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Validation of IRDFF-v1.04(&v1.05) Dosimetry Library Using SINBAD Shielding Benchmark Experiments

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February 2015

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ABSTRACT

A Data Development Project and a Coordinated Research Project of the International Atomic Energy Agency (IAEA) aimed at updating the library of dosimetry cross sections "International Reactor Dosimetry File: IRDFF" are underway. To validate the new evaluations the thermal neutron capture cross-sections were first compared against the Keyzero and Mughabghab values as well as against the previous IRDFF-2002 and -90 data. Furthermore, a series of shielding benchmarks available from the SINBAD database were used to check and validate the new IRDFF dosimetry file, version v1-04 (updated ^{6}Li(n,t) data were taken from v1.05). Several benchmark experiments performed at the Frascati Neutron Generator (FNG), ENEA Frascati, and in ASPIS, AEA Technology,Winfrith were analysed. The main purpose of repeating the calculations with the new dosimetry cross sections was to check for any improvement between measured and calculated reaction rates (compared to IRDF-2002 as well as IRDF-90) and removal of some inconsistent trends in the results for different monitors. Since the dosimetry data represent a relatively small part of the overall uncertainty, the major part coming from the transport cross section and model approximations, these results can be considered as an indirect validation of the new IRDFF dosimetry library. The compensation of errors between the transport cross sections and dosimetry data is likely.To obtain additional information potentially useful to conclude on the impact of transport and dosimetry cross-section uncertainties and their compensation,as well as on the computer code modelling uncertainties, the results using different transport cross-sections and computer codes (DOORS and MCNP) are presented for several benchmark analyses.

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Contents

1. Introduction

IRDFF [1, 2] is a standardised neutron dosimetry reaction cross section library recently prepared at IAEA. The main application involves the flux measurements by activation technique in areas like reactor pressure vessel surveillance and benchmark experiment analysis for fission and fusion reactor studies. The file incorporates a large number of new experimental data which has become available since the release of the previous version of the dosimetry file, IRDF-2002 [3].

2. Comparison with integral constants for neutron activation analysis

Similar validation exercise as performed in the past to validate the IRDF-2002 and IRDF-90 libraries was repeated for the radiative capture reactions in IRDFF. The comparison of the thermal capture cross sections between the IRDFF, IRDF-2002, IRDF-90 and the experimental KAYZERO [4] and Mughabghab[5,6] values is shown in Table 1 for 15 reaction cross section, referring either to the total radiative capture cross section, or the excitation of long-lived metastable states. The method used is described in [7].

Table 1: Comparison of thermal capture cross sections from various sources. Difference ("*Diff*") is given with respect to the Keyzero values. Yellow highlighted are differences exceeding 2 σ interval, and in pink larger differences (^{93}Nb does not include the excitation of the metastable state).

Target	Product	Mughabghab [1]			Kayzero/Nudat [2]		IRDFF		IRDF-2002		IRDF-90/V2	
		σ_0 [b]	$\Delta\sigma_0$ [%]	Diff [%]	σ_0 [b]	$\Delta\sigma_0$ [%]	σ_0 [barns]	Diff [%]	σ_0 [barns]	Diff [%]	σ_0 [barn]	Diff [%]
Na-23	Na-24	0.53	0.9	3.3	0.513	0.57	0.528	2.9	0.528	2.9	0.528	2.9
Sc-45	Sc-46	27.2	0.7	3.6	26.26	0.40	27.208	3.6	27.21	3.6	27.22	3.7
Mn-55	Mn-56	13.36	0.4	1.3	13.18	0.92	13.278	0.7	13.42	1.8	13.42	1.8
Fe-58	Fe-59	1.316	1.9	1.0	1.30	2.66	1.315	1.2	1.301	-0.1	1.15	-12
Co-59	Co-60	37.18	0.2				37.18		37.18		37.24	
Cu-63	Cu-64	4.52	0.4	-2.4	4.63	0.90	4.471	-3.4	4.471	-3.4	4.473	-3.4
Nb-93	Nb-94m	1.15	4.3		0.86		1.156	34	1.156	34	1.156	34
Ag-109	Ag-110m	3.91	1.1		3.94	2.88	4.214	7.0	4.214	7.0	4.689	19.0
In-115	In-116m	202	1.0		160.24	6.23	159.8	-0.3	166.5	3.9	166.5	3.9
La-139	La-140	9.04	0.4	-4.1	9.42	1.78	9.042	-4.0	9.042	-4.0		
Ta-181	Ta-182	20.5	2.4	-0.4	20.59	7.59	20.68	0.4	20.68	0.5		
W-186	W-187	38.5	1.3	-8.2	41.92	2.67	38.095	-9.1	38.49	-8.2		
Au-197	Au-198	98.65	0.1	0.0	98.65	0.09	98.70	0.1	98.77	0.1	98.79	0.1
Th-232	Th-233	7.35	0.4	-0.3	7.37	0.34	7.338	-0.4	7.405	0.4	7.401	0.4
U-238	U-239	2.68	0.7	-0.1	2.68	0.43	2.686	0.2	2.718	1.3	2.710	1.0

3. Validation against Benchmark Experiments

Benchmark experiments are of great value to check the quality of nuclear data and computational tools. In order to preserve the information on the benchmark experiments relevant for fission reactor (pressure vessel), fusion and accelerator shielding applications the SINBAD project [8] was initiated at the OECD/NEA Data Bank and RSICC. The database contains at present detailed description (including the geometry, measurement quantities and conditions, and results with the corresponding uncertainties) of 100 benchmark experiments.

To determine the progress achieved with the new file the following shielding benchmarks from the SINBAD database, covering fast to thermal neutron energy range, were recalculated using the new IRDFF dosimetry library:

- FNG-ITER Blanket Bulk Shield (1995)
- FNG Silicon Carbide (2001)
- FNG Tungsten (2002)
- FNG HCPB Tritium Breeder Module Mock-up (2005)
- FNG-HCLL Tritium Breeder Module Mock-up (not yet included in SINBAD) (2009)
- Winfrith Iron (ASPIS) (1975).

The five FNG benchmarks were performed at ENEA Frascati using the FNG 14-MeV-fusion-neutron source generator. These are also the most recent among the studied benchmarks and can be considered as more reliable and precise. ASPIS benchmark dates back to the 1970-ies and suffers from several approximations in the description of the neutron source and the geometrical set-up.

Details on these benchmarks (except for the FNG-HCLL) are available in the SINBAD database and can be obtained on request from the OECD/NEA or RSICC and in literature [8-17]. SINBAD compilations include the complete description of the source, geometry, measurements and examples of transport as well as cross section sensitivity and uncertainty analysis and inputs. Reaction rates measuredin these benchmarks are listed in Table 2. Both Monte Carlo and deterministic transport calculationsperformed in the past using older transport (FENDL-2 [19], -2.1 [20], EFF-3 [21]) and dosimetry cross sections (IRDF90, IRDF2002) were supplemented with new computations using IRDFF and, in few selected cases, FENDL-3 transport library.

Table 2: Dosimetry reactions measured at the benchmark experiments considered in this study.

Reactions	FNG-ITER Blanket	FNG SiC	FNG W	FNG HCPB TBM	FNG HCLL TBM	ASPIS Iron
^{93}Nb(n,2n) ^{92m}Nb	X	X	X	X	X	
^{58}Ni(n,2n) ^{57}Ni	X		X		X	
^{90}Zr(n,2n) ^{89}Zr			X		(X)	
^{27}Al(n,α) ^{24}Na	X	X	X	X	X	
^{32}S(n,p) ^{32}P						X
^{56}Fe(n,p) ^{56}Mn	X		X			
^{58}Ni(n,p) ^{58}Co	X	X	X	X	X	
^{115}In(n,n') ^{115m}In	X		X		X	X
^{103}Rh(n,n') ^{103m}Rh						X
^{55}Mn(n,γ) ^{56}Mn	X		X		X	
^{197}Au(n,γ) ^{198}Au	X	X	X	X	X	X
TPR(^{6}Li(n,t) $^{4}\alpha$)				X	X	

Five of the benchmark experiments considered in the study were performed at ENEA Frascati, Italy using the 14 MeV (d,t) neutron source (deuterium atoms accelerated onto a tritium target) produced at the Frascati Neutron Generator (FNG) Facility. The strength of the d-T neutron source was determined by the associated alpha-particles(±2%). ASPIS Iron benchmark was performed at Winfrith, UK using the fission plate neutron source.

The calculations were performed using the MCNP-5 [23] Monte Carlo code and the DORT 2D and TORT 3D [18]discrete ordinates transport codes. MCNP-5 calculations used FENDL-2.1 and 3 pointwise cross-sections. Specially developed source subroutine is needed at present for the MCNP-5 calculations.

In the DORT and TORT deterministic calculations S_{16}/P_5 approximations were adopted. FNG benchmark analysis by the DORT and TORT codes required the use of the GRTUNCL first collision source code in order to mitigate ray effects. Transport cross sections were taken from the FENDL-2,-2.1 and -3 multi-group libraries, and processed by the TRANSX-2 [22]code to obtain problem dependent self-shielded cross sections in 175 (FENDL-2 & 2.1) and 211 (FENDL-3) energy groups.

For the use with the deterministic codes DORT and TORT IRDFFcross sections were processed using the NJOY-99 [23]code into the same energy groups (175/211), choosing the iw=8 weighting option, which was found to be in the best agreement with the reference point-wise MCNP results. Results of the MCNP calculations performed at ENEA Frascati are included in the SINBAD compilation. The agreement of the DORT/TORT calculations with those using the MCNP code is in general within few %. The relative statistical uncertainty in the MCNP calculations is generally below 2-3% (1σ) for fast and < 4% for thermal reactions. Activation reaction rates where calculated using the track length estimator (tally f4 of MCNP).

Agreement between the measurements and calculations depends on several parameters, such as the quality of the measured results on one side and on the computation side on the transport and dosimetry cross-sections, geometry model simplifications and method approximations. In the C/E comparison are therefore hidden the contributions of all these factors, dosimetry data not representing the most important source of uncertainties. Indeed, the uncertainties in the dosimetry data represent in general a minor contribution comparing to the impact of the uncertainties in the transport cross. In addition compensation effects are likely to be present between transport and dosimetry data. We should be therefore aware that estimation of the quality of the IRDFF library based on C/E comparison is somewhat difficult and not utmost reliable.

An estimation of the uncertainty due to the computational method and transport cross sections can be obtained by comparing the computations performed using deterministic and Monte Carlo codes (DORT-TORT and MCNP-5) and using different evaluations of the cross sections (FENDL-2, 2.1 and -3).

3.1 FNG Bulk SS Shield Experiment (1995)

The experiment was performed to validate the International Thermonuclear Experimental Reactor (ITER) inboard shielding design. The ENEA FNG 14-MeV-fusion-neutron source was used to perform measurements of neutron penetration within 94-cm-thick mock-up of the first-wall, blanket, vacuum vessel, and toroidal field coils. The block was made of copper, stainless steel/Perspex layers, followed by a smaller block made of alternating plates of copper and stainless steel simulating the magnet.

Table 3: Ratios between the detector responses calculated using the IRDFF and IRDF-2002 files for the FNG Bulk shield Experiment.

Det. posit.	***Reaction rate ratios: IRDFF/IRDF2002***							
[cm]	^{27}Al(n,α)	^{55}Mn(n,γ)	**^{56}Fe(n,p)**	^{58}Ni(n,2n)	**^{58}Ni(n,p)**	^{93}Nb(n,2n)	**^{115}In(n,n')**	**^{197}Au(n,γ)**
3.43	0,982	1,070	0,989	0,994	0,985	1,006	0,995	0,990
10.32	0,985	1,060	0,992	0,989	0,991	1,006	0,995	0,990
17.15	0,986	1,051	0,993	0,985	0,993	1,006	0,996	0,991
23.95	0,987	1,045	0,994	0,982	0,995	1,006	0,996	0,991
30.8	0,988	1,037	0,995	0,978	0,996	1,006	0,996	0,991
41.85	0,989	1,024	0,996	/	0,998	1,005	0,996	0,991
46.85	0,989	1,076	0,996	/	0,998	1,005	0,996	0,990
53.8	0,989	1,052	0,997	/	0,998	1,005	0,996	0,991
60.55	0,990	1,046	0,997	/	0,999	1,006	0,996	0,990
67.4	/	1,047	0,997	/	0,999	1,005	0,996	0,991
74.4	0,990	1,045	0,998	/	0,999	1,006	0,996	0,991
81.1	0,990	1,044	/	/	0,999	1,005	0,996	0,991
87.75	/	/	/	/	1,000	1,005	/	0,990
92.15	/	/	/	/	1,000	1,005	/	0,988

Activation foils were placed along the centre line of the experimental block in line with the source axis at 14 locations from 3.43 cm up to 92.15 cm from the front surface of the experimental block. The following

reactions were measured: ^{27}Al(n,α), ^{55}Mn(n,γ), ^{56}Fe(n,p), ^{58}Ni(n,2n), ^{58}Ni(n,p), ^{93}Nb(n,2n), ^{115}In(n,n') and ^{197}Au(n,γ). Errors from counting statistics, uncertainty of detector calibrations, and the uncertainty of the source intensity are included with the reaction rate results.

3.2 FNG Benchmark Experiment on Tungsten (2002)

The purpose of the experiment was to validate the tungsten cross sections in the European Fusion File (EFF), as tungsten is a candidate material for high flux component in the fusion reactor and its development is pursued in the European Fusion Technology Program. The experimental assembly consisted of a block of tungsten alloy, DENSIMET, in pieces of various shapes, assembled to obtain a size of about 42-47 cm (L) x 46.85 cm (H) and 49 cm in thickness and located in front of the FNG target, 5.3 cm from the 14-MeV FNG neutron source.

