/B-VI ENDF/B-VI	ENDF/B-VI ENDF/B-VI	ENDF/B-VI.8 ENDF/B-VI.8
Be-9	ENDF/B-VI	JENDL-FF	JENDL-FF
Pb	ENDF/B-VI		ENDF/B-VI.8
C-12	ENDF/B-VI (C-nat)	JENDL-FF	JENDL-FF
O-16	ENDF/B-VI	JENDL-FF	ENDF/B-VI.8
Si-28	BROND-2	ENDF/B-VI.8	ENDF/B-VI.8

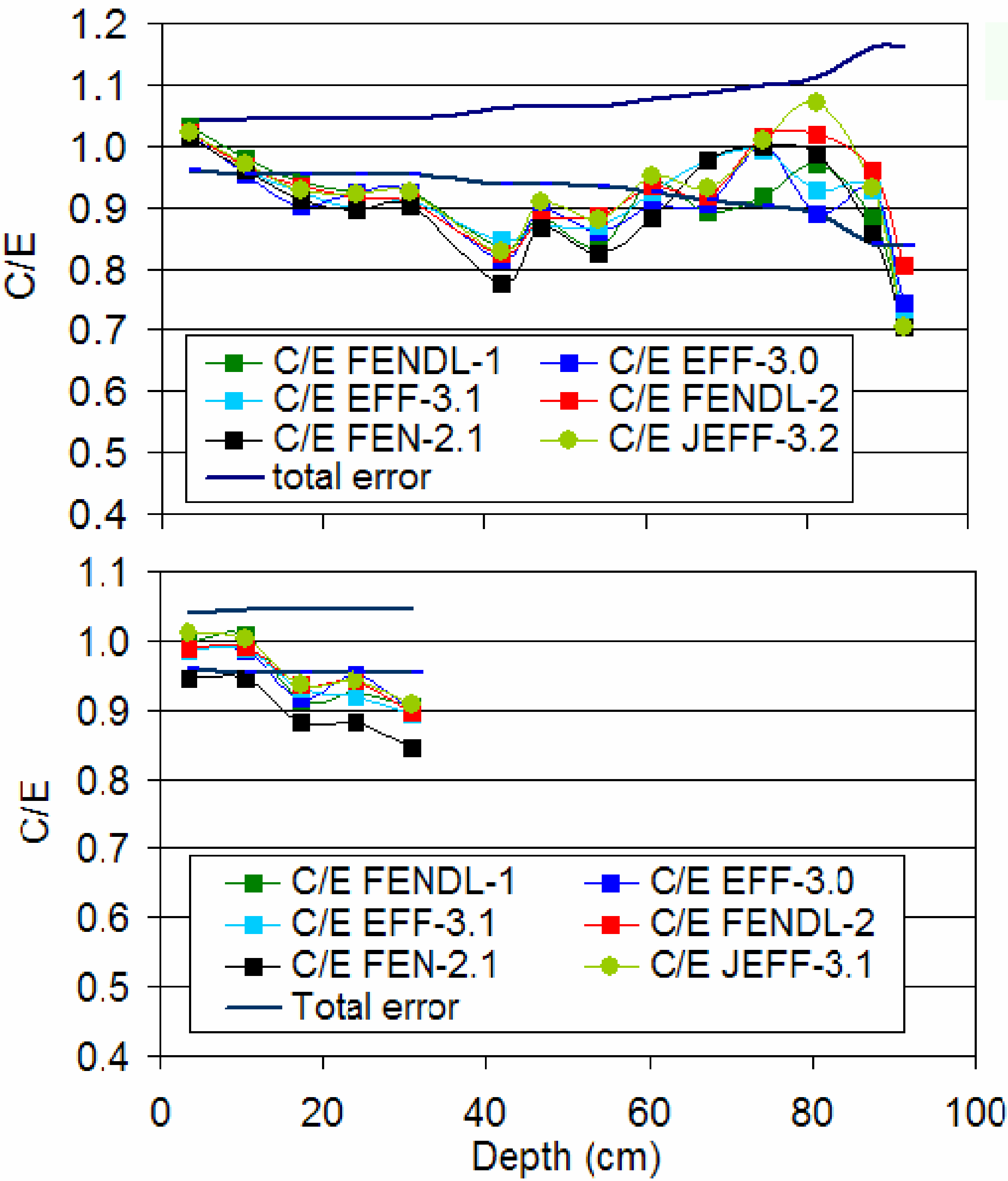
Bulk Shield experiment

Mock-up of the ITER inboard first wall / shielding blanket / vacuum vessel / toroidal magnet



- Measurements of the neutron flux as a function of depth by activation foils

Bulk Shield experiment



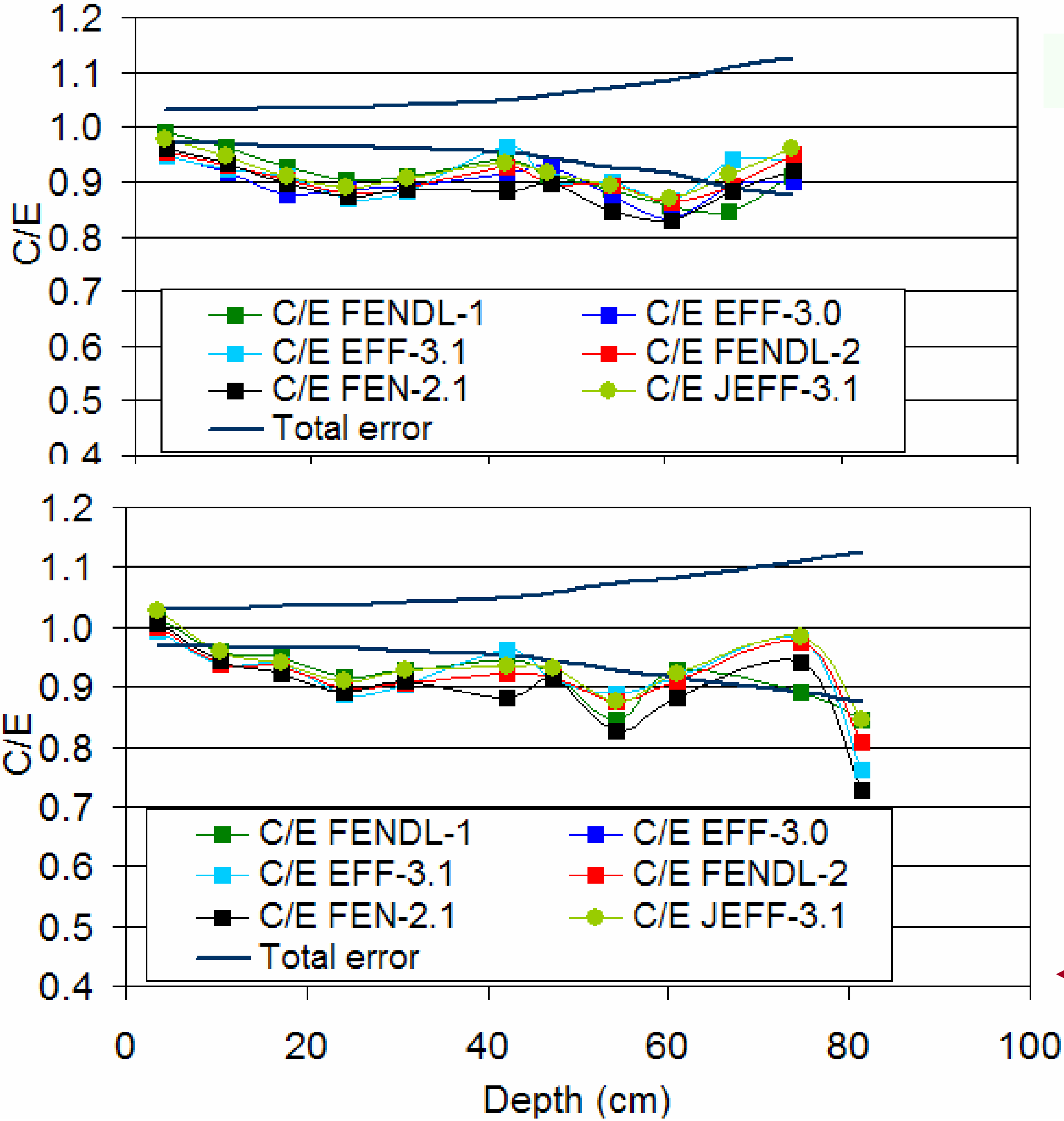
Neutron energy E> 10 MeV

Nb-93(n,2n)

Ni-58(n,2n)

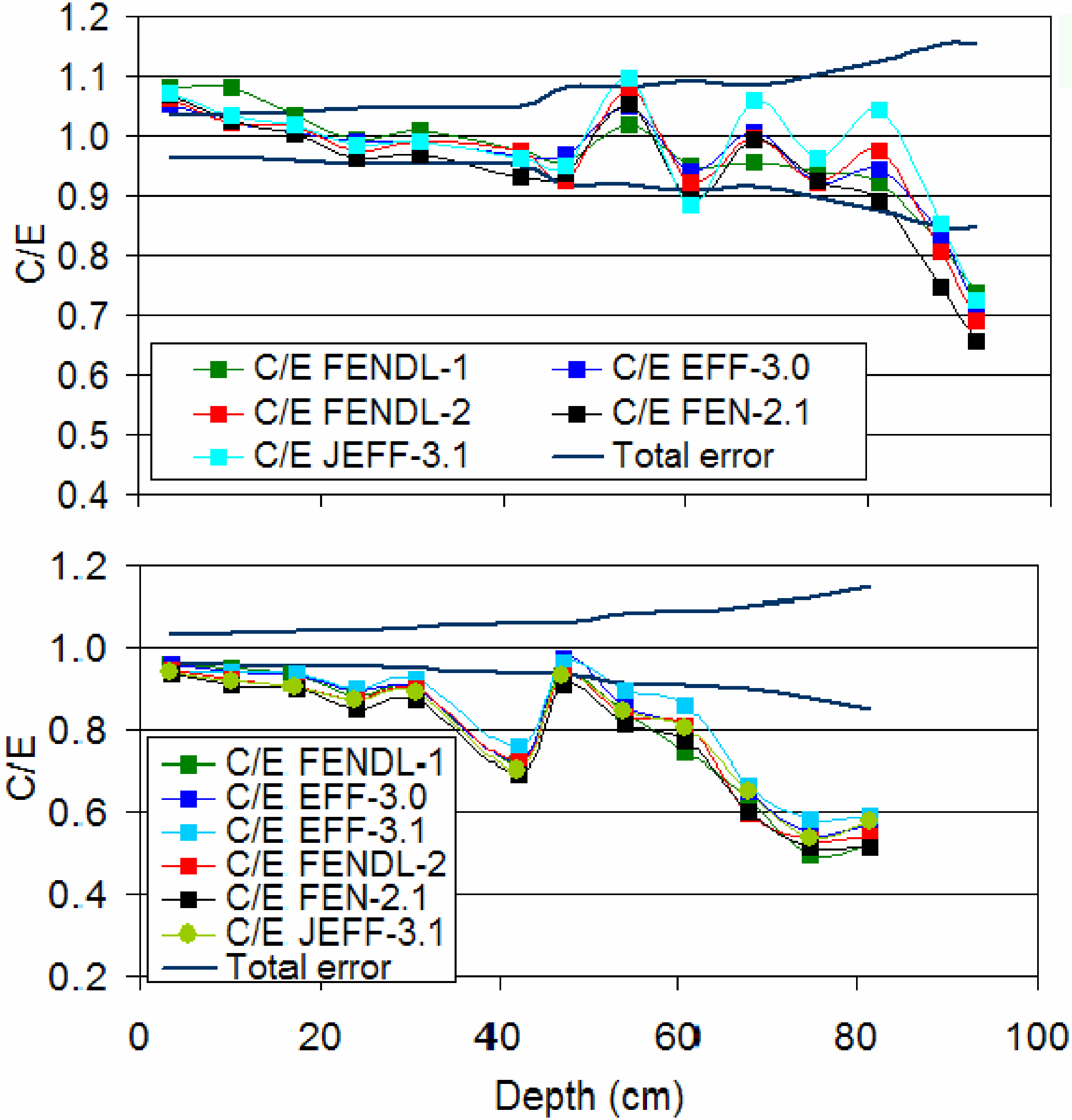
Bulk Shield experiment

Neutron energy E> 3 MeV



Fe-56(n,p)

Al-27(n,a)



Bulk Shield experiment

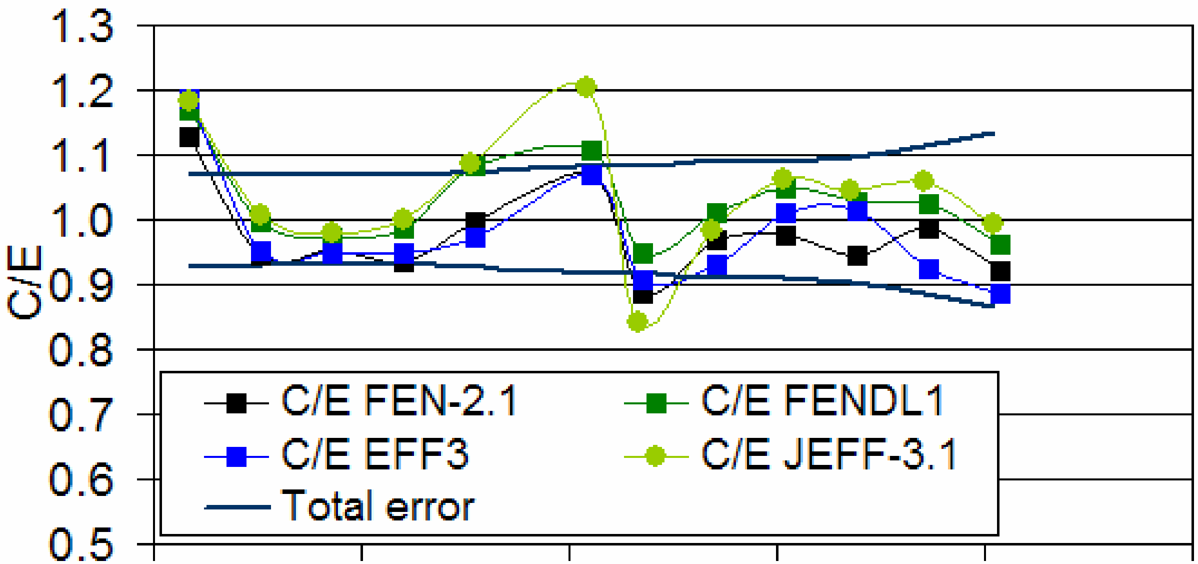
Neutron energy E> 0.8 MeV

Ni-58(n,p)

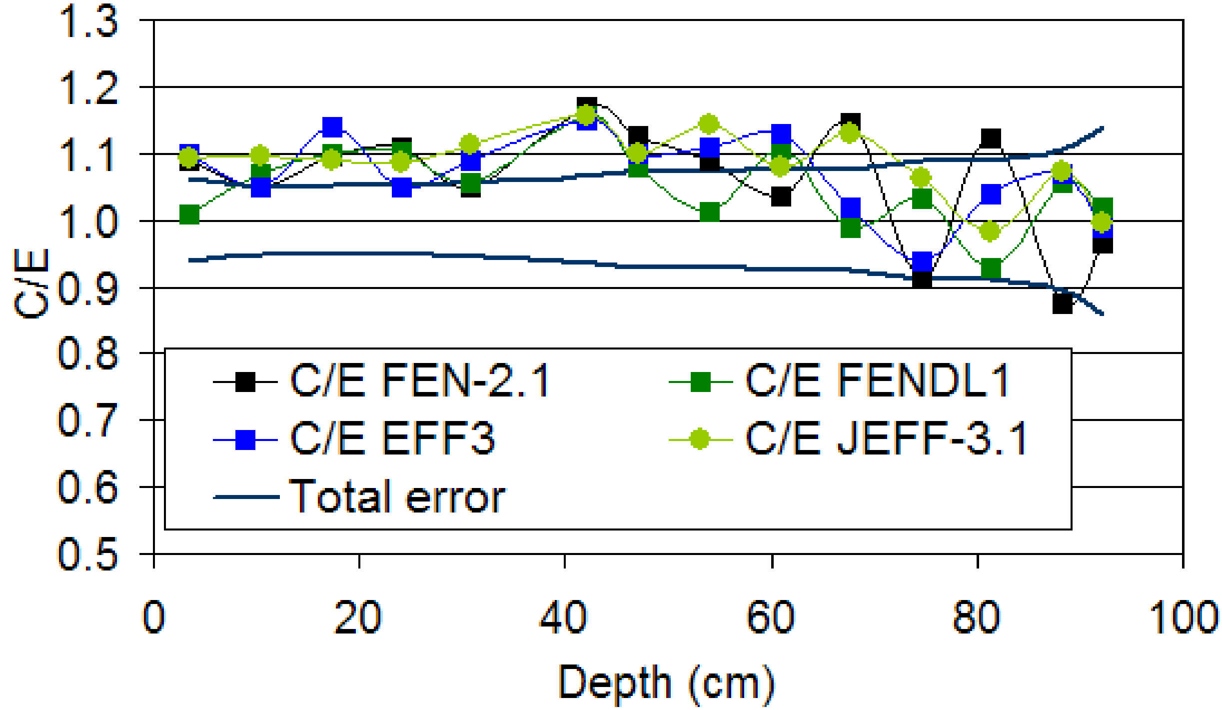
In-115(n,n')

Bulk Shield experiment

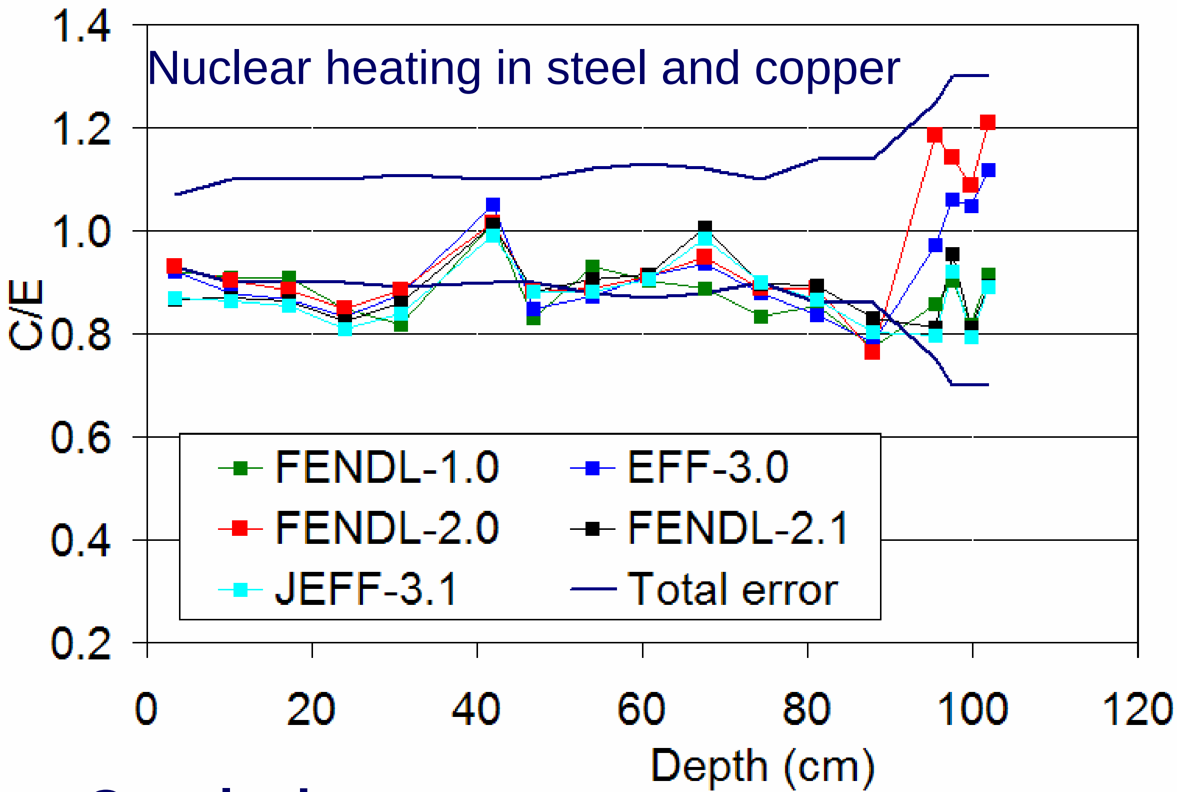
Neutron energy
E ≈ eV



Mn-55(n,γ)



Au-197(n,γ)



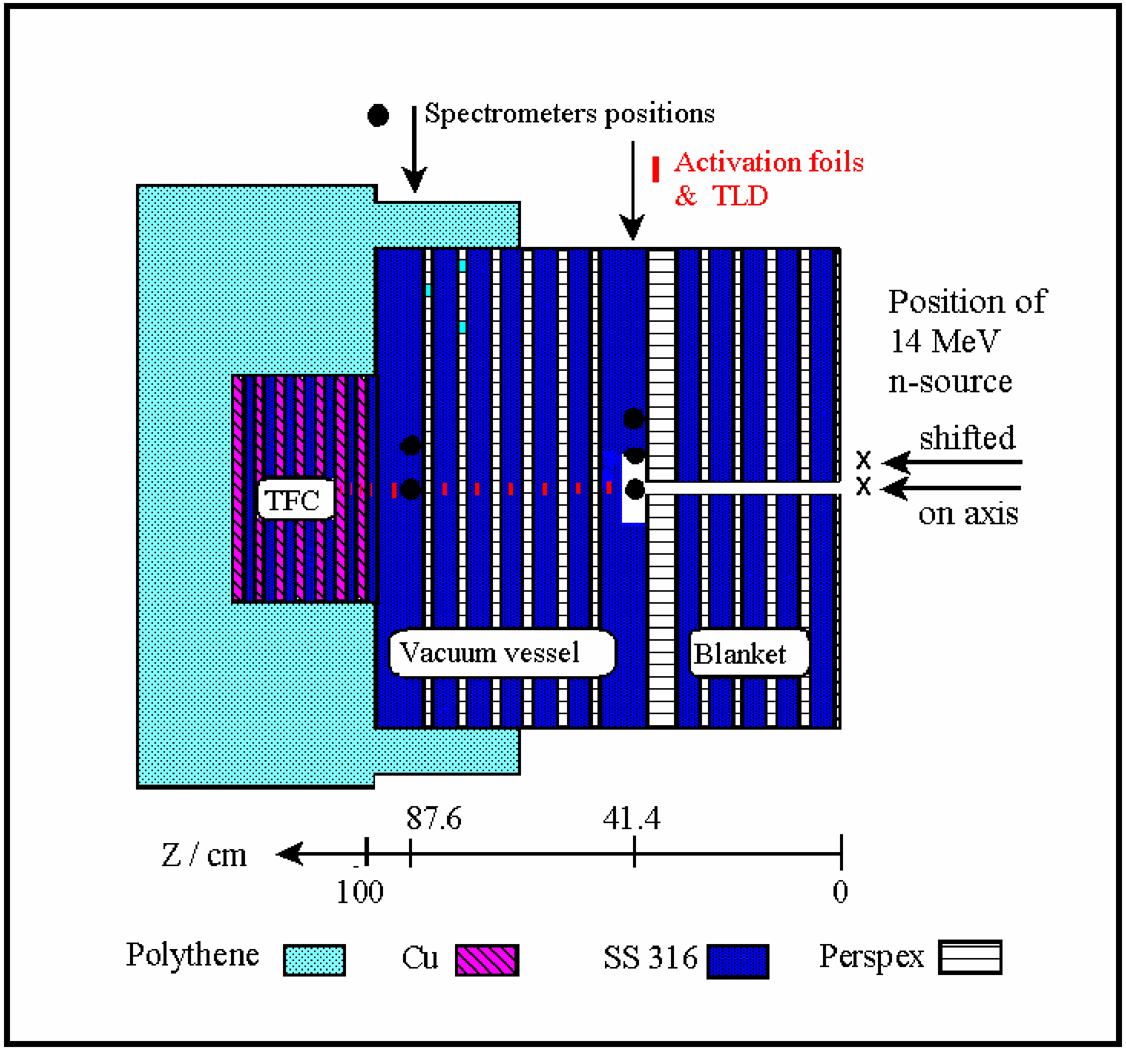
Bulk Shield experiment

Conclusions :