Neutron reaction rates and gamma heating were measured at four positions along the central beam axes of the block, at approximately 5, 15 25 and 35 cm in the W block. The following 9 reaction rates, covering fast and thermal neutron energies, were used in this exercise: ^{93}Nb(n,2n), ^{58}Ni(n,2n), ^{90}Zr(n,2n), ^{27}Al(n,α), ^{56}Fe(n,p), ^{58}Ni(n,p), ^{115}In(n,n'), ^{197}Au(n,γ)and ^{55}Mn(n,γ). The gold foil thickness was 0.05 mm; of manganese foils 0.2 mm, and the thickness of other foils was 1 mm. The diameter of the foils was 18 mm.

SINBAD compilation includes also the results of the analyses performed at ENEA Frascati by the Monte Carlo code MCNP-4C using the point-wise cross sections derived from EFF-2.4 and FENDL-2.0 [6].

Table 4: Ratios between the detector responses based on the IRDFF and IRDF-2002 files for the FNG W Experiment.

Position	***Reaction rate ratios: IRDFF/IRDF2002***								
(cm)	*^{27}Al(n,α)*	*^{55}Mn(n,γ)*	***^{56}Fe(n,p)***	***^{58}Ni(n,2n)***	***^{58}Ni(n,p)***	***^{90}Zr(n,2n)***	*^{93}Nb(n,2n)*	***^{115}In(n,n')***	*^{197}Au(n,γ)*
5	0,982	1,054	0,989	0,961	0,985	1,004	1,006	0,995	1,010
15	0,984	1,068	0,991	0,960	0,989	1,002	1,006	0,996	1,012
25	0,985	1,083	0,992	0,959	0,991	1,000	1,006	0,997	1,013
35	0,986	1,097	0,993		0,993	0,999	1,005		1,013

3.3 FNG Benchmark Experiment on Silicon Carbide (SiC) (2001)

The purpose is to validate the cross sections of Si and C in the European Fusion File (EFF), as the SiC, in the form of ceramic matrix (SiC-fiber/SiC), is a candidate structural material for the fusion reactor and its development is pursued in the European Fusion Technology Program.

Theexperimental set-up consisted of a block of sintered SiC (45.72 cm x 45.72 cm, 71.12 cm in thickness), located in front of the FNG target, 5.3 cm from the 14-MeV d-T neutron source. Inside the block, four experimental positions at different penetration depths were available to locate detectors of various types (activation foils, TLD holders, active spectrometers).

Four different reactions: ^{197}Au(n,γ), ^{58}Ni(n,p), ^{27}Al(n,α) and ^{93}Nb(n,2n) were used to derive the neutron flux, from thermal energy up to the fusion neutron peak. The reaction rates were measured at four experimental positions, 10.41 cm, 25.65 cm, 40.89 cm and 56.13 cm respectively from the block surface, using the radiometric techniques based upon the use of absolutely calibrated HPGe detectors. The overall contribution to the quoted uncertainty comes from the HPGe calibration (±2%), measured activity (<±3%) and total neutron yield (±3%).

Table 5: Ratios between the detector responses obtained using the IRDFF and IRDF-2002 files for the FNG SiC Experiment.

Position (cm)	***Reaction rate ratios: IRDFF/IRDF2002***			
	^{27}Al(n,α)	^{58}Ni(n,p)	^{93}Nb(n,2n)	^{197}Au(n,γ)
10.41	0.986	**0.993**	1.006	**0.982**
25.65	0.989	0.998	1.006	**0.982**
40.89	0.990	**0.999**	1.006	**0.984**
56.13	0.990	**1.000**	1.006	**0.985**

3.4 FNG-HCPB Tritium Breeder Module Mock-up Benchmark (2005)

The benchmark experiment was performed at the 14 MeV FNG facility in order to validate the computational tools and nuclear data required for the design of the Helium-Cooled Pebble Bed (HCPB) Breeder Blanket, one of the Breeder Blanket Modules to be tested in ITER. In particular the beryllium cross-sections and the tritium breeding performance were tested.

The experimental block consisted of a stainless steel (AISI-316) box with the (x-z) cross section 31 cm x 31 cm, and 29 cm thick (y-axis). The box was filled with metallic beryllium and contained two double layers made of breeder material (Li_2CO_3 powder). The breeder layers were 1.2 cm thick each, and separated by 1 mm thick stainless steel walls. The 14 MeV FNG neutron source was located 5.3 cm in front of the block.

Neutron dosimetry reaction rates, tritium production rates and gamma heating were measured at several positions in the experimental block. The detector foils measuring ^{27}Al(n,α), ^{58}Ni(n,p), ^{93}Nb(n,2n) and ^{197}Au(n,γ) reactions were placed in the breeder layers at four positions along the central beam axes of the block at y=4.2, 9.6, 15.7 and 22 cm from the front surface of the mock-up. Altogether 16 measurement positions were available.

The Tritium production rate (TPR) in the breeder cassettes was measured using Lithium carbonate (Li_2CO_3) pellets located at four different penetration depths (~4.2 to ~23.1 cm depth). Eight measurement locations divided in two symmetrical positions with respect to the mock-up axis and to the neutron source were used. The pellets were all prepared by JAERI by a dry pressure procedure starting from a Li2CO3 powder, with 99% certified purity, with no other material added. The pellets were 13 mm in diameter, 1.93 mm thick, with a weight of 405 mg, and 6Li content equal to 7.5% (natural enrichment). Stacks of 12 pellets were located in each experimental position.

Table 6: Ratios between the detector responses based on the IRDFF and IRDF-2002 files for the FNG HBPB TBM Experiment.

Position* (cm)	***Reaction rate ratios: IRDFF/IRDF2002***			
	^{27}Al(n,α)	**^{58}Ni(n,p)**	^{93}Nb(n,2n)	^{197}Au(n,γ)
~4.2	0,994	1,000	1,005	1,012
~10.5	0,993	1,000	1,005	1,012
~16.8	0,993	1,000	1,006	1,013
~23.1	0,992	1,000	1,006	1,015

*average detector position. Precise location depends slightly on the dosimetry foils

Table 7: Ratios between tritium production rates based on the IRDFF-v1.05 and IRDF-2002 files for the FNG HBPB TBM Experiment.

Pellet No.	^{6}Li(n,t) reaction rate ratios: IRDFF/IRDF2002			
	ENEA2	ENEA4	ENEA6	ENEA8
1	0,998	0,998	0,998	0,998
2	0,997	0,997	0,997	0,997
3	0,997	0,997	0,997	0,997
4	0,997	0,997	0,997	0,997
5	0,998	0,998	0,998	0,998
6	0,997	0,997	0,997	0,997
7	0,997	0,997	0,997	0,997
8	0,997	0,997	0,997	0,997
9	0,998	0,998	0,998	0,998
10	0,997	0,997	0,997	0,997
11	0,997	0,997	0,997	0,997
12	0,997	0,997	0,997	0,997

3.5 FNG-HCLL Tritium Breeder Module Mock-up Benchmark (2009)

The tritium breeding-module helium-cooled lithium-lead benchmark experiment (TBM HCLL) was performed in 2009at the 14 MeV FNG facility in order to validate the computational tools and nuclear data required for the design of another Breeder Blanket Modules to be tested in ITER, the Helium-Cooled Lithium Lead (HCLL) Breeder Blanket. The ability to correctly predict the tritium breeding was of prime interest. The HCLL mock-up consists of a block of 45 cm x 51.66 cm side-view and 34.6 cm long, placed 5.3 cm in front of the 14 MeV FNG neutron source. The block is composed of 11 alternating layers of LiPb bricks (3.6 cm high) and EUROFER-97 plates (0.915 cm thick). Two additional thin layers and a back reflector of Polyethylene have been introduced.

In the first experimental set-up the fast and the thermal neutron flux was measured using Al, Ni, Nb, In, Au an Mn activation foils up to the depth of about 30 cm. The second experiment was devoted to the measurement of the Tritium Production Rates (TPR) and TLD. The TPR responses were measured both with the natural (7.5 % ^{6}Li) and 95% enriched Li_2CO_3 pellets. Sets of 3 pellets have been introduced at 7 radial positions starting from 3.65 cm to 28.55 cm in the mock-up.

Table 8: Ratios between the detector responses calculated using the IRDFF and IRDF-2002 files for the FNG HCLL Experiment.

Det. posit.	***Reaction rate ratios: IRDFF/IRDF2002***						
[cm]	^{27}Al(n,α)	**^{58}Ni(n,p)**	^{93}Nb(n,2n)	^{58}Ni(n,2n)	**^{115}In(n,n')**	^{55}Mn(n,γ)	**^{197}Au(n,γ)**
0,000	/	/	1,006	/	/	/	/
1,430	0,981	0,981	1,006	0,961	/	1,172	0,998
5,700	0,982	0,986	1,006	0,961	0,994	/	0,998
9,820	0,983	0,988	1,006	0,961	/	1,180	0,999
14,03	0,983	0,990	1,006	0,960	/	1,181	0,999
18,25	0,984	0,992	1,006	0,960	0,995	/	0,999
22,28	0,984	0,992	1,006	0,960	/	1,179	0,999
26,38	0,985	0,993	1,006	0,959	/	1,172	1,000
30,55	0,985	0,994	1,006	/	0,996	/	1,003

3.6 Winfrith Iron Benchmark Experiment (ASPIS) (~1975):

The objective/purpose of the experiment was the determination of neutron spectra and detector reaction ratesat different depth in about 1m thick bulk iron shield.

The source was a fission converter plate driven by a thermal flux from the extended graphite reflector of the NESTOR reactor. The energy spectrum of the source is the one of neutrons emitted from the fission of ^{235}U. The iron shield consisted of 24 mild steel plates 183x191x5.08 cm^3 stacked one behind the other. This array is followed by a 10.16 cm steel plate followed by a 30.5 cm iron shot concrete block.

Detector activation measurements were carried out at 17 different depths into the iron shield from 5.72, up to 114.30 cm. The detectors used were: ^{32}S(n,p), ^{115}In(n,n'), ^{103}Rh(n,n'), ^{197}Au(n,γ).

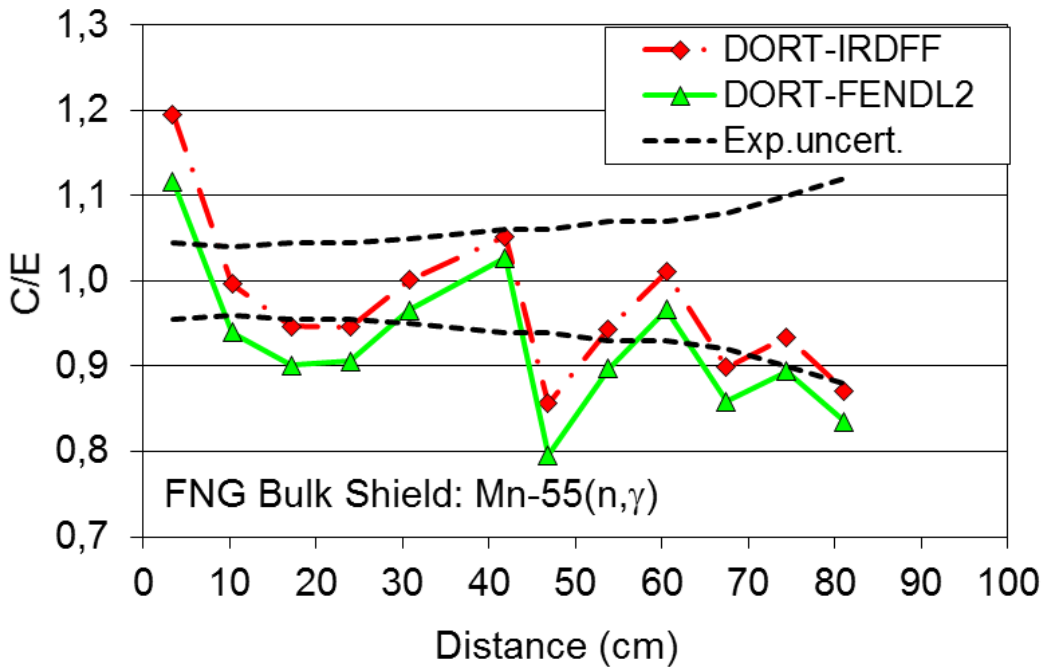
The experiment was performed in the 1970-ies and belongs therefore to older experiment with relatively high measurement uncertainties. In addition only a rather simplified geometry description is available, including some approximations and adjustment which were necessary at the time to permit 2D calculations in a reasonable CPU time. In particular the shield density was adjusted to account for the gaps between the Iron blocks, the fission plate and the neutron source distribution was approximated by an analytical expression, etc.