Neutron and gamma fluxes (He-production, radiation damage)
well predicted within ± **15 %** uncertainty at the VV and
± **30 %** at the TF coil
(underestimation)

Nuclear heating well predicted within ± **15 %** uncertainty in FW, SB and VV
± **30 %** in TF coils
(underestimation)

Streaming experiments

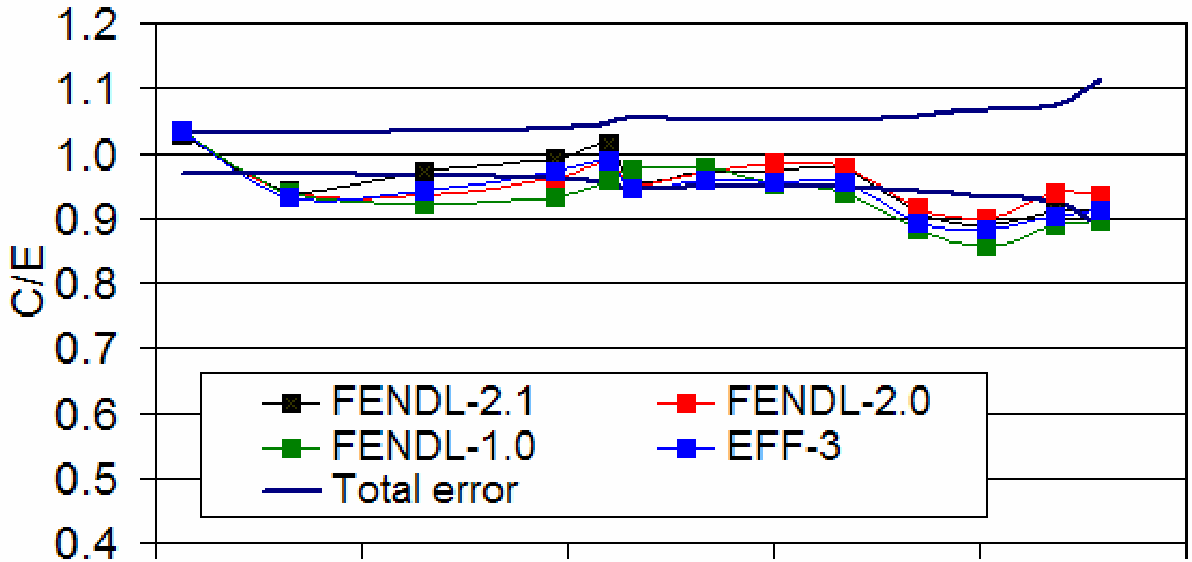


Mock-up of the ITER inboard first wall/shielding blanket /vacuum vessel/toroidal magnet with a streaming channel (3 cm diam)

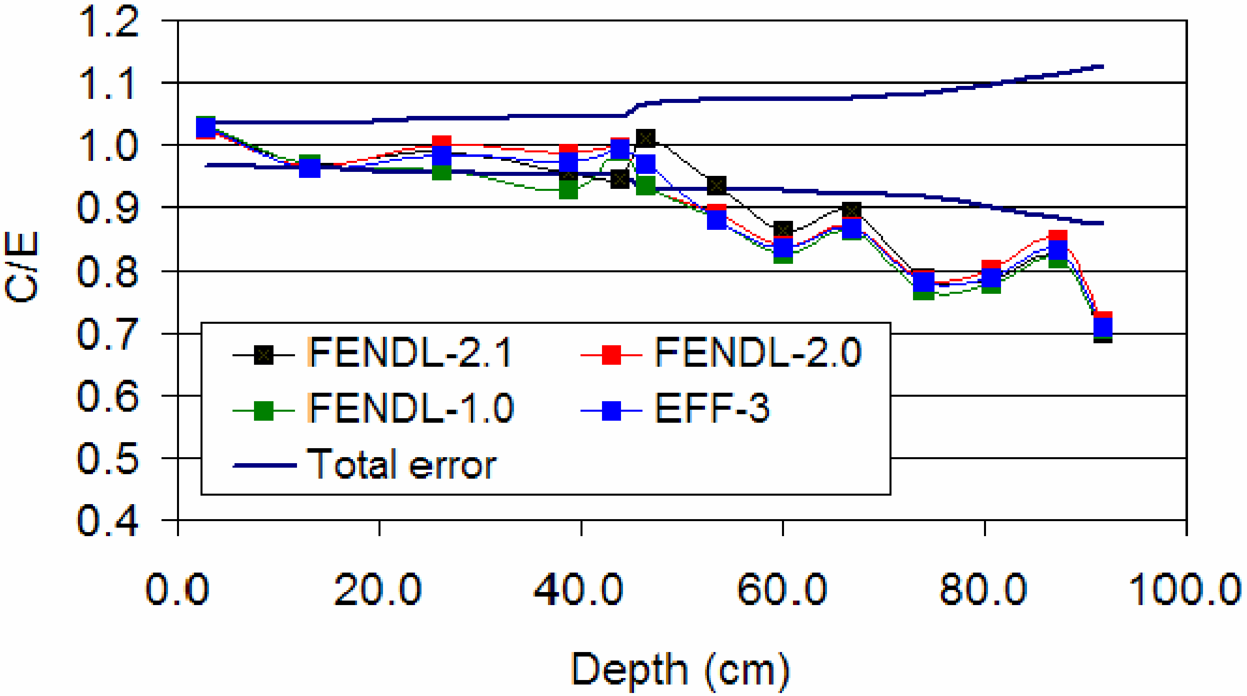
- Measurements of the neutron flux as a function of depth by activation foils