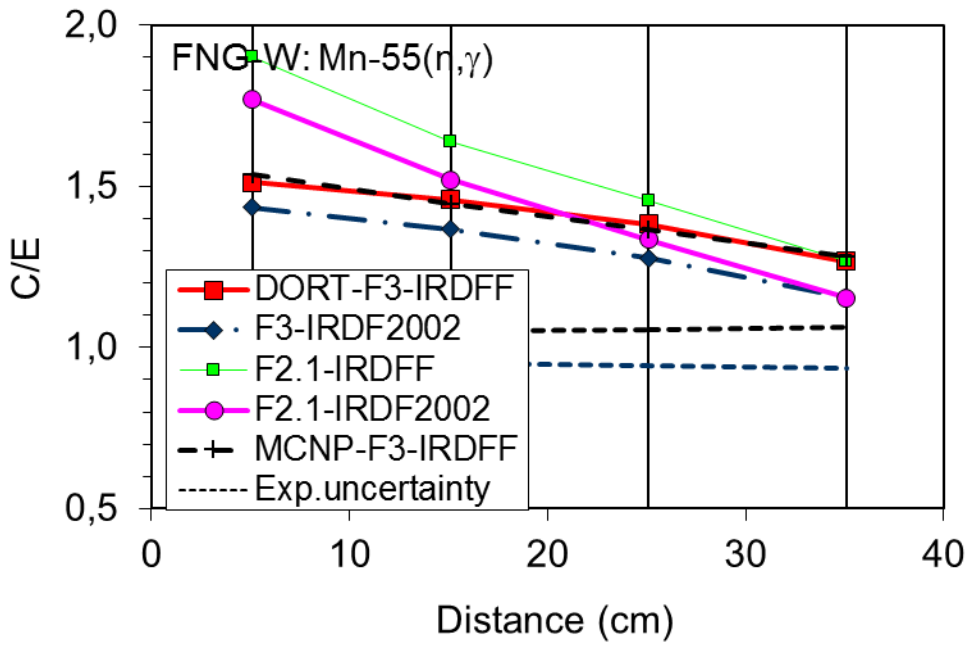
Calculations were performed using the DORT code and the FENDL-2 175-group cross sections.

Calculated ^{32}S(n,p) are all within the measurement uncertainties (Fig. 10). In the case of ^{103}Rh(n,n') (Fig. 11) and ^{115}In(n,n') (Fig. 6) the measurements and calculations are in reasonable agreement, degrading nevertheless with the depth in the block. This is possibly due to the method and transport cross section uncertainties, in particular the use of 175-group cross sections may not provide sufficient details needed for the deep penetrations. Another probable source of discrepancy may be the computational model (geometry, source) approximations. A rather simplified 2-D computational model has been proposed by the authors. Particularly bad C/E agreement was found for the ^{197}Au(n,γ) reactions rates (results are not provided here).

Table 9: Ratios between the detector responses calculated using the IRDFF and IRDF-2002 files for the ASPIS Iron Experiment.

Position (cm)	***Reaction rate ratios: IRDFF/IRDF-2002***		
	^{103}Rh(n,n')	***^{115}In(n,n')***	*^{32}S(n,p)*
5.72	**1.000**	**0,996**	**1,081**
11.43	**1.000**	**0,997**	**1,088**
17.15	**1.000**	**0,997**	**1,093**
22.86	**1.000**	**0,998**	**1,098**
28.58	**1.000**	**0,998**	**1,102**
34.29	**1.000**	**0,998**	**1,106**
40.01			**1,110**
45.72	**1.000**	**0,999**	**1,114**
51.44	**1.000**	**1,000**	**1,115**
57.15	**1.000**	**1,000**	**1,117**
62.87	**1.000**	**1,000**	**1,118**
68.58	**1.000**		**1,119**
74.3	**1.000**		
85.73	**1.000**		
91.44	**1.000**		
102.87	**1.000**		
114.30	**1.000**		


1,3
1,2
1,1
1,0
0,9
0,8
0,7
C/E
DORT-IRDFF
DORT-FENDL2
Exp.uncert.
FNG Bulk Shield: Mn-55(n,γ)
0
10
20
30
40
50
60
70
80
90
100
Distance (cm)


2,0
1,5
1,0
0,5
C/E
FNG-W: Mn-55(n,γ)
DORT-F3-IRDFF
F3-IRDF2002
F2.1-IRDFF
F2.1-IRDF2002
MCNP-F3-IRDFF
Exp.uncertainty
0
10
20
30
40
Distance (cm)

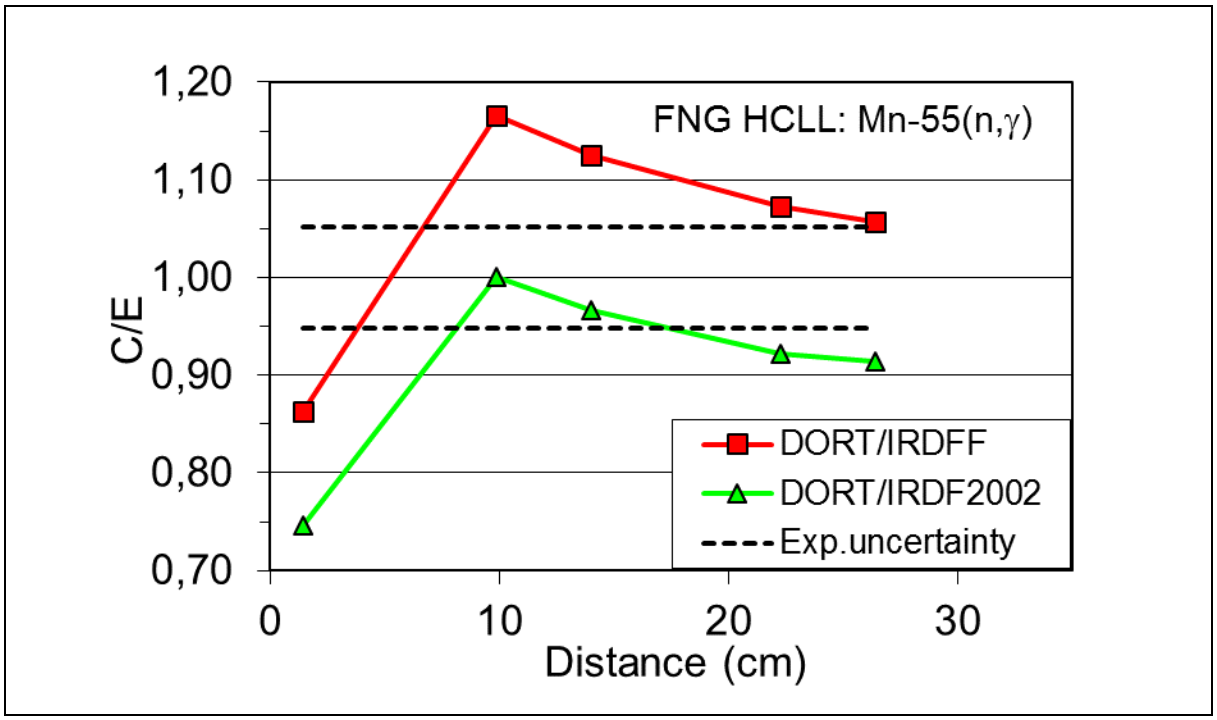
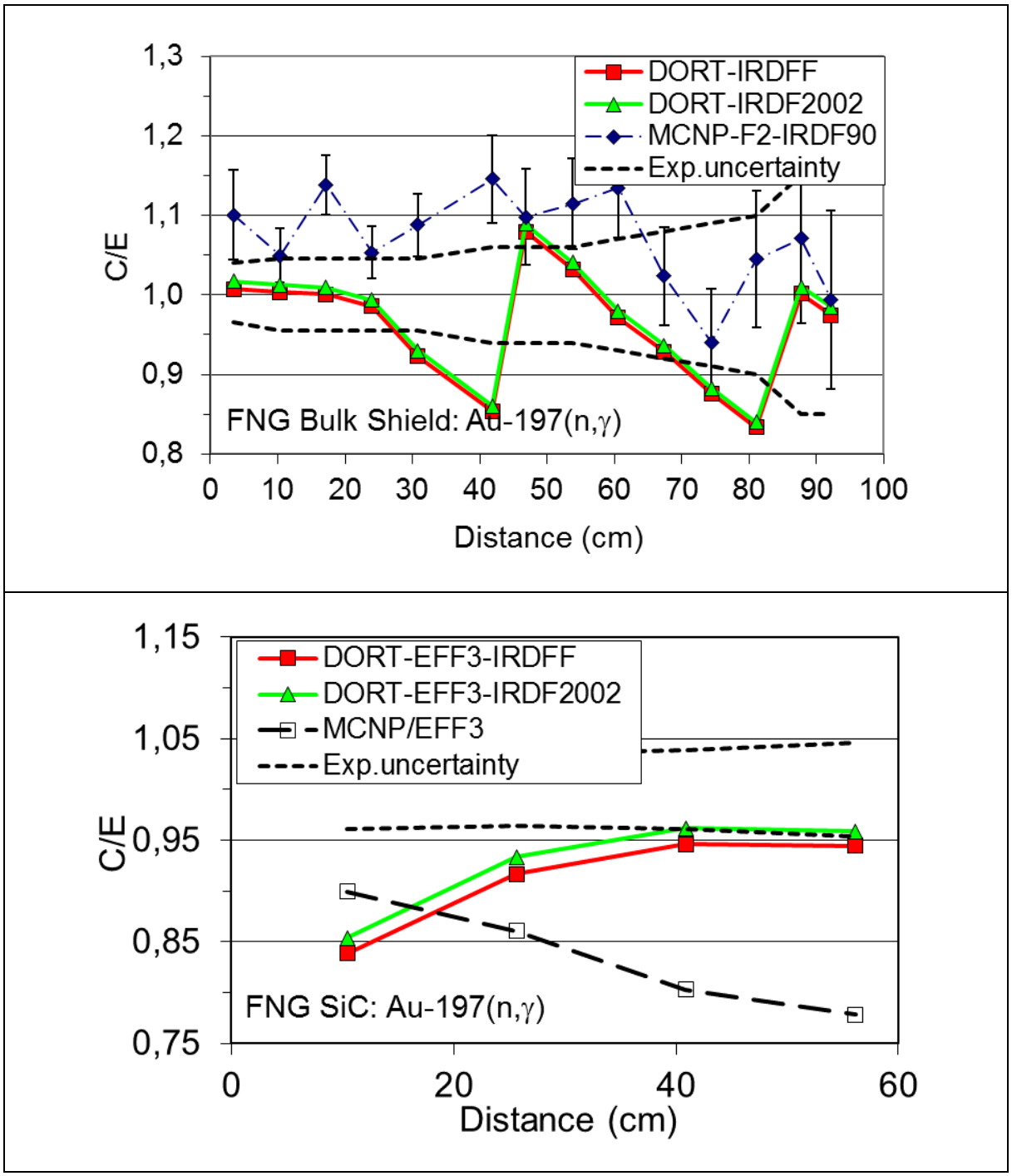
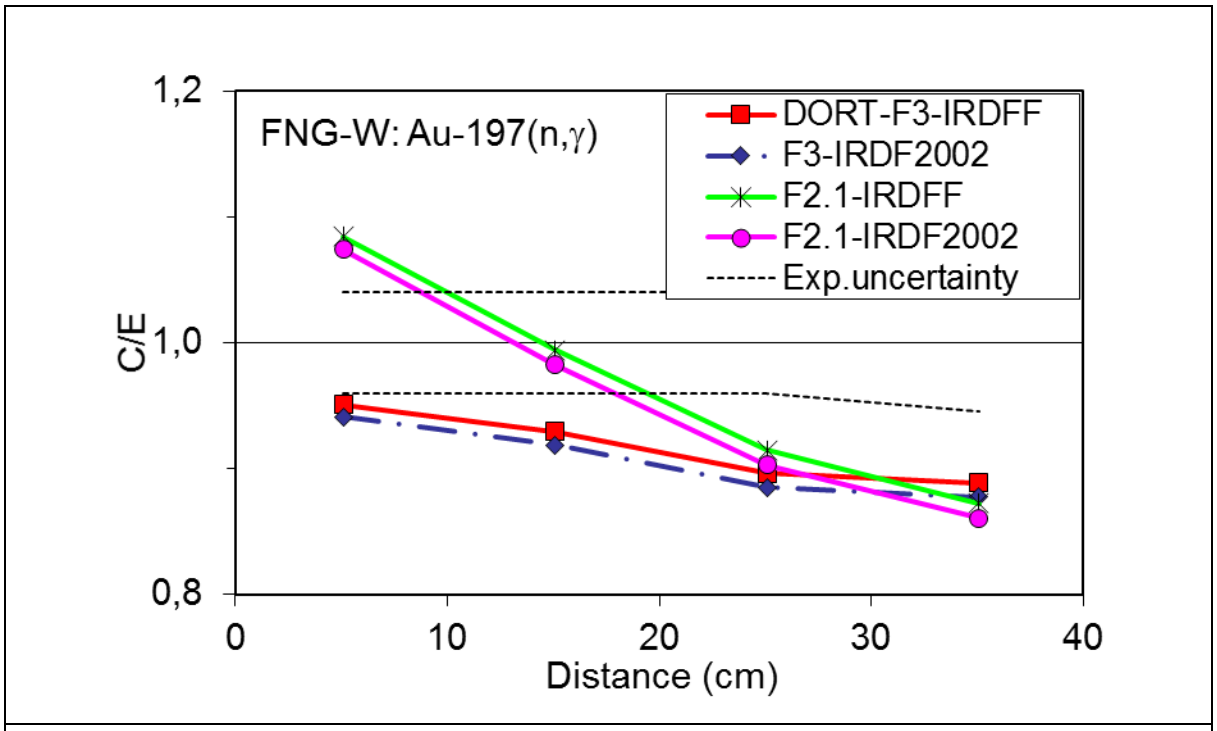
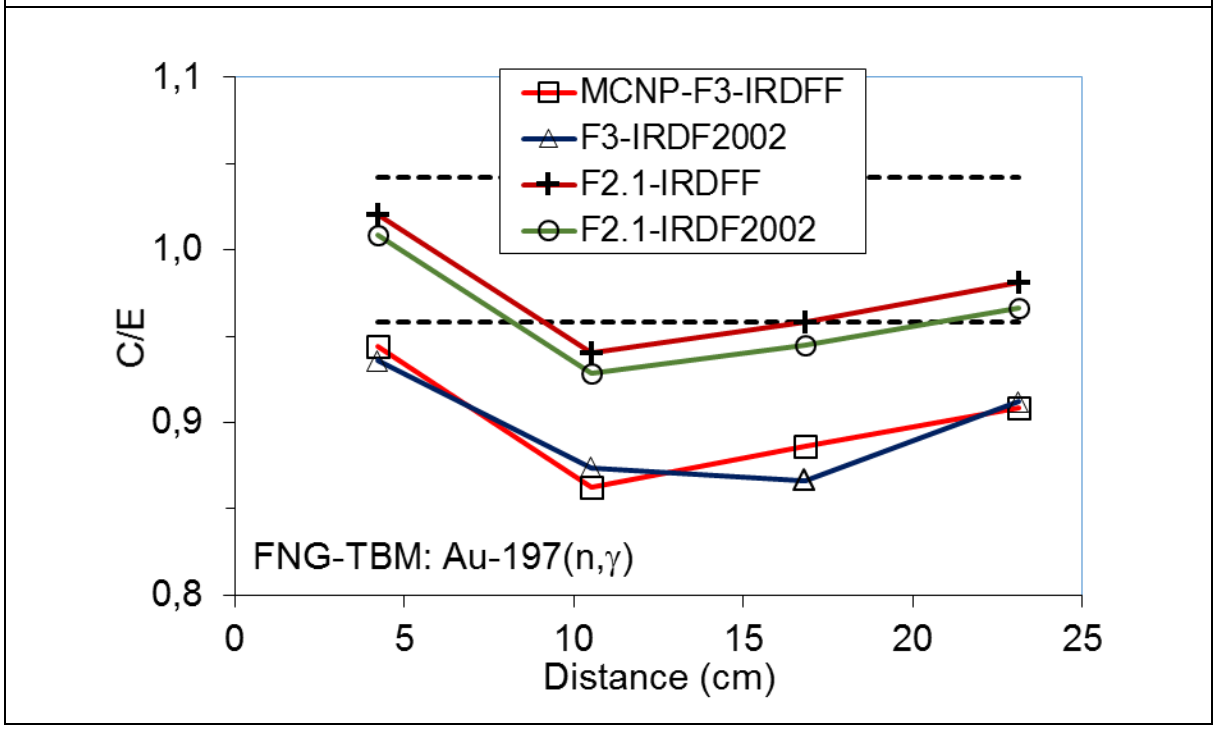


Fig. 1: *^{55}Mn(n,γ) detector cross section in IRDF evaluations: Calculated/Experimental (C/E) detector responses for the FNB Bulk-shield, Tungsten and HCLL benchmarks based on calculations with different libraries and computer codes. Dashed lines delimit the ± 1 σ standard deviations of the measurements. The uncertainties shown with the DORT results correspond to the uncertainties due to the detector cross section uncertainties (where calculated), and those shown with the results of MCNP to the statistical uncertainty.*


1,3
1,2
1,1
1,0
0,9
0,8
C/E
DORT-IRDFF
DORT-IRDF2002
MCNP-F2-IRDF90
Exp.uncertainty
FNG Bulk Shield: Au-197(n,γ)
0
10
20
30
40
50
60
70
80
90
100
Distance (cm)
1,15
1,05
0,95
0,85
0,75
C/E
DORT-EFF3-IRDFF
DORT-EFF3-IRDF2002
MCNP/EFF3
Exp.uncertainty
FNG SiC: Au-197(n,γ)
0
20
40
60
Distance (cm)


FNG-W: Au-197(n,γ)
DORT-F3-IRDFF
F3-IRDF2002
F2.1-IRDFF
F2.1-IRDF2002
Exp.uncertainty
C/E
1,2
1,0
0,8
0
10
20
30
40
Distance (cm)


MCNP-F3-IRDFF
F3-IRDF2002
F2.1-IRDFF
F2.1-IRDF2002
FNG-TBM: Au-197(n,γ)
C/E
1,1
1,0
0,9
0,8
0
5
10
15
20
25
Distance (cm)

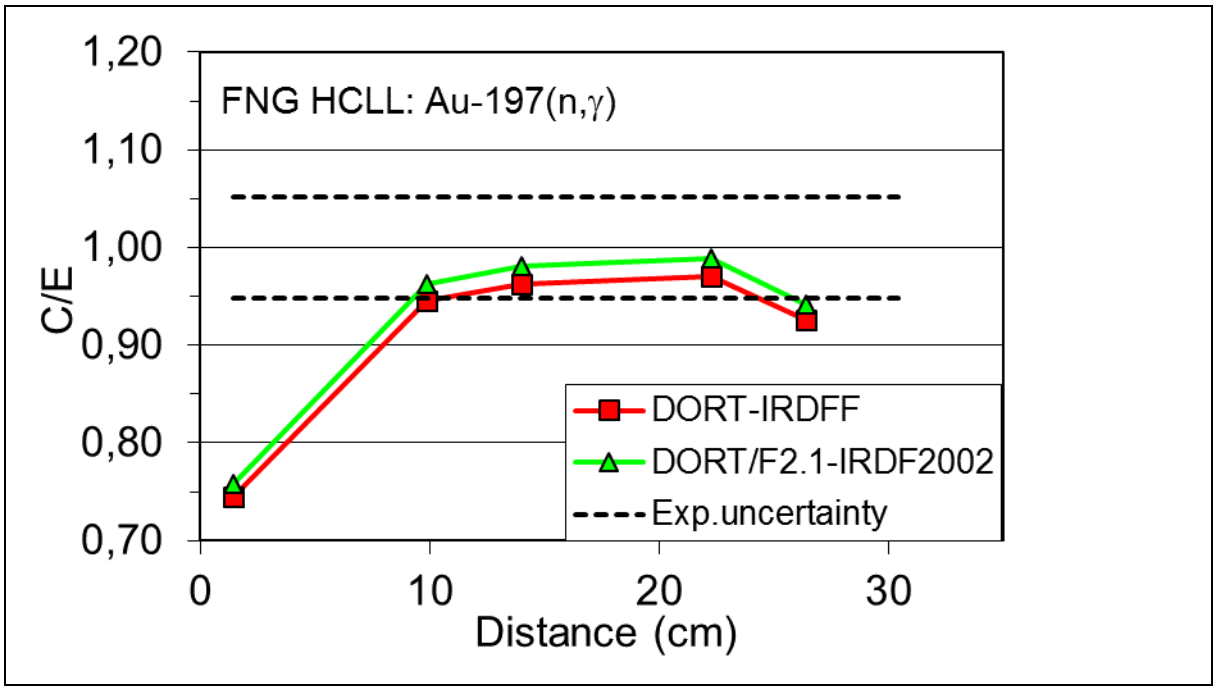
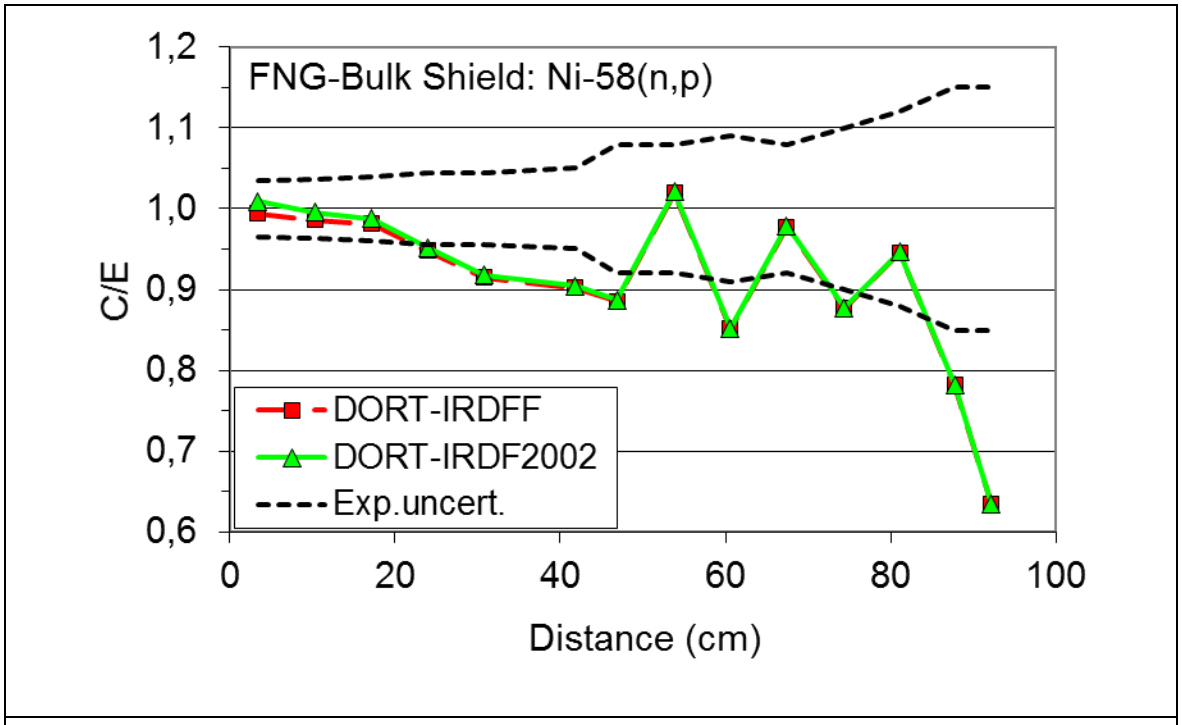
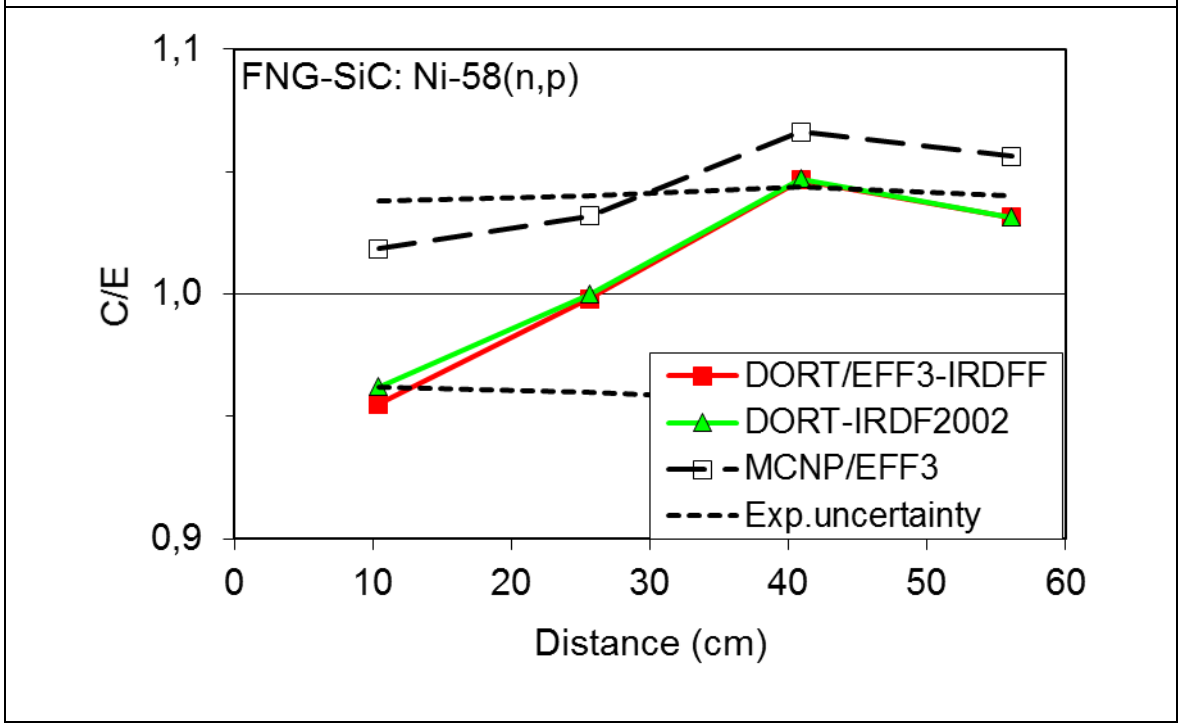
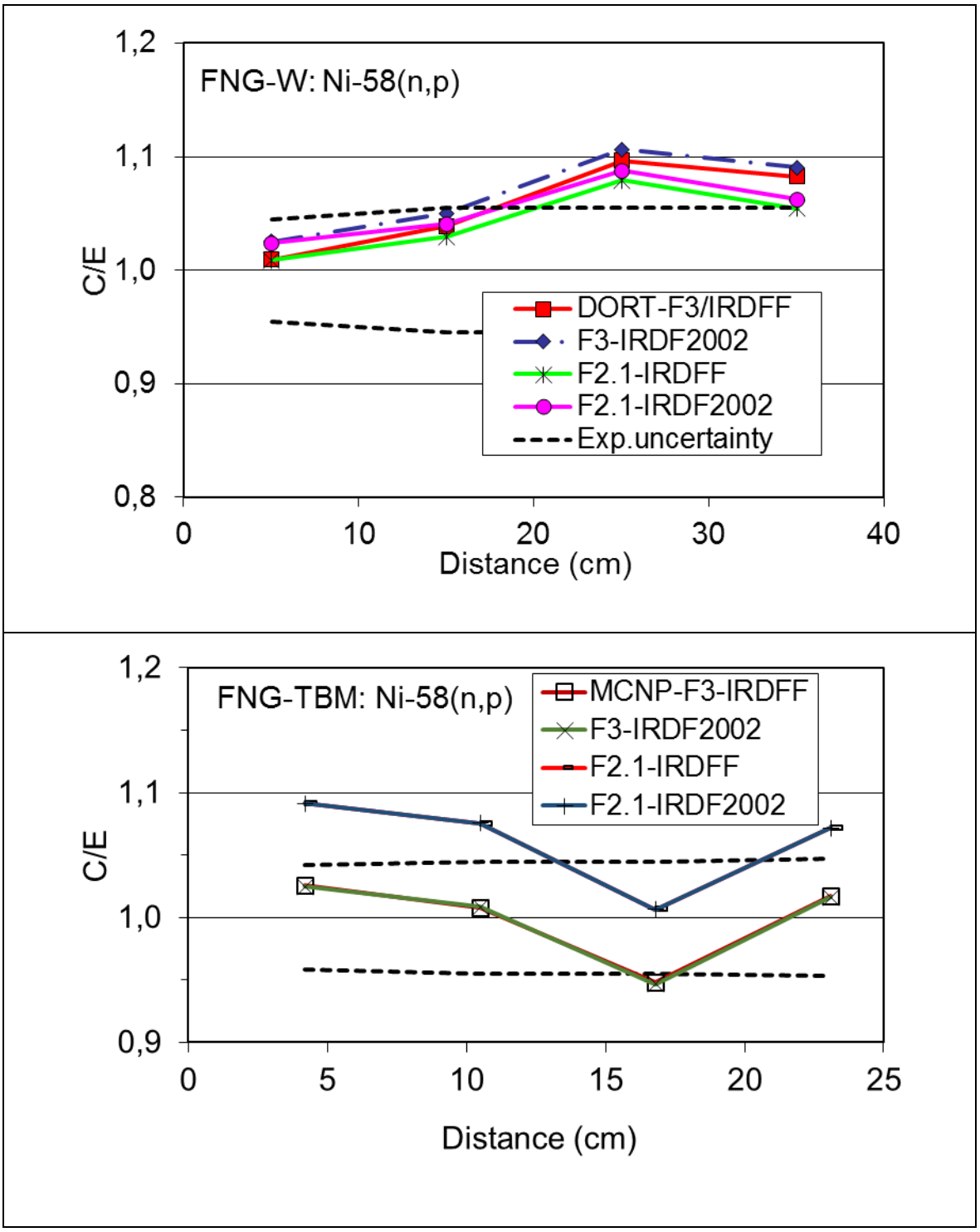