✓ in the channel
✓ in the box
✓ in the shield behind

Streaming experiment

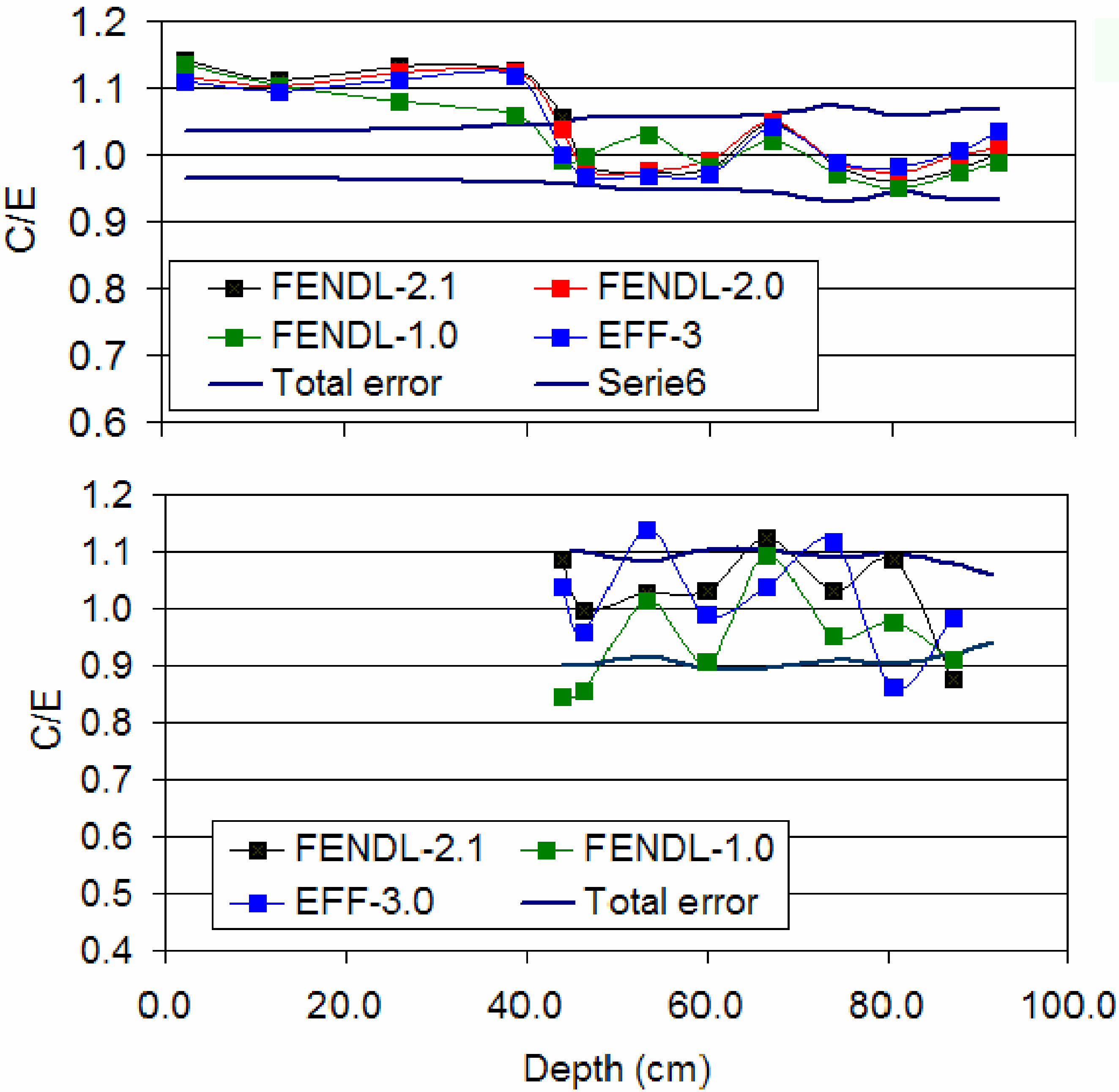


Nb-93(n,2n)
E > 10 MeV



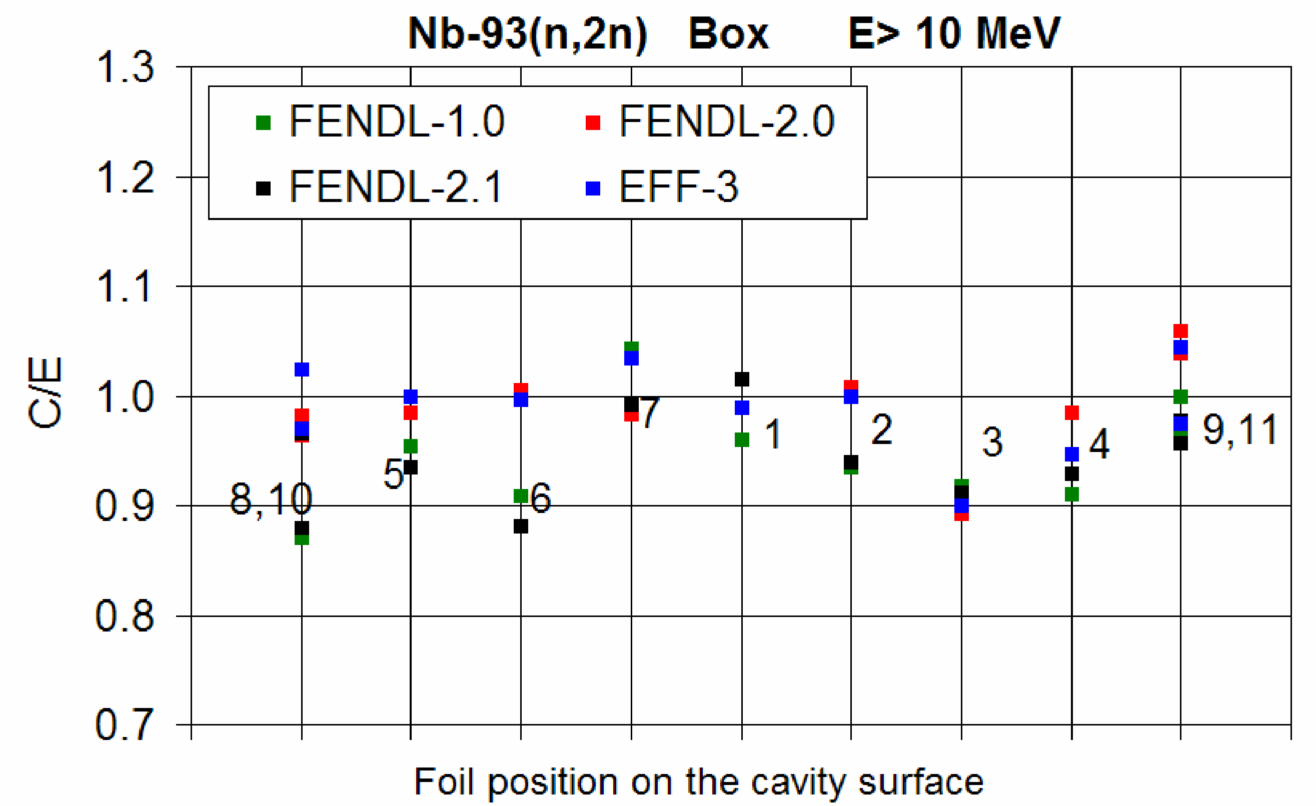
Al-27(n,a)
E > 5 MeV

Streaming experiment



Ni-58(n,p)
E > 1.5 MeV

Au-197(n,g)
E ≈ 5 eV



Streaming experiment

Activation measutrements in the cavity

Similar results are obtained with the other activation reactions

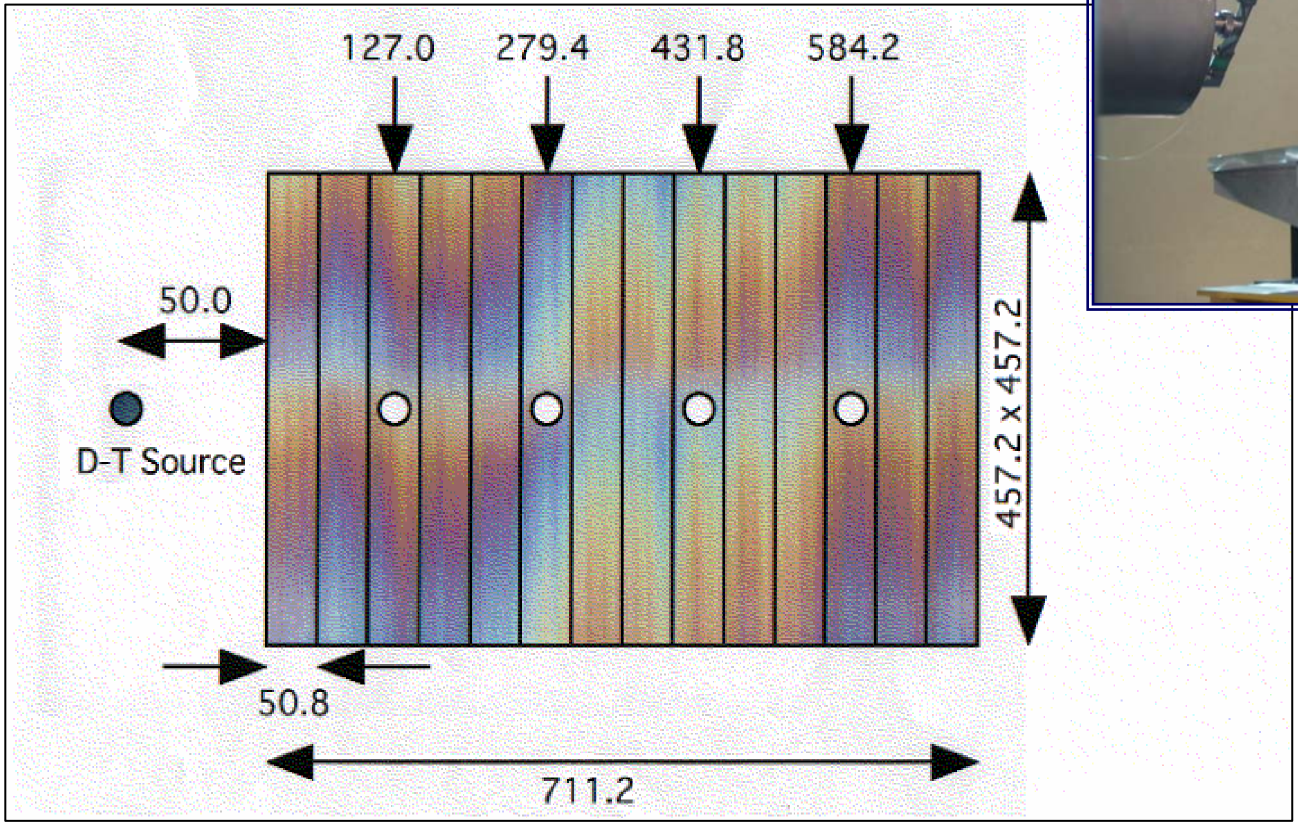
Conclusions :

Results & uncertainties similar to those obtained in bulk shield

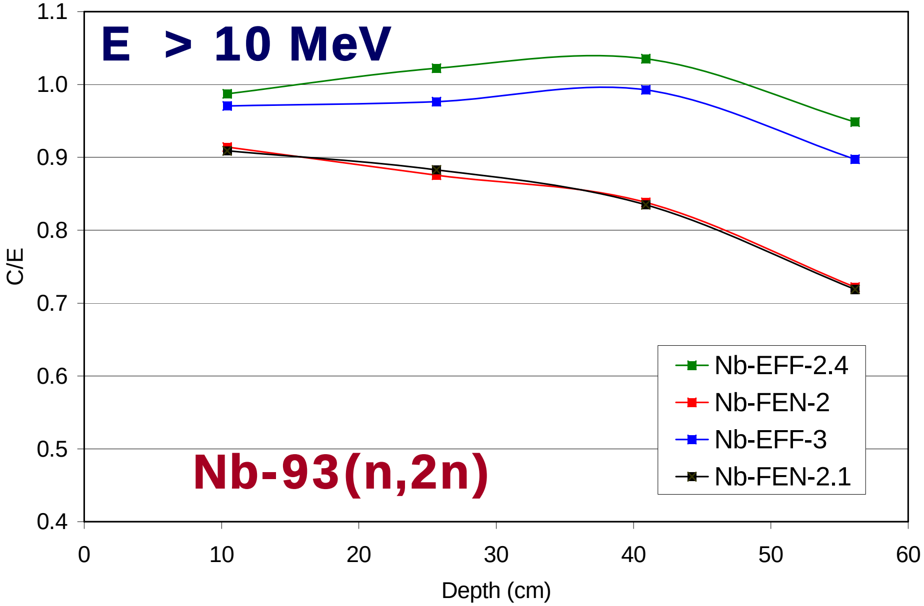
The presence of penetrations does not deteriorate C/E values

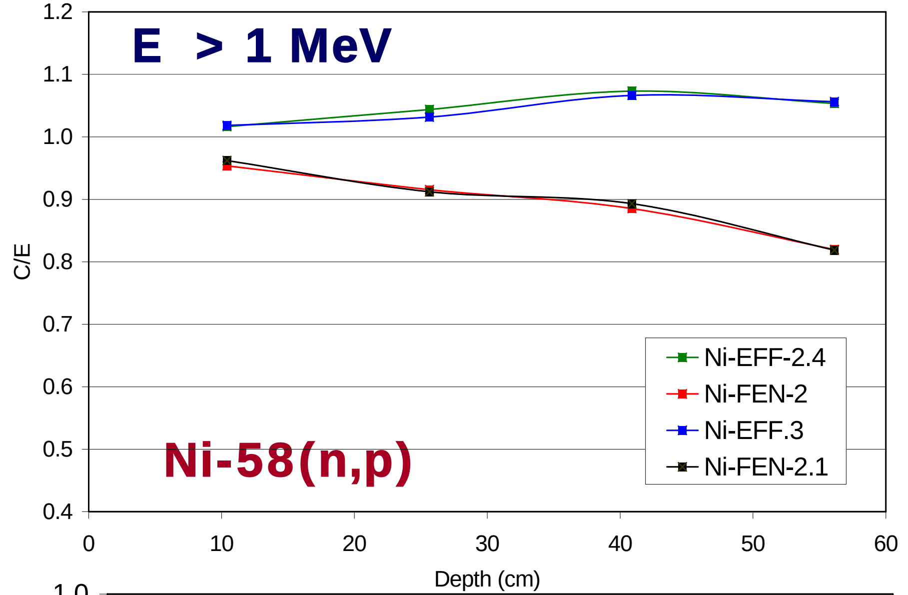
Siicon Carbide (SiC) experiments

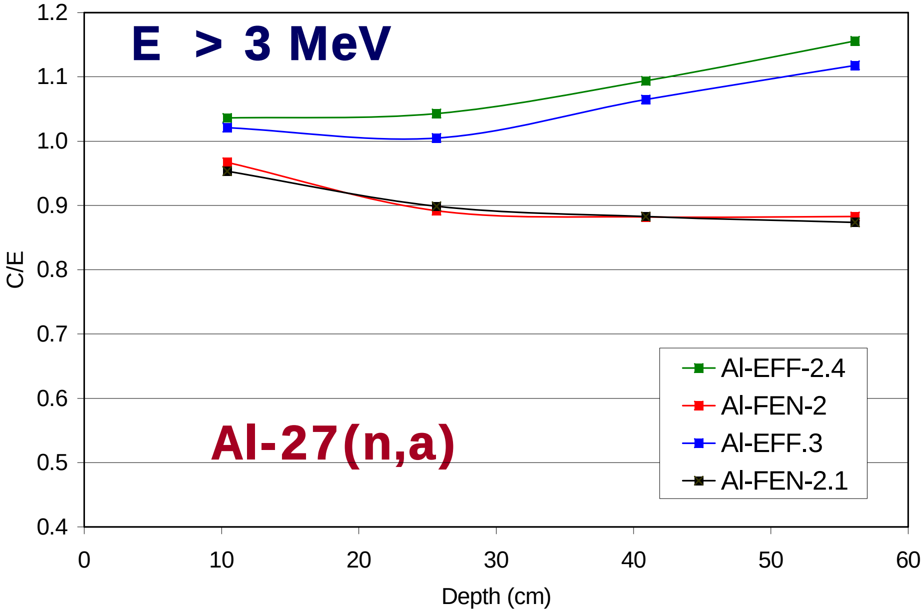
Silicon Carbide block (SiC, advanced low-activation structural material)

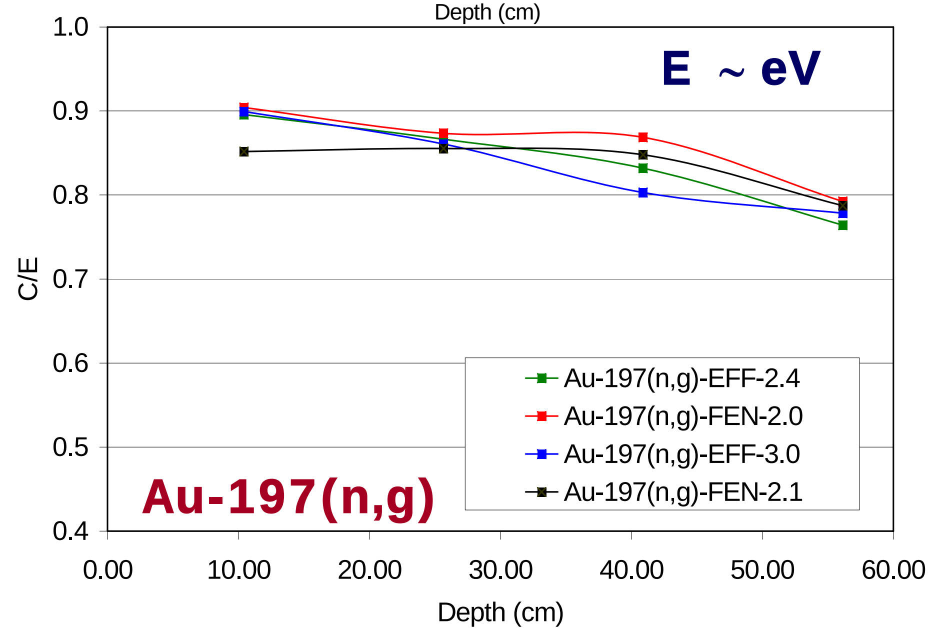


- Measurements of the neutron flux in four positions at different depths by activation foils





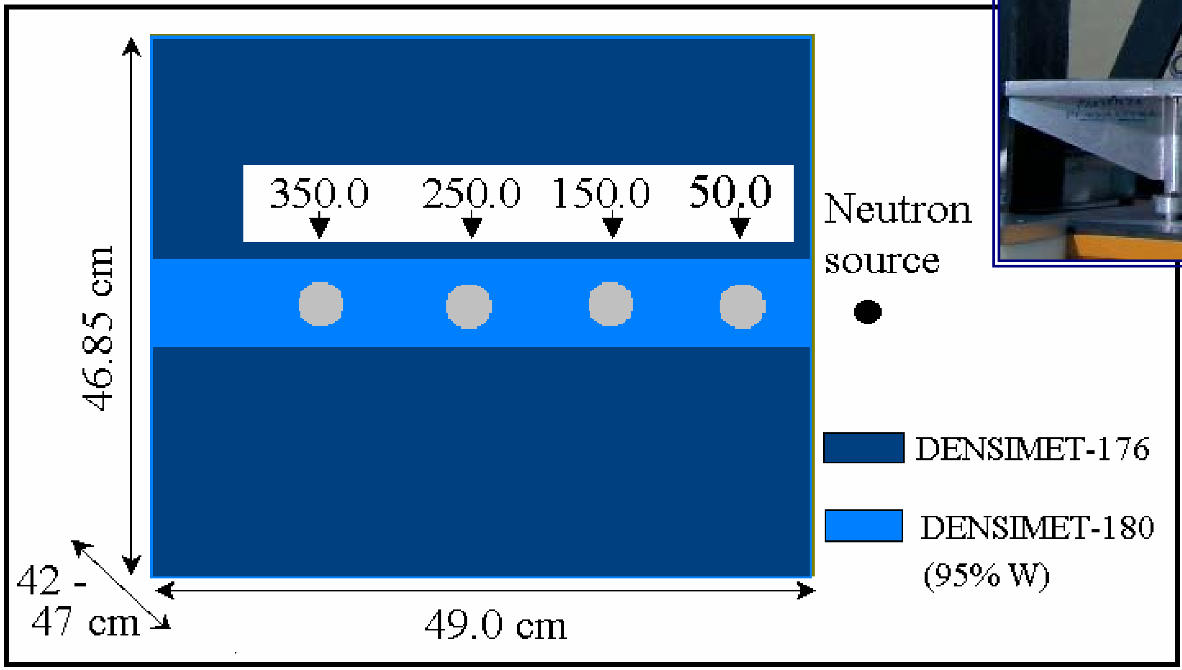


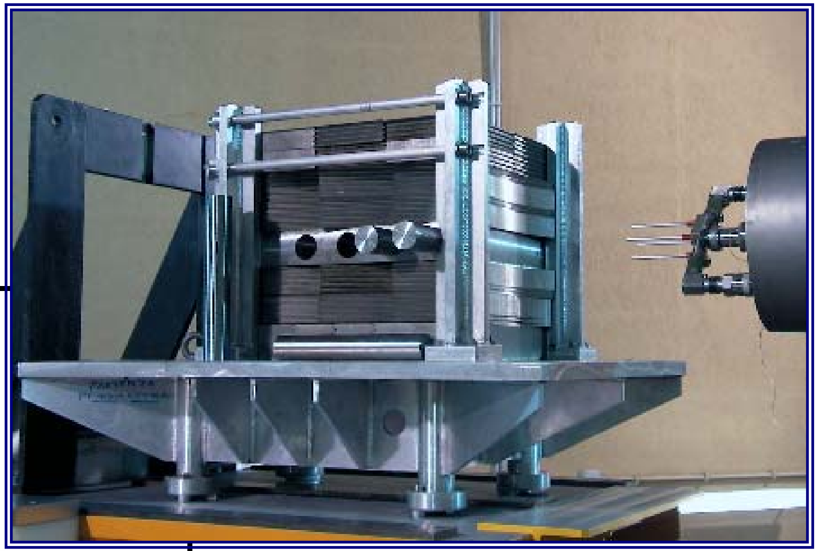


Conclusions: Significant underestimation of the fast neutron flux

Tungsten (W) experiments

Tungsten block (armour material for plasma facing components)



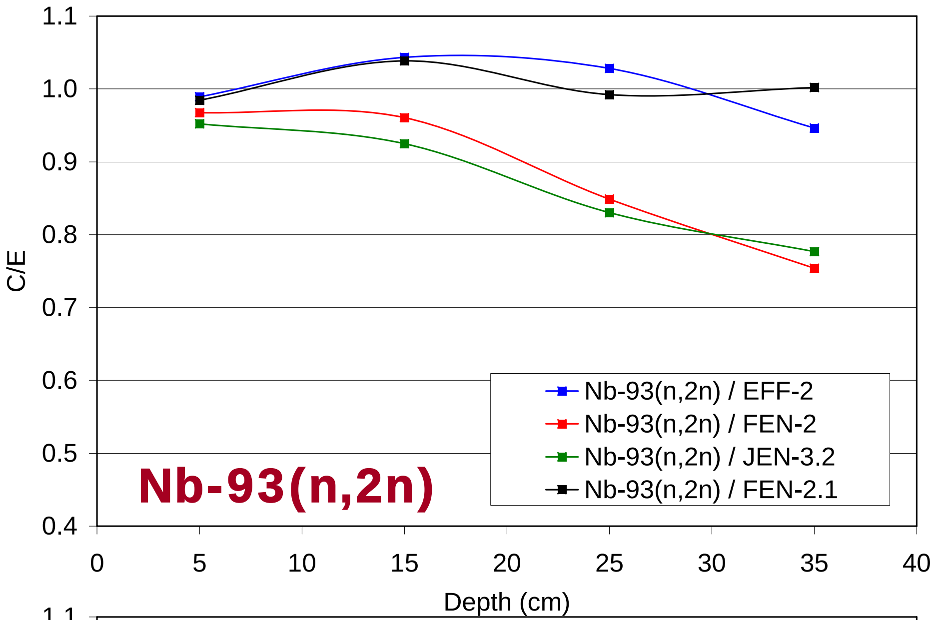


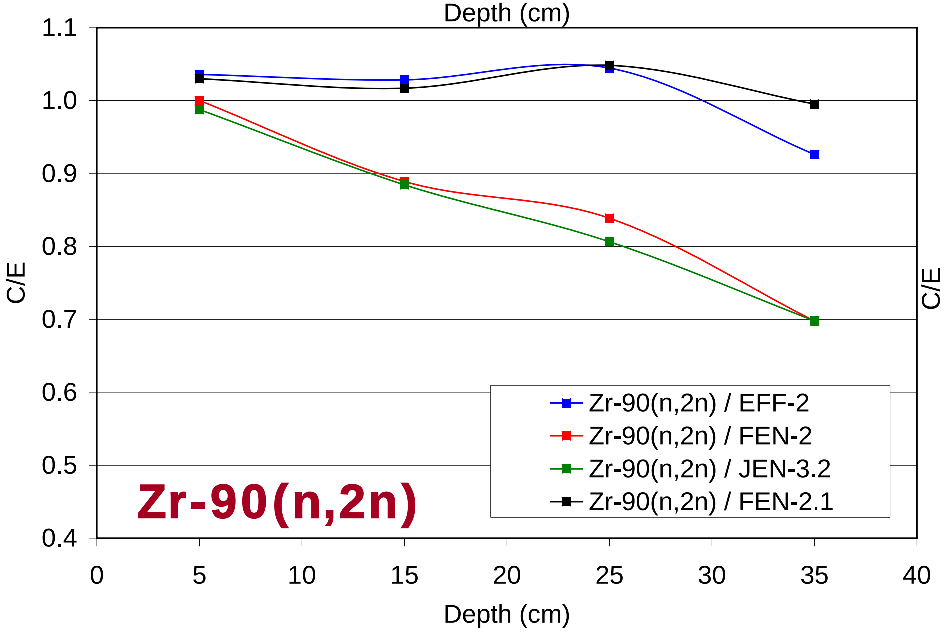
DENSIMET-176 (93.2%w W, 2.6%w Fe, 4.2%w Ni, 17.70 g/cm^3).
DENSIMET-180 (95.0%w W, 1.6%w Fe, 3.4%w Ni, 18.075 g/cm^3)

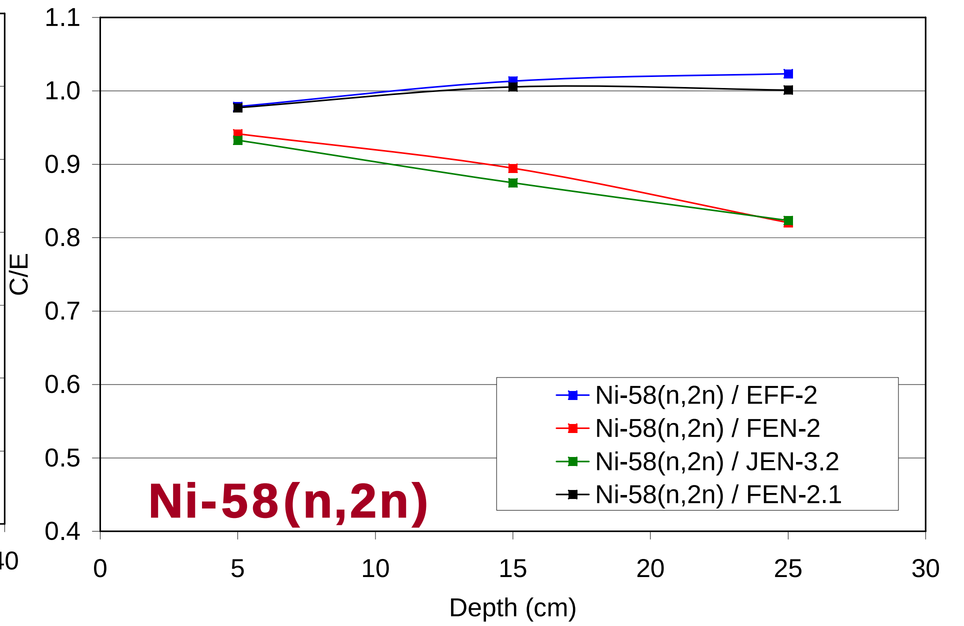
- Measurements of the neutron flux in four positions at different depths by activation foils