Fig. 2: *^{198}Au detector cross section in IRDF evaluations: C/E detector responses for the FNG benchmarks based on calculations with different libraries and computer codes (MCNP5 Monte Carlo code are compared against those of the DORT deterministic code). FENDL-2 (F2), -2.1 (F2.1) and EFF3 cross sections were used in the analyses. Dashed lines delimit the ± 1 σ standard deviations of the measurements.*


FNG-Bulk Shield: Ni-58(n,p)
C/E
1,2
1,1
1,0
0,9
0,8
0,7
0,6
0
20
40
60
80
100
Distance (cm)
DORT-IRDFF
DORT-IRDF2002
Exp.uncert.


FNG-SiC: Ni-58(n,p)
C/E
1,1
1,0
0,9
0
10
20
30
40
50
60
Distance (cm)
DORT/EFF3-IRDFF
DORT-IRDF2002
MCNP/EFF3
Exp.uncertainty


FNG-W: Ni-58(n,p)
C/E
1,2
1,1
1,0
0,9
0,8
0
10
20
30
40
Distance (cm)
DORT-F3/IRDFF
F3-IRDF2002
F2.1-IRDFF
F2.1-IRDF2002
Exp.uncertainty
FNG-TBM: Ni-58(n,p)
C/E
1,2
1,1
1,0
0,9
0
5
10
15
20
25
Distance (cm)
MCNP-F3-IRDFF
F3-IRDF2002
F2.1-IRDFF
F2.1-IRDF2002

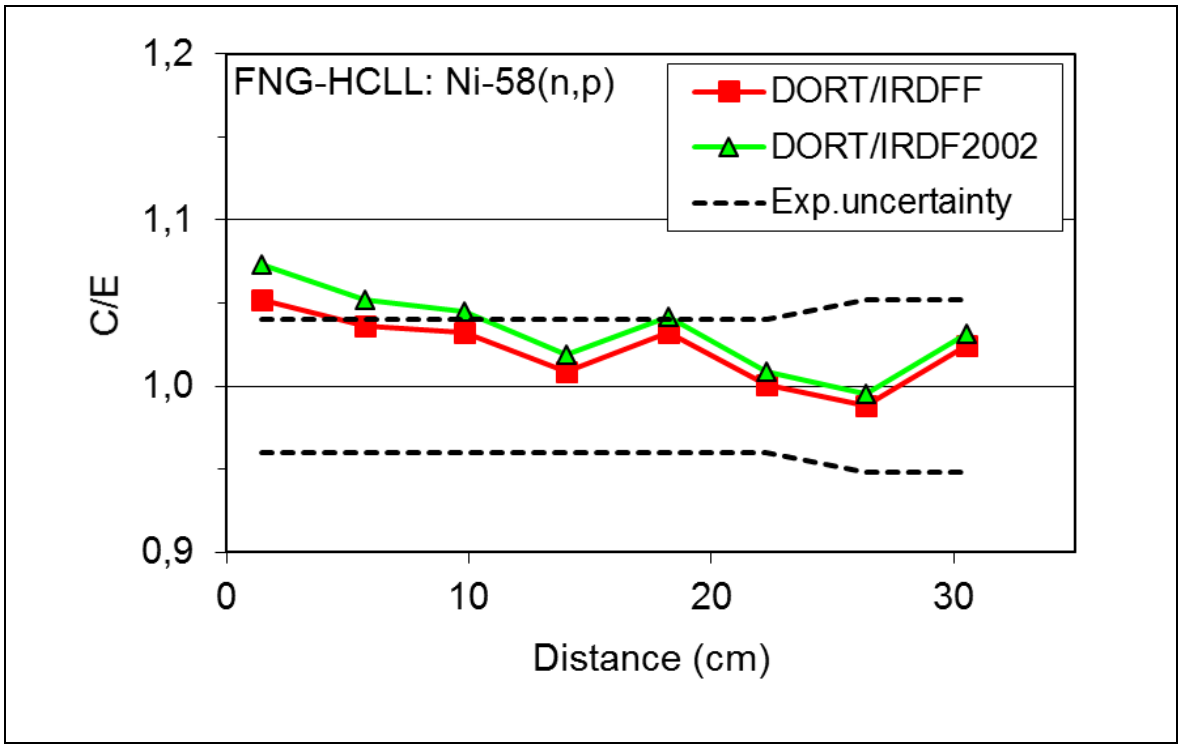
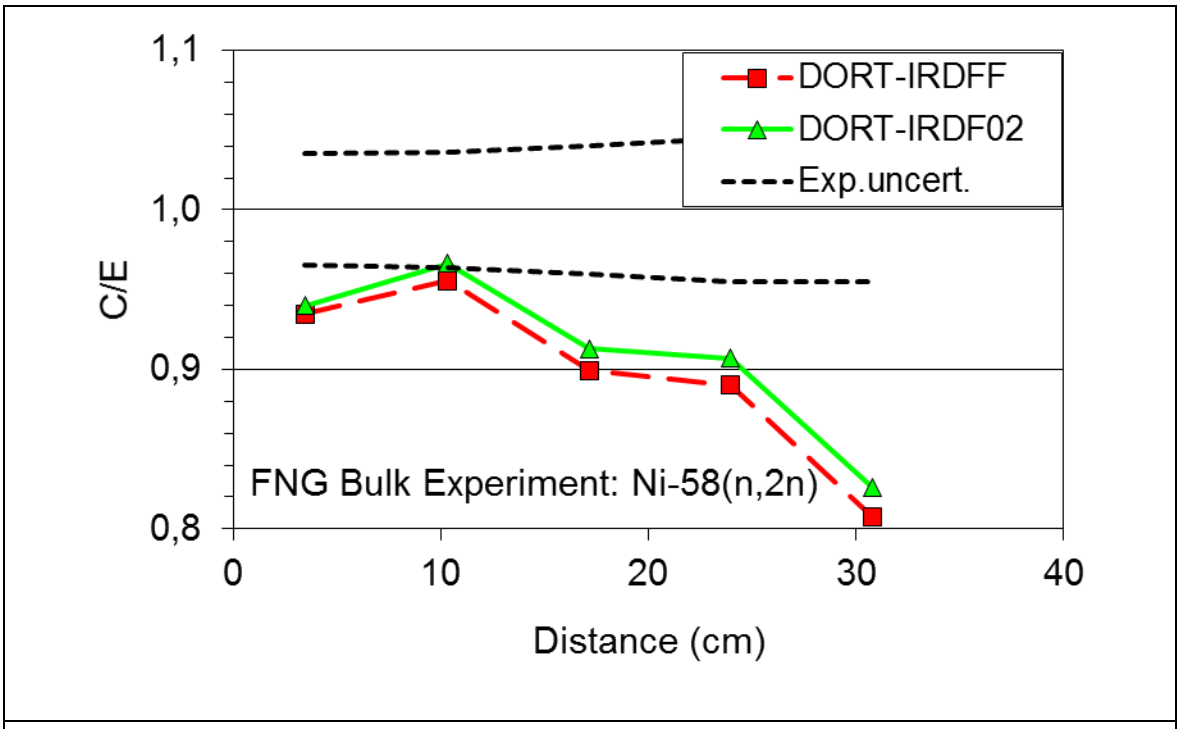
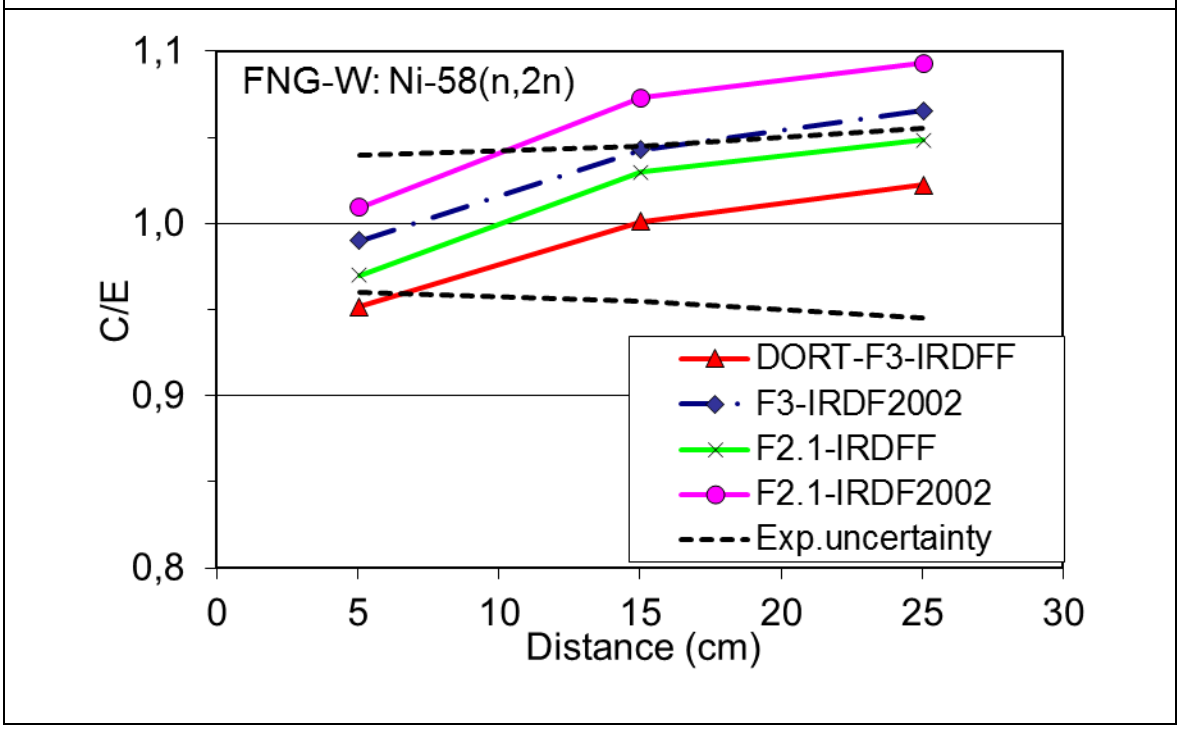


Fig. 3: *^{58}Ni(n,p) detector cross section in IRDF evaluations: C/E detector responses for several FNG benchmarks based on calculations with different libraries and computer codes (MCNP5 Monte Carlo code are compared against those of the DORT deterministic code). FENDL-2.1 (F2.1), -3 (F3) and EFF3 cross sections were used in the analyses. Dashed lines delimit the ± 1 σ standard deviations of the measurements.*


1,1
1,0
0,9
0,8
C/E
DORT-IRDFF
DORT-IRDF02
Exp.uncert.
FNG Bulk Experiment: Ni-58(n,2n)
0
10
20
30
40
Distance (cm)


1,1
1,0
0,9
0,8
C/E
FNG-W: Ni-58(n,2n)
DORT-F3-IRDFF
F3-IRDF2002
F2.1-IRDFF
F2.1-IRDF2002
Exp.uncertainty
0
5
10
15
20
25
30
Distance (cm)