W experiment

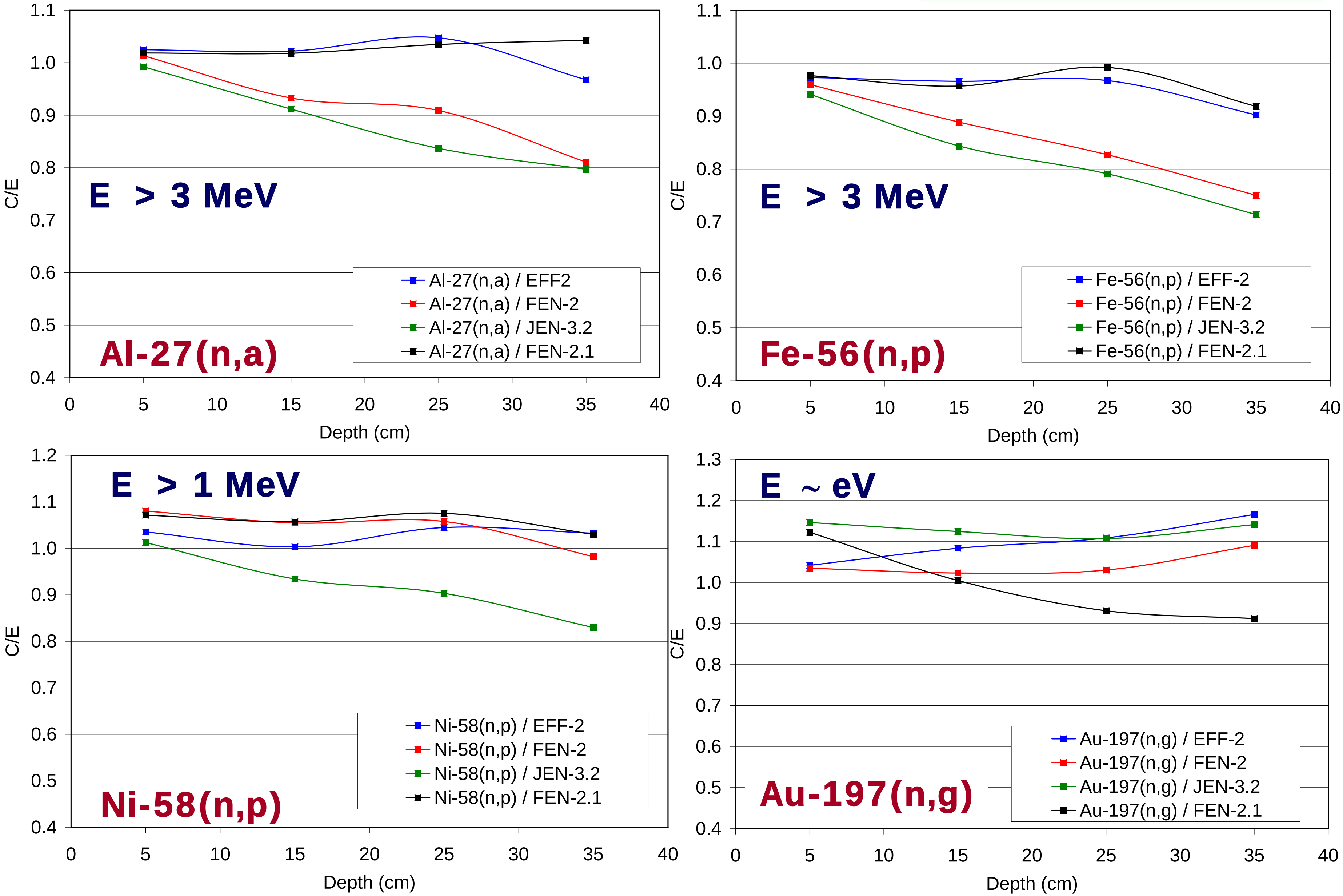
E > 10 MeV







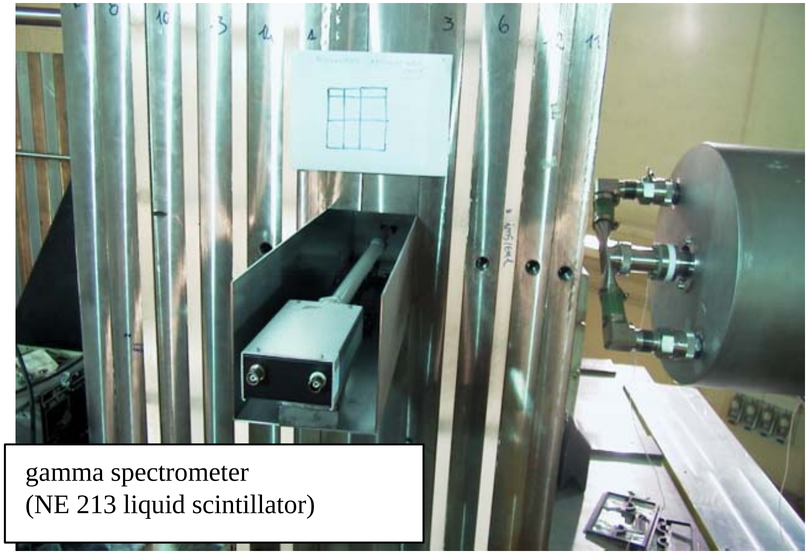
W experiment

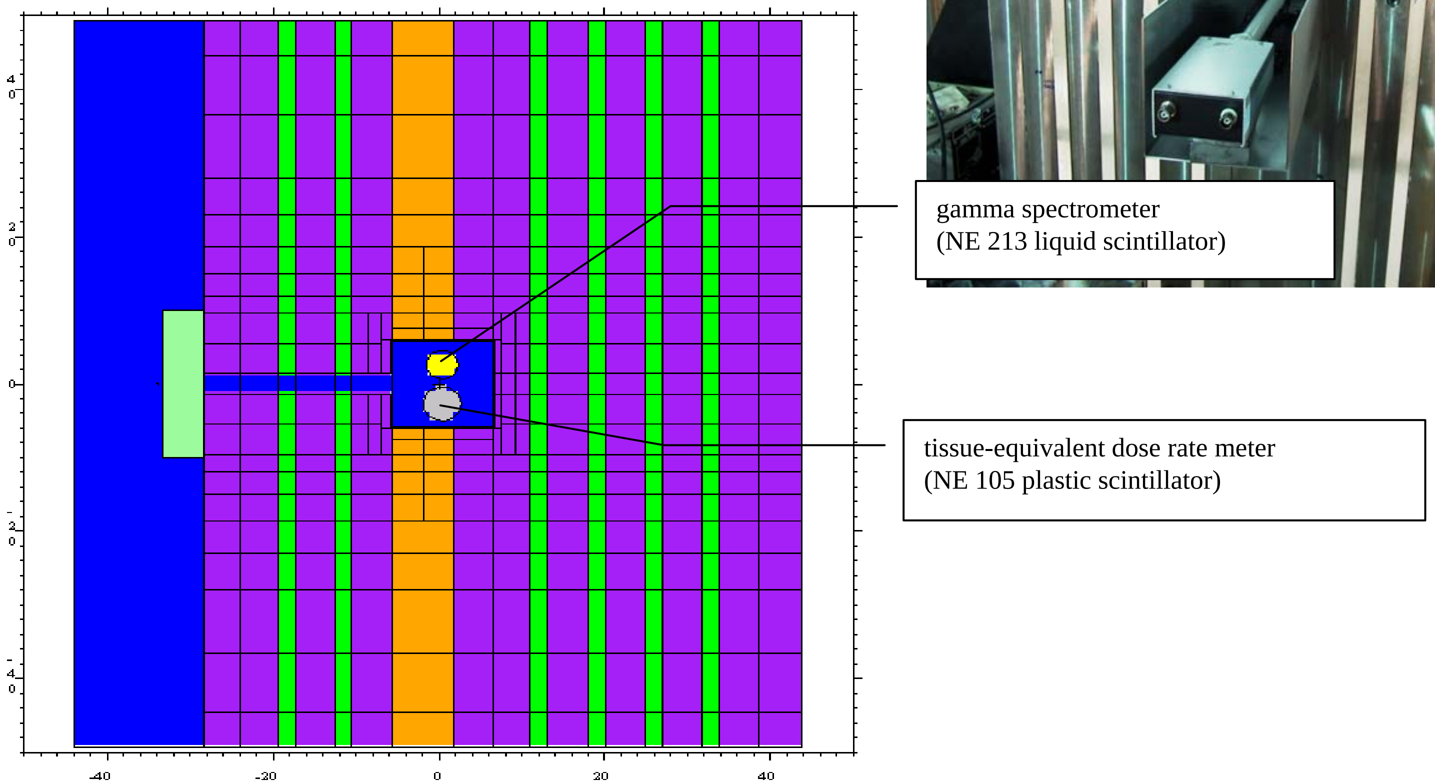


Conclusion: Significant improvement from FENDL-2.0 to FENDL-2.1

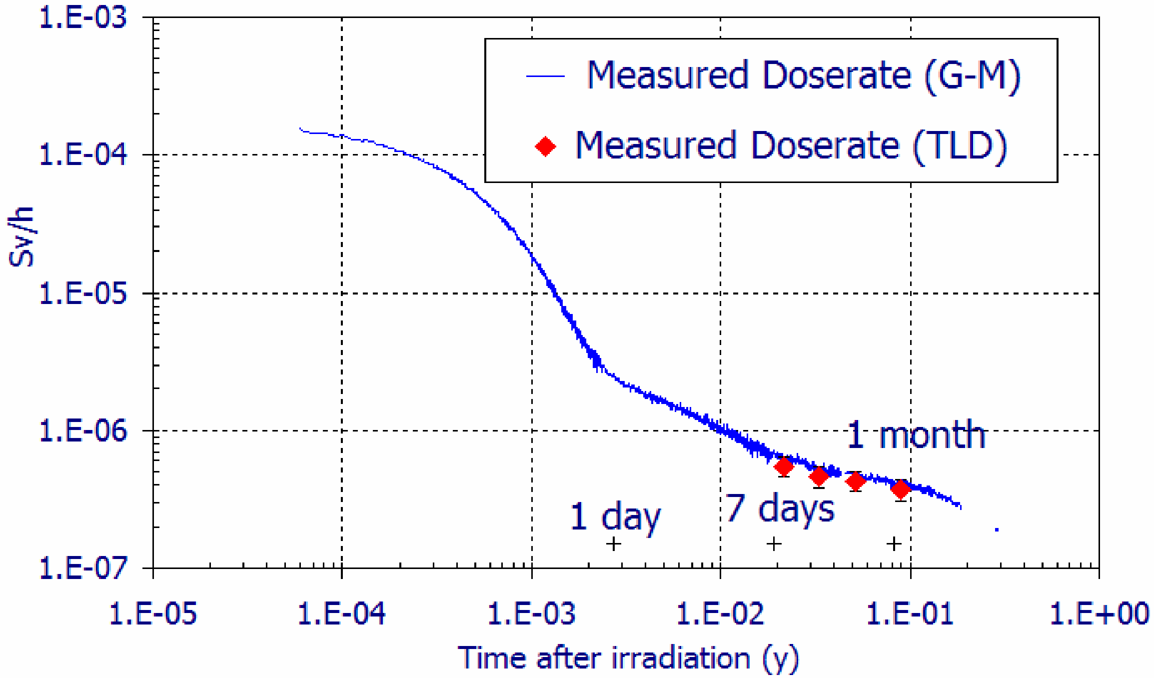
Dose rate experiments

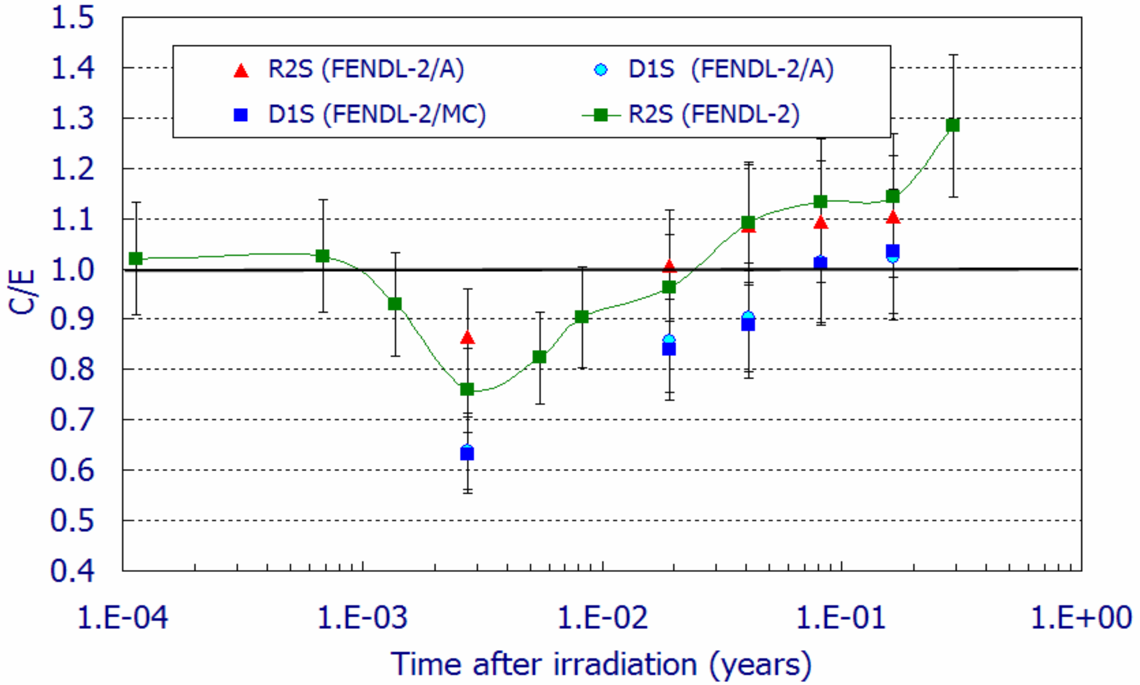
Mock-up of the ITER vacuum vessel





Measurement of the shutdown dose rate after long irradiation with 14 MeV neutrons