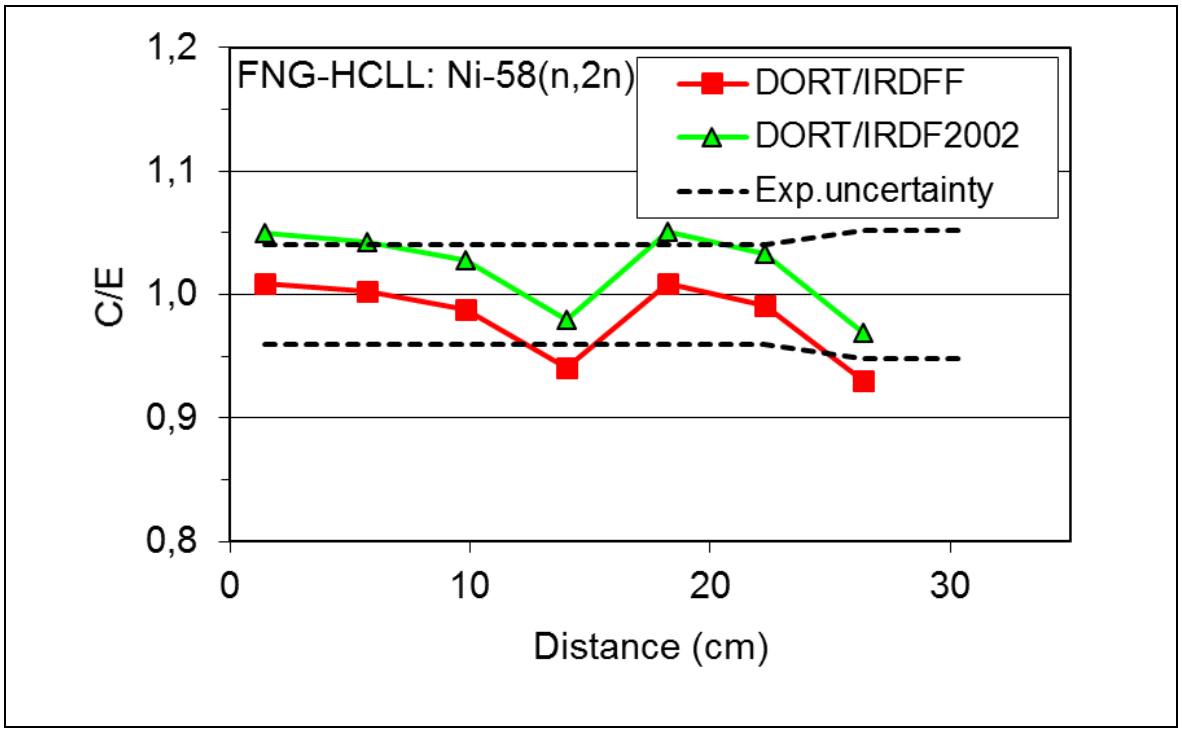


***Fig. 4**: ^{58}Ni(n,2n) detector cross section in IRDF evaluations: C/E detector responses for several FNG benchmarks based on calculations with different libraries and DORT deterministic computer code. FENDL-2.1 (F2.1), -3 (F3) and EFF3 cross sections were used in the analyses. Dashed lines delimit the ± 1 σ standard deviations of the measurements.*

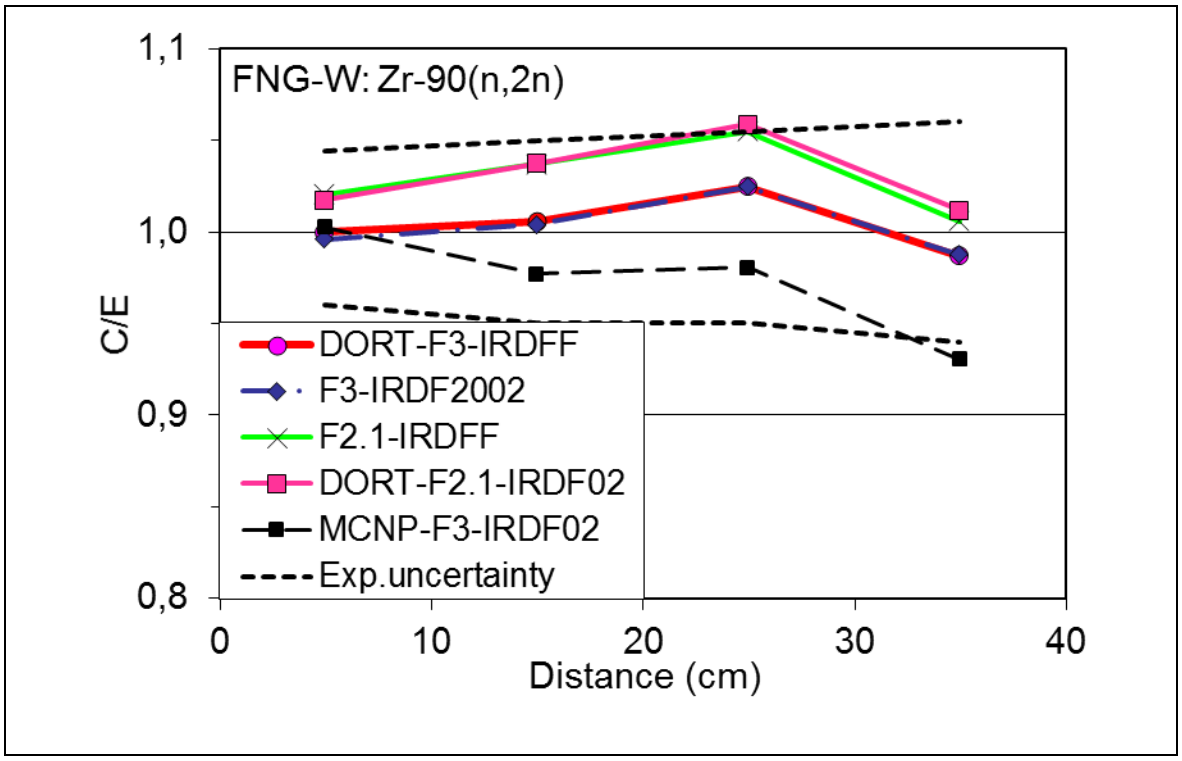
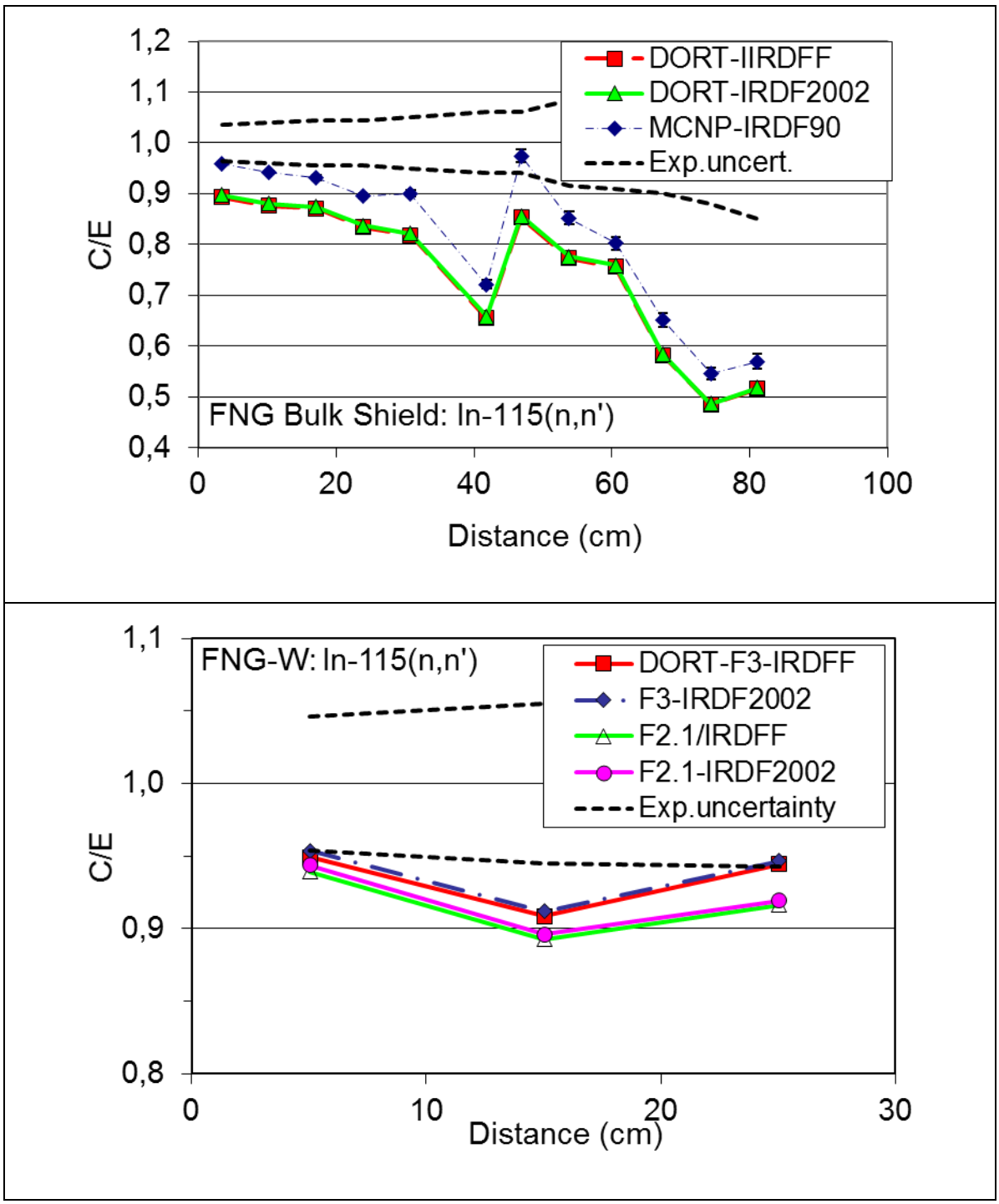


Fig. 5*: Comparison of measured and calculated ^{90}Zr(n,2n) activity at different depths for the FNG Tungsten benchmark; comparison between DORT and MCNP provides an estimate of modelling uncertainties in the deterministic calculation. FENDL-2.1 (F2.1) and -3 (F3) cross sections were used in the analyses. Dashed lines delimit the ± 1 σ experimental uncertainty bounds.*


1,2
1,1
1,0
0,9
0,8
0,7
0,6
0,5
0,4
C/E
0
20
40
60
80
100
Distance (cm)
DORT-IIRDFF
DORT-IRDF2002
MCNP-IRDF90
Exp.uncert.
FNG Bulk Shield: In-115(n,n')
1,1
1,0
0,9
0,8
C/E
0
10
20
30
Distance (cm)
FNG-W: In-115(n,n')
DORT-F3-IRDFF
F3-IRDF2002
F2.1/IRDFF
F2.1-IRDF2002
Exp.uncertainty

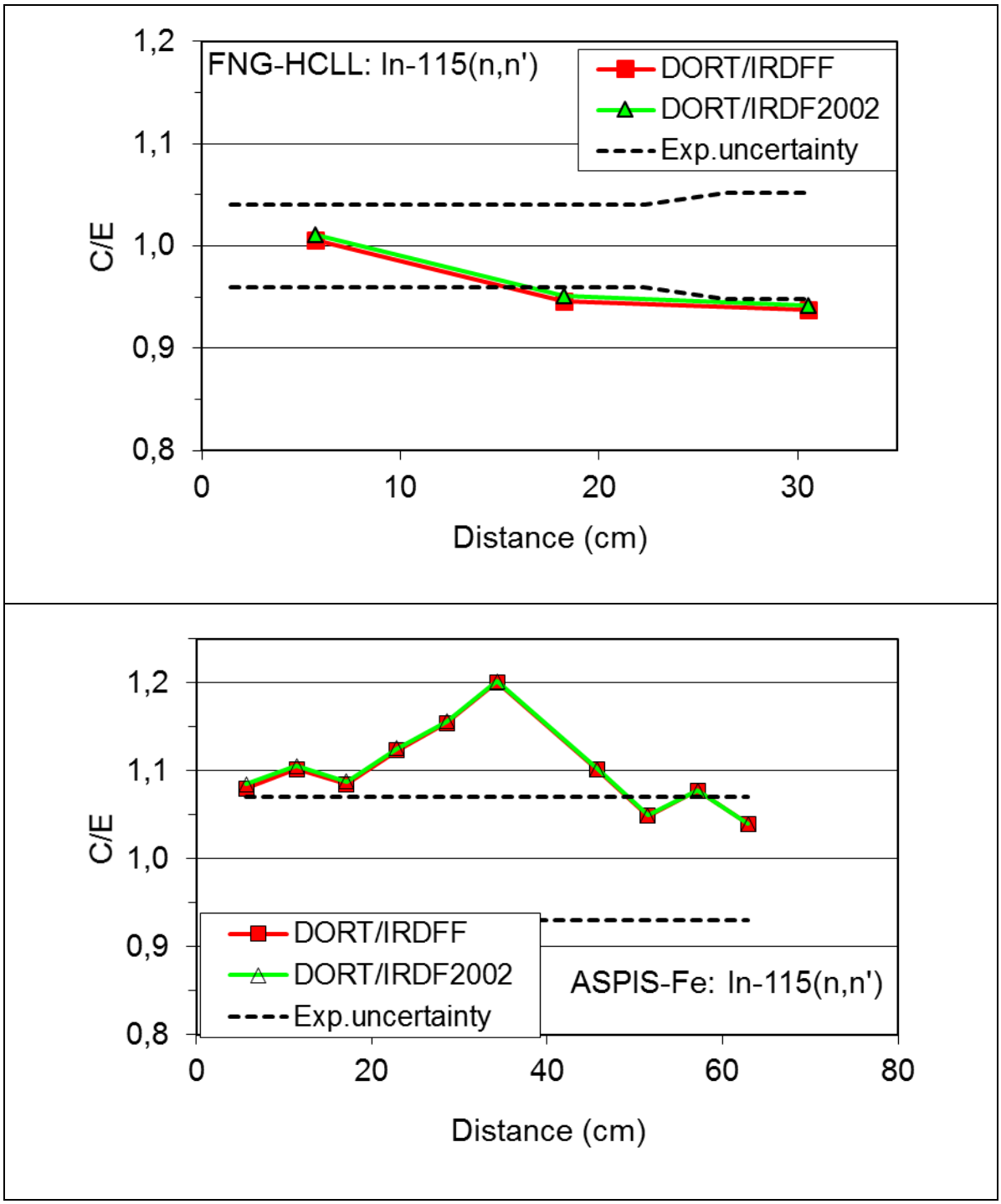


***Fig. 6**: Comparison of measured and calculated ^{115}In activity at different depths for several benchmark considered in the analysis using DORT deterministic code. FENDL-2.1 (F2.1) and -3 (F3) cross sections were used in the analyses. Dashed lines delimit the ± 1 σ experimental uncertainty bounds.*

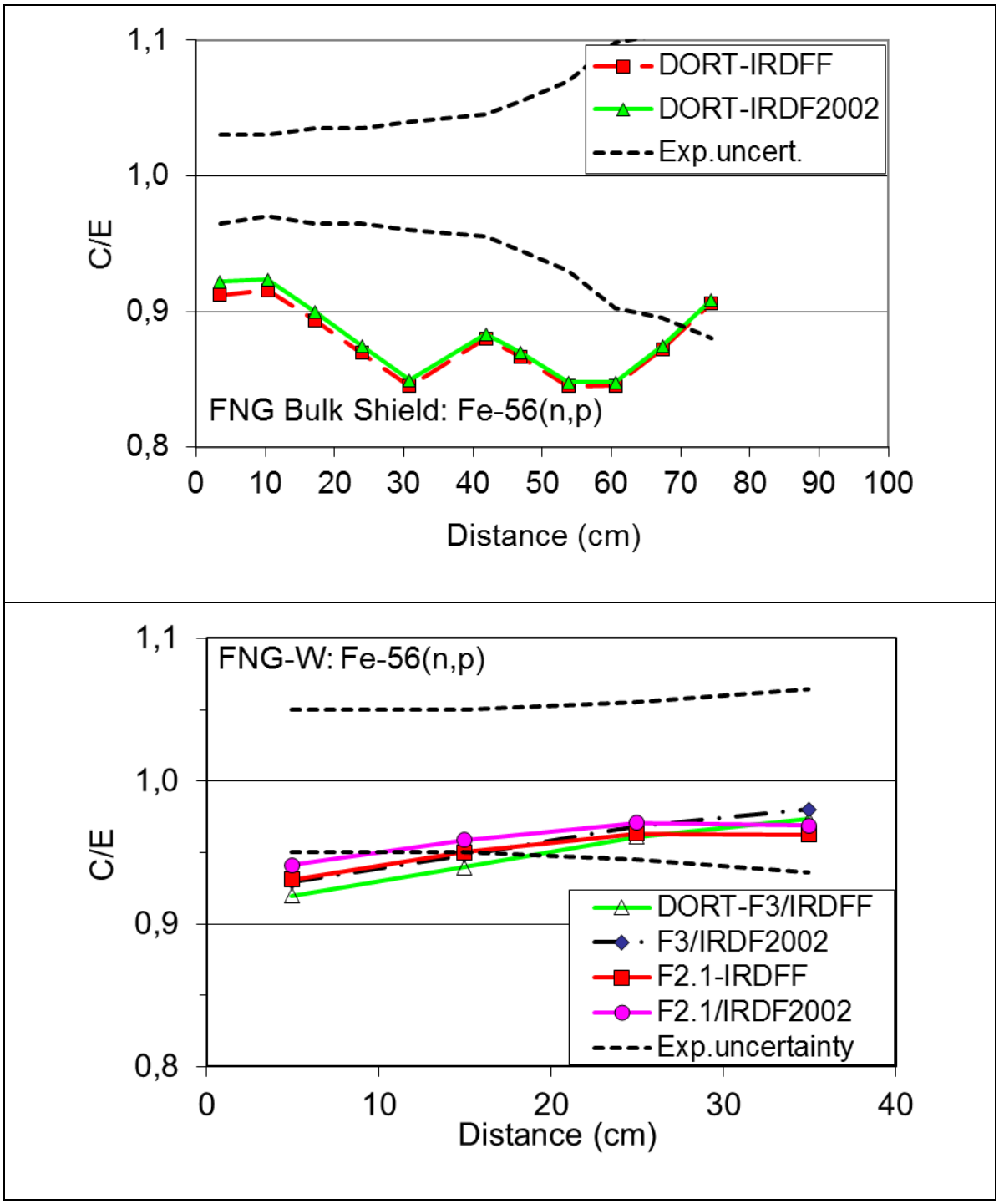
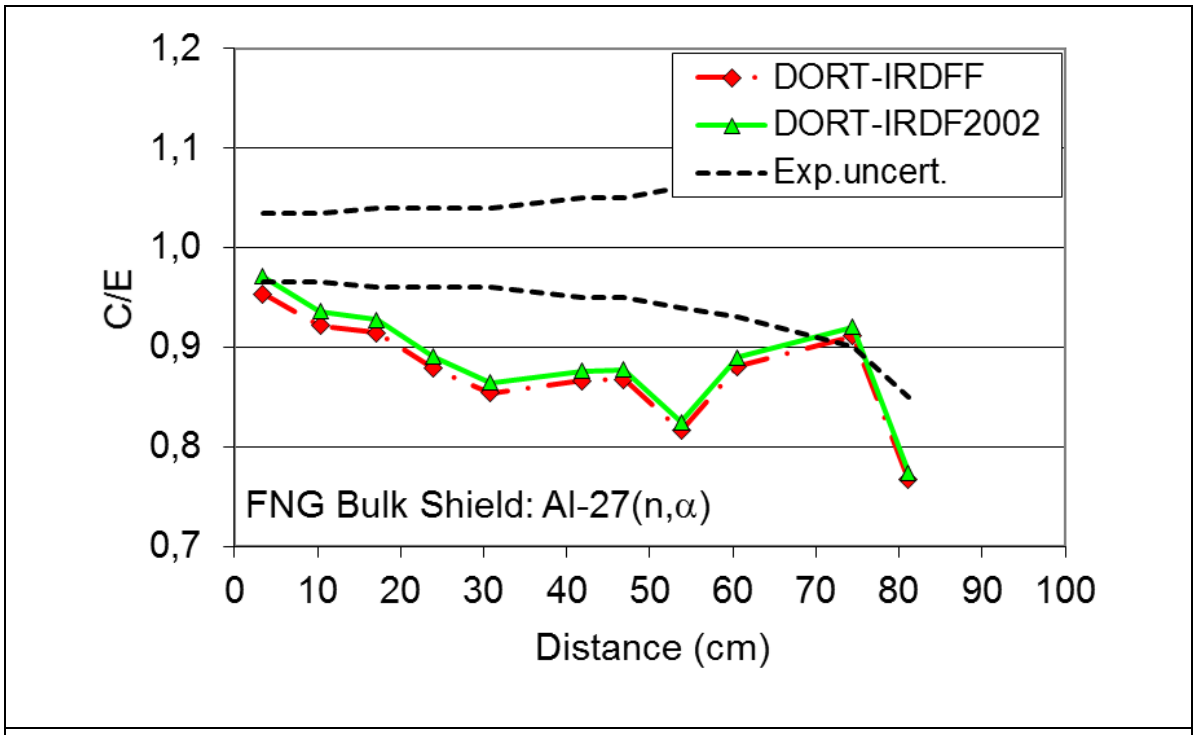
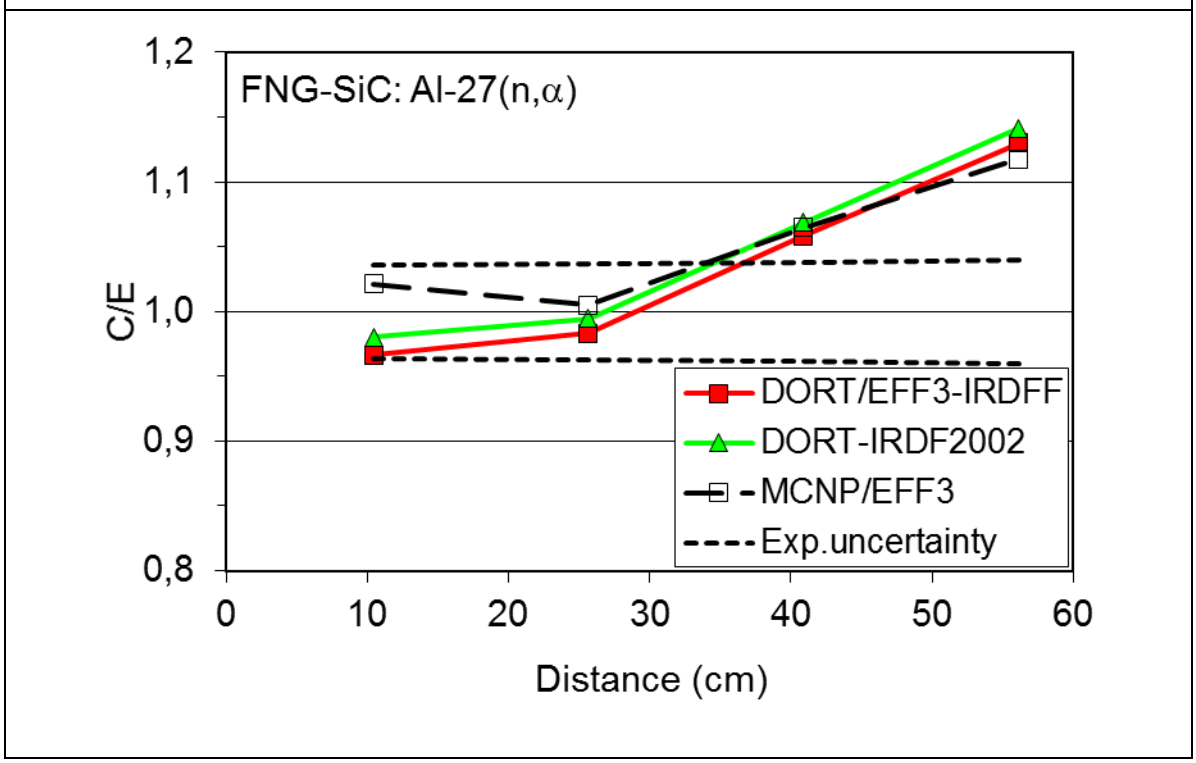
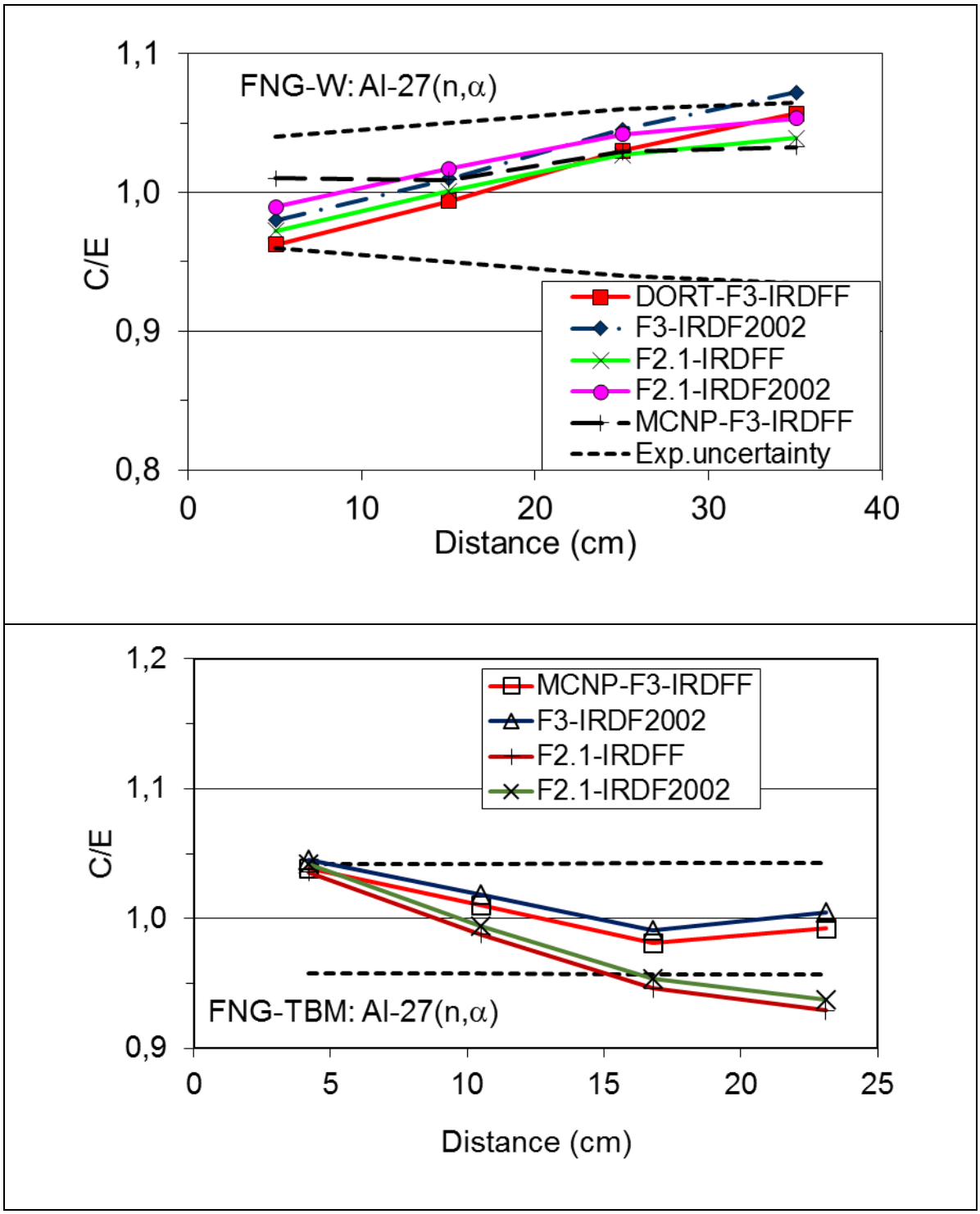


***Fig. 7**: ^{56}Fe detector: comparison of measured and calculated ^{56}Fe activity at different depths for the benchmarks considered in the analysis using the DORT deterministic code. FENDL-2.1 (F2.1) and -3 (F3) cross sections were used in the analyses. Dashed lines delimit the ± 1σ experimental uncertainty bounds.*


1,2
1,1
1,0
0,9
0,8
0,7
C/E
DORT-IRDFF
DORT-IRDF2002
Exp.uncert.
FNG Bulk Shield: Al-27(n,α)
0
10
20
30
40
50
60
70
80
90
100
Distance (cm)


1,2
1,1
1,0
0,9
0,8
C/E
FNG-SiC: Al-27(n,α)
DORT/EFF3-IRDFF
DORT-IRDF2002
MCNP/EFF3
Exp.uncertainty
0
10
20
30
40
50
60
Distance (cm)


FNG-W: Al-27(n,α)
C/E
Distance (cm)
DORT-F3-IRDFF
F3-IRDF2002
F2.1-IRDFF
F2.1-IRDF2002
MCNP-F3-IRDFF
Exp.uncertainty
FNG-TBM: Al-27(n,α)
C/E
Distance (cm)
MCNP-F3-IRDFF
F3-IRDF2002
F2.1-IRDFF
F2.1-IRDF2002

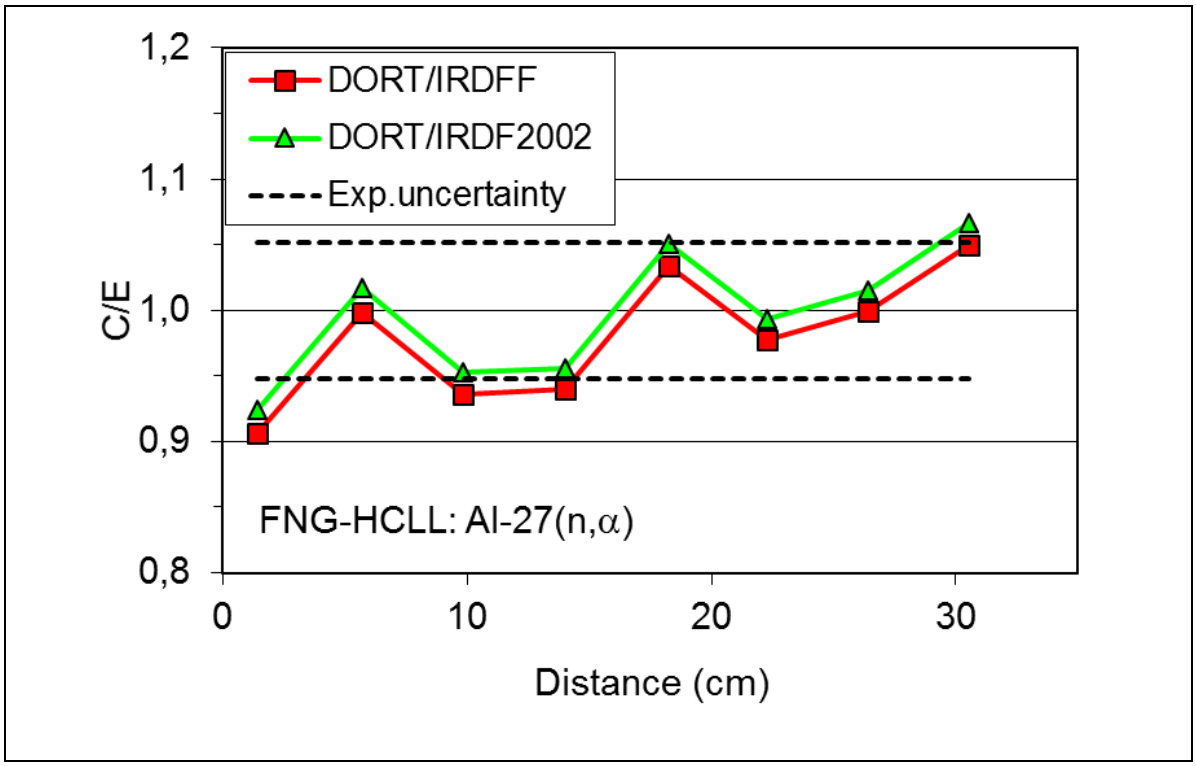
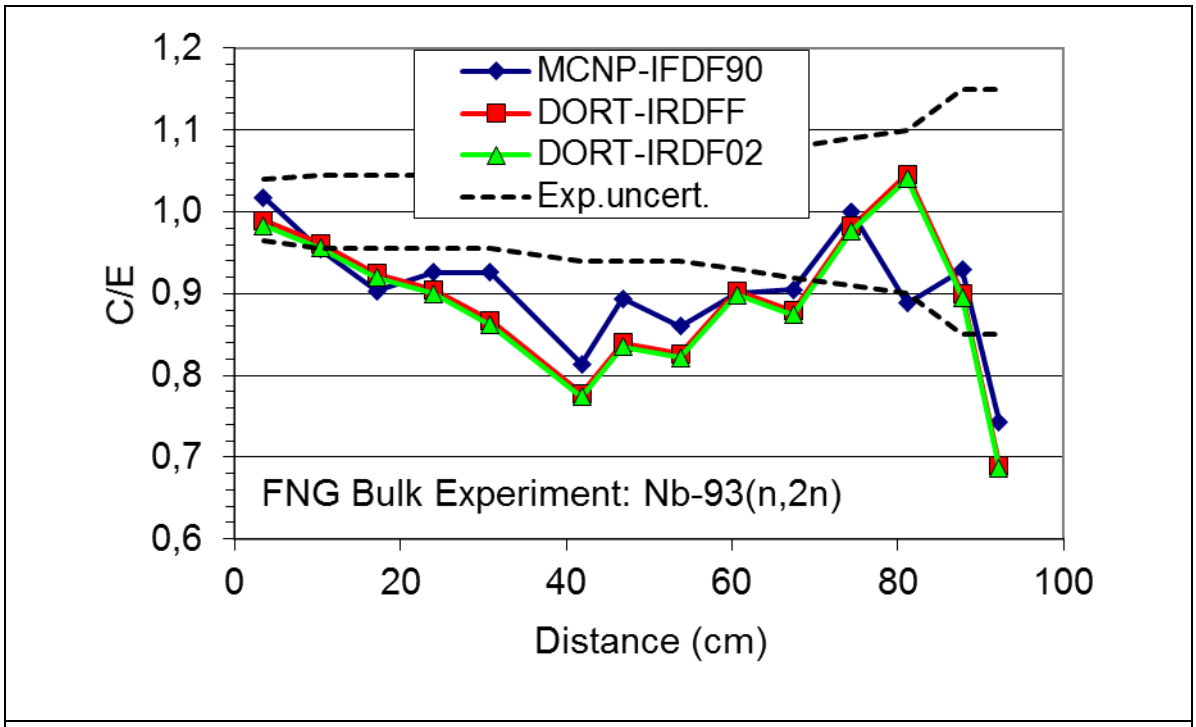
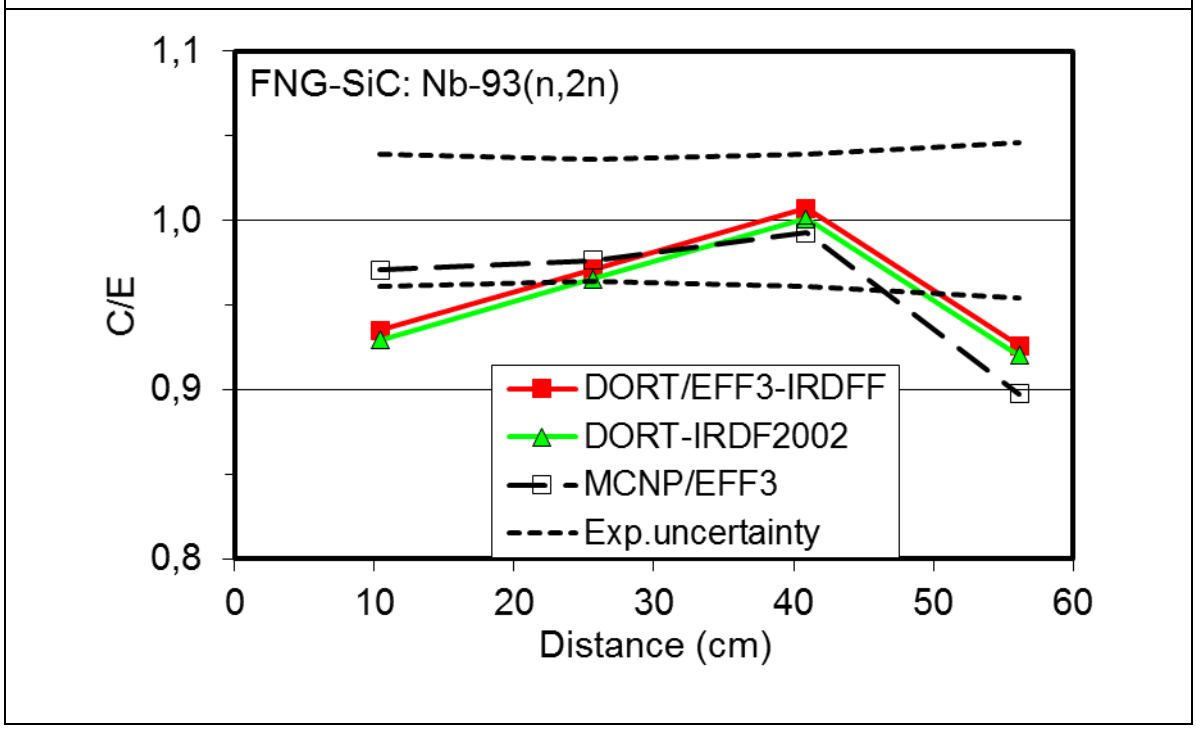
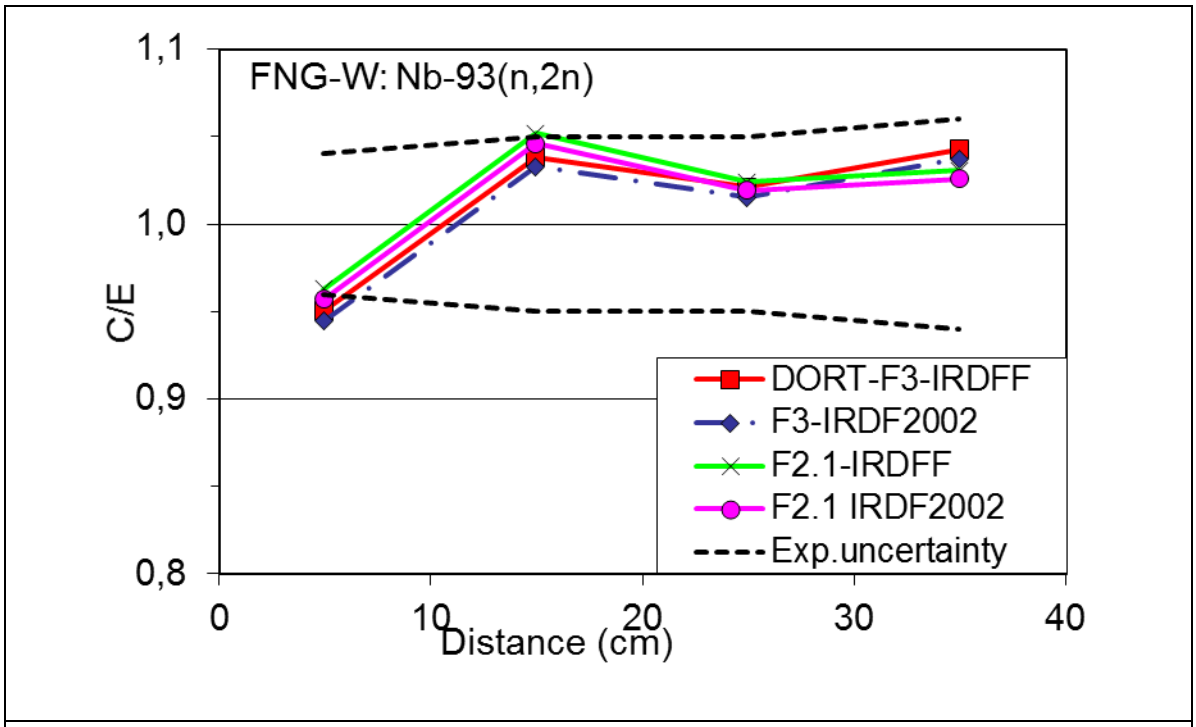