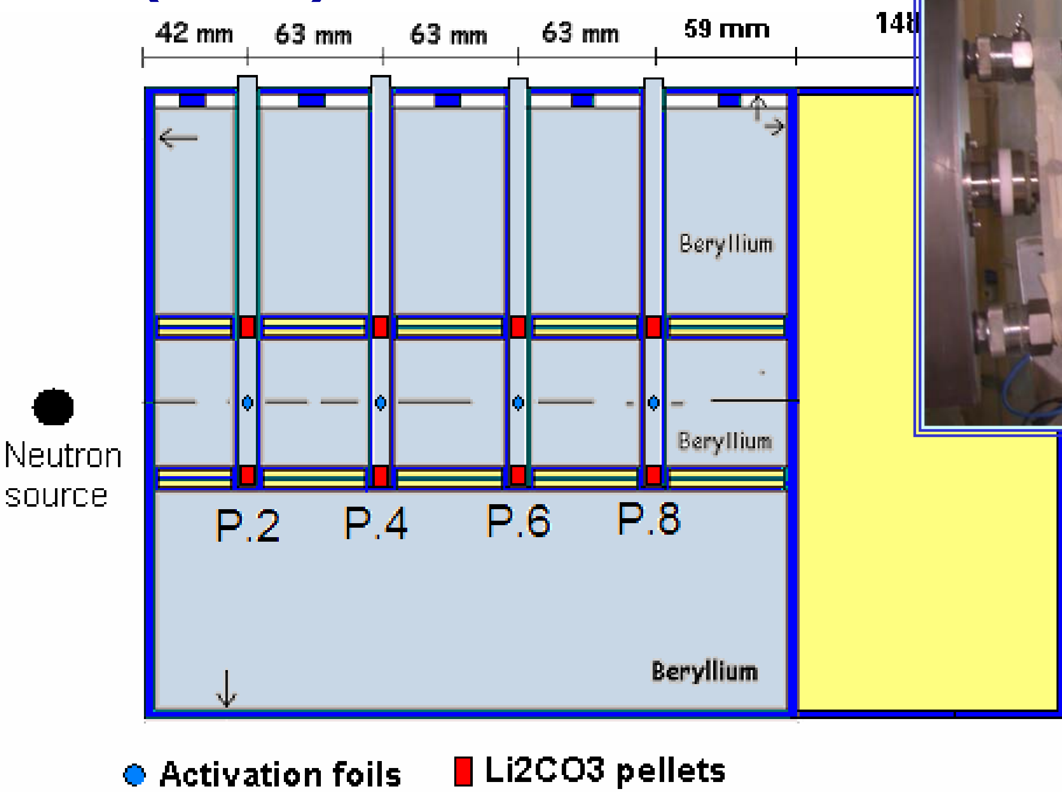
- Numerical tools developed combining transport & activation codes (MCNP,FISPACT)
- Validation of different approaches of combination: D1S, R2S

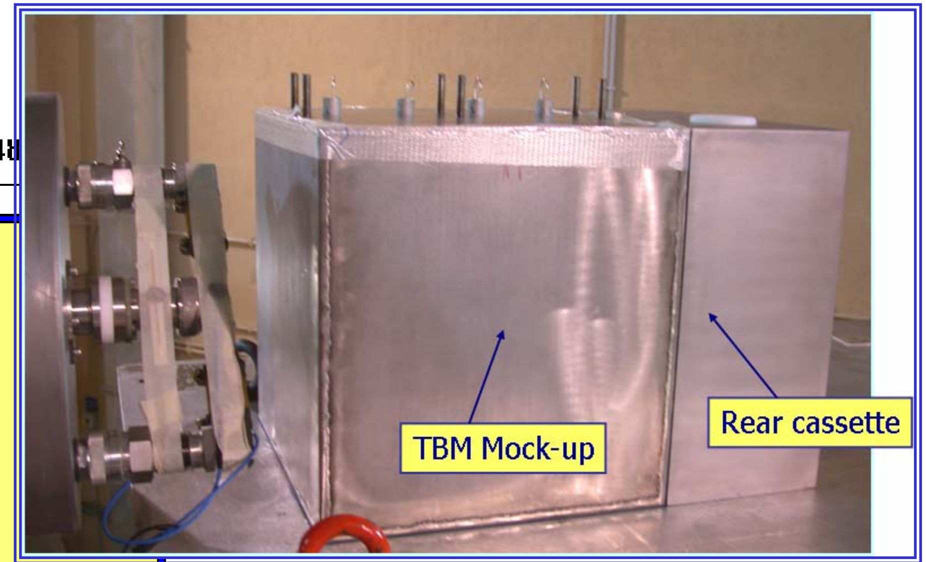
Conclusions:

Shut down dose rate at the vacuum vessel level can be predicted within ±25% uncertainty up to 4 months decay time

HCPB Breeder blanket experiments

Mock-up of the EU breeder blanket Helium Cooled Pebble Bed (HCPB)



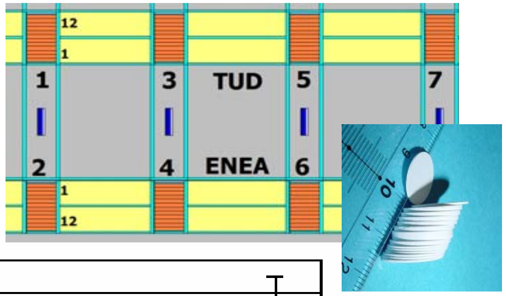


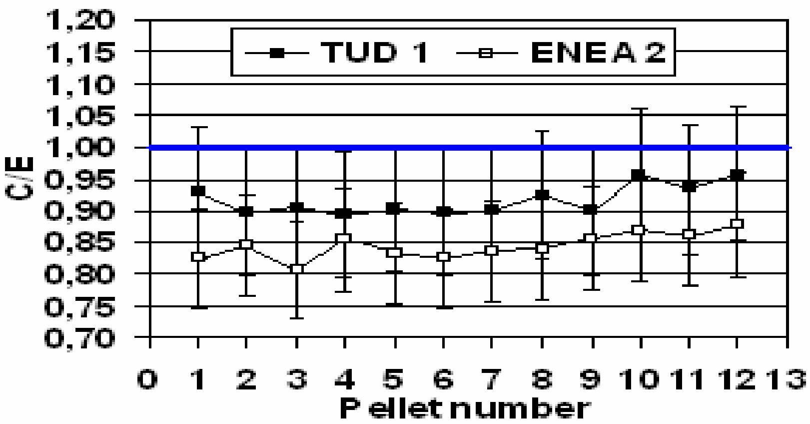
Measurements of tritium production in 4 positions P.2 – P.8 by Li_2CO_3 pellets (nat. Li)(12 pellet/position) and of the neutron flux in the central Be layer by activation foils

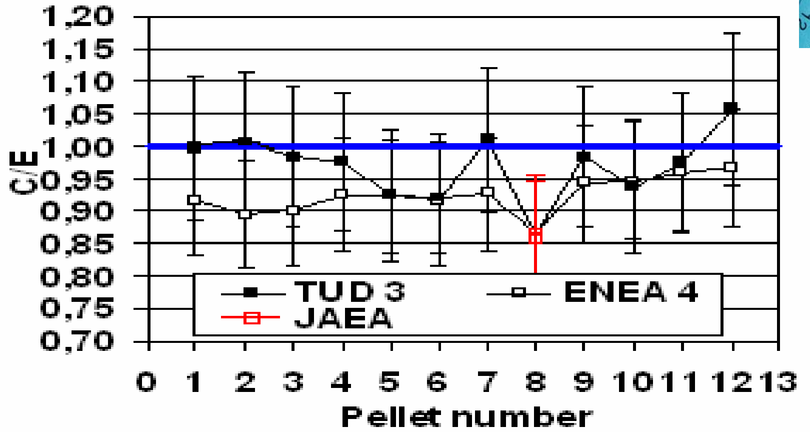
C/E Comparison for T measurements

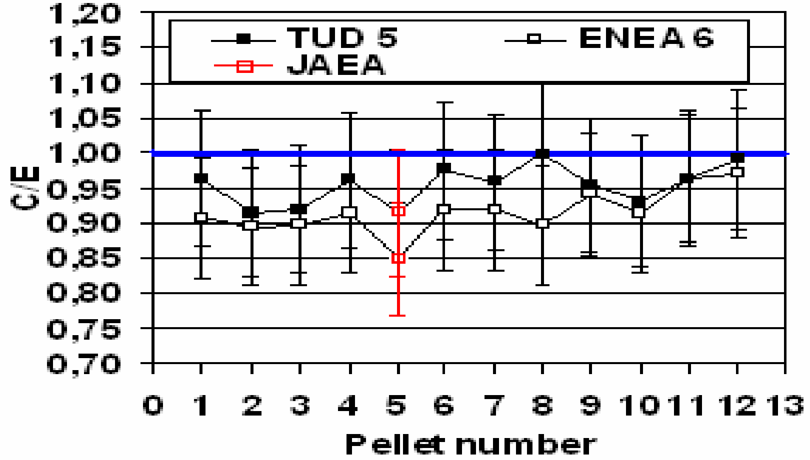
Analysis performed with **EFF-3**

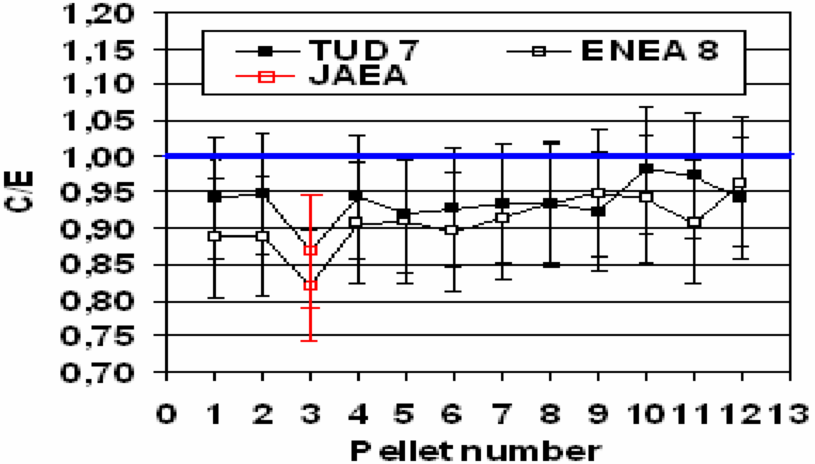
Very similar results obtained with **FENDL-2.1**











Conclusions:

Total uncertainty on C/E comparison ~9% (2 σ)

C/E sligthly underestimated by 5-15%, generally within total uncertainty

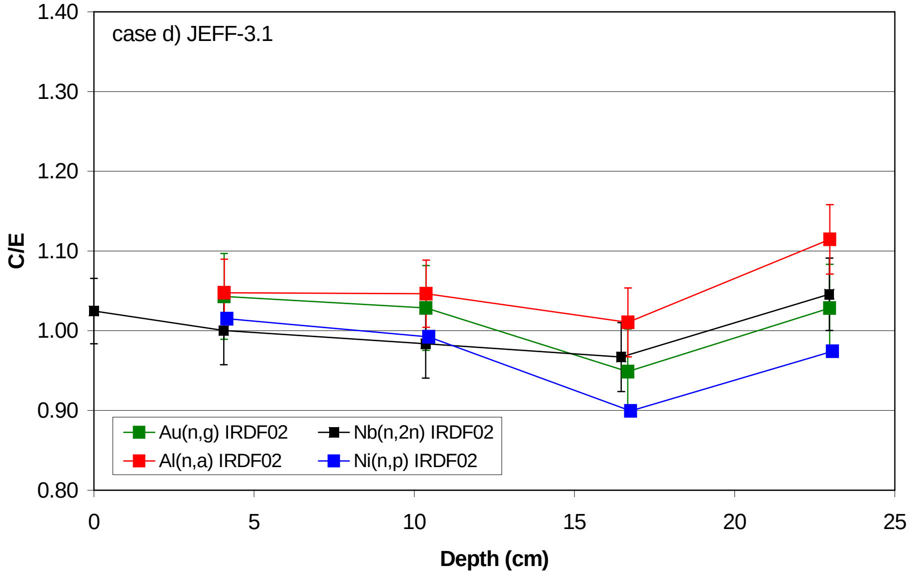
Cross section sensitivity/uncertainty analysis (FZK, NEA-DB)

Sensitivities (%/%) of calculated T- production vs cross sections

	cross section	Li-6(n,t)				Li-7(n,n't)			
		TUD 1	TUD 3	TUD 5	TUD 7	TUD 1	TUD 3	TUD 5	TUD 7
Be-9	elastic	1.999	2.091	1.784	1.672	0.048	-0.001	-0.053	-0.130
	(n,2n)	0.716	0.710	0.664	0.611	-0.016	-0.191	-0.398	-0.619
Li-6	(n,t)	0.326	0.248	0.179	0.152	0.000	0.000	0.000	0.000
Li-7	(n,n't)	0.001	0.001	0.000	0.000	0.990	0.982	0.972	0.960
C-12,O-16		< 0.1							

Total uncertainties (2σ) on total T- production vs cross sections

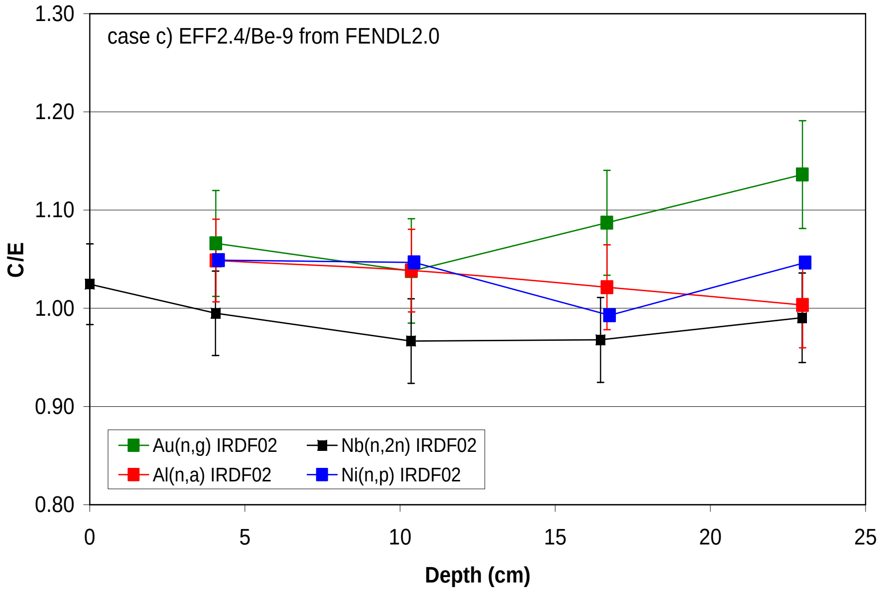
	Be9	Li6	Li7	O16	C12	total
TUD 1	3.5%	0.30%	0.60%	0.30%	0.10%	**3.58%**
TUD 3	4.3%	0.20%	0.40%	0.30%	0.03%	**4.33%**
TUD 5	4.0%	0.20%	0.30%	0.40%	0.03%	**4.04%**
TUD 7	3.5%	0.10%	0.20%	0.40%	0.03%	**3.53%**

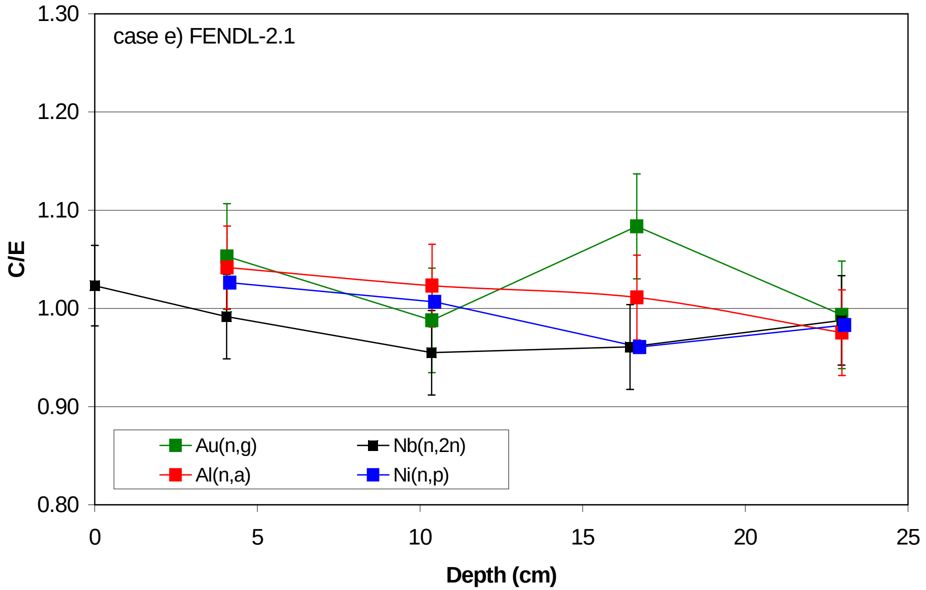


Analysis of activation measurements in Beryllium

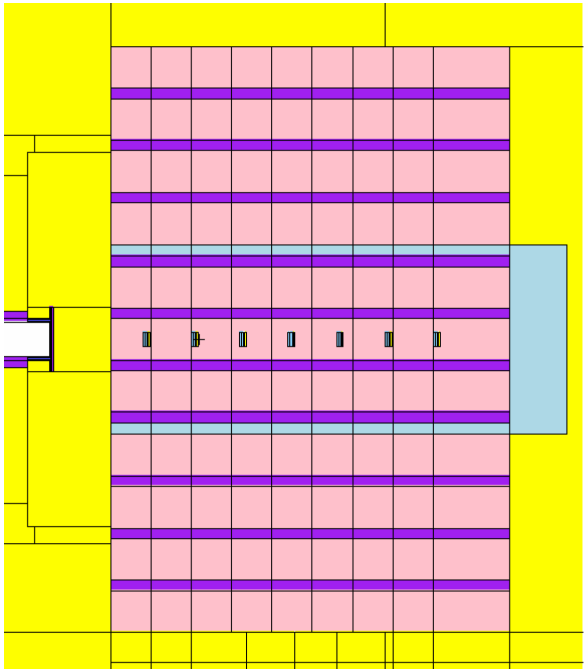
Conclusions

Neutron flux well predicted in Be within ± **5-10%** uncertainty (shielding properties)





HCLL Breeder blanket experiments (2008-2009)



LiPb (15.7 at% nat-Li) 630 kg

Eurofer 11 plates, 9 mm thick

Polyethylene

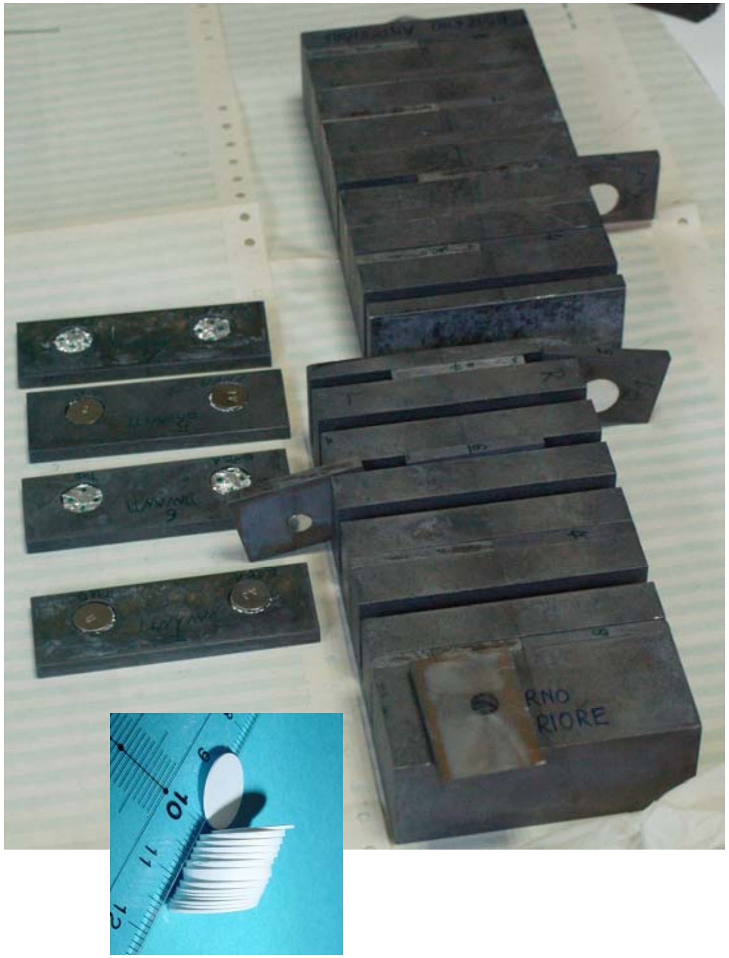
Mock-up of the EU breeder blanket Helium Cooled Pebble Bed (HCPB)

Measurements of tritium production in 15 positions by

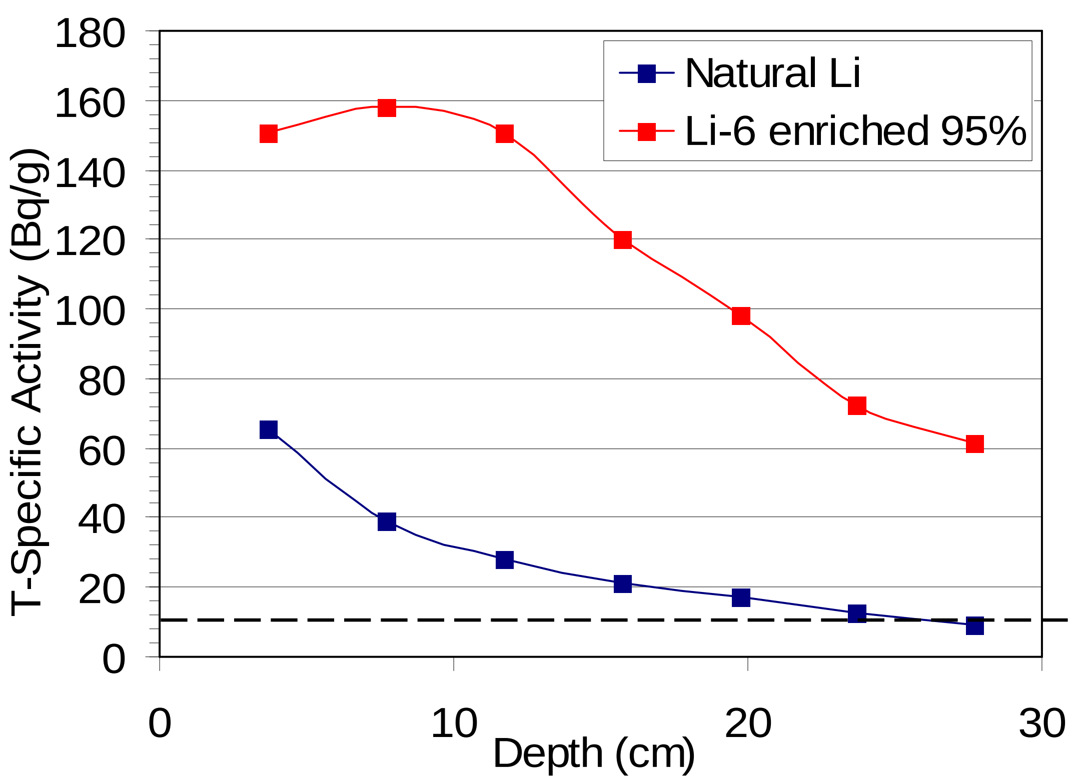
- Li_2CO_3 pellets (nat. Li & Li-6 enr.)
- TLDs (TLD-600,TLD-700)

and of the neutron flux in LiPb by activation foils

(started on 26/11, in progress)



The use of two types of Li_2CO_3 pellets (nat. Li and 95% Li-6 enriched) will allow to separate contribution from Li-6 and L-7 tritium producing reactions.



Conclusions

- Shielding, activation and dose rate calculations for ITER validated for many materials / components using FENDL- 2.1 reference library
- Neutron fluxes predicted in stainless steel/water shield assemblies within ± 30% uncertainty at 1 m depth. Underestimation of fast neutron flux observed
- Significant underestimation of the fast neutron flux is found in SiC with FENDL-2.1 (20% at 50 cm)
- Significant improvement from FENDL-2.0 to FENDL-2.1 in tungsten
- Very good prediction of neutron flux in HCPB blanket mock-up (Be/ Li_2CO_3) Tritium production underestimated by 5-15%, generally within total uncertainty (± 9%, 2σ)

•HCLL blanket experiment in progress

•Only main structural in vessel materials investigated so far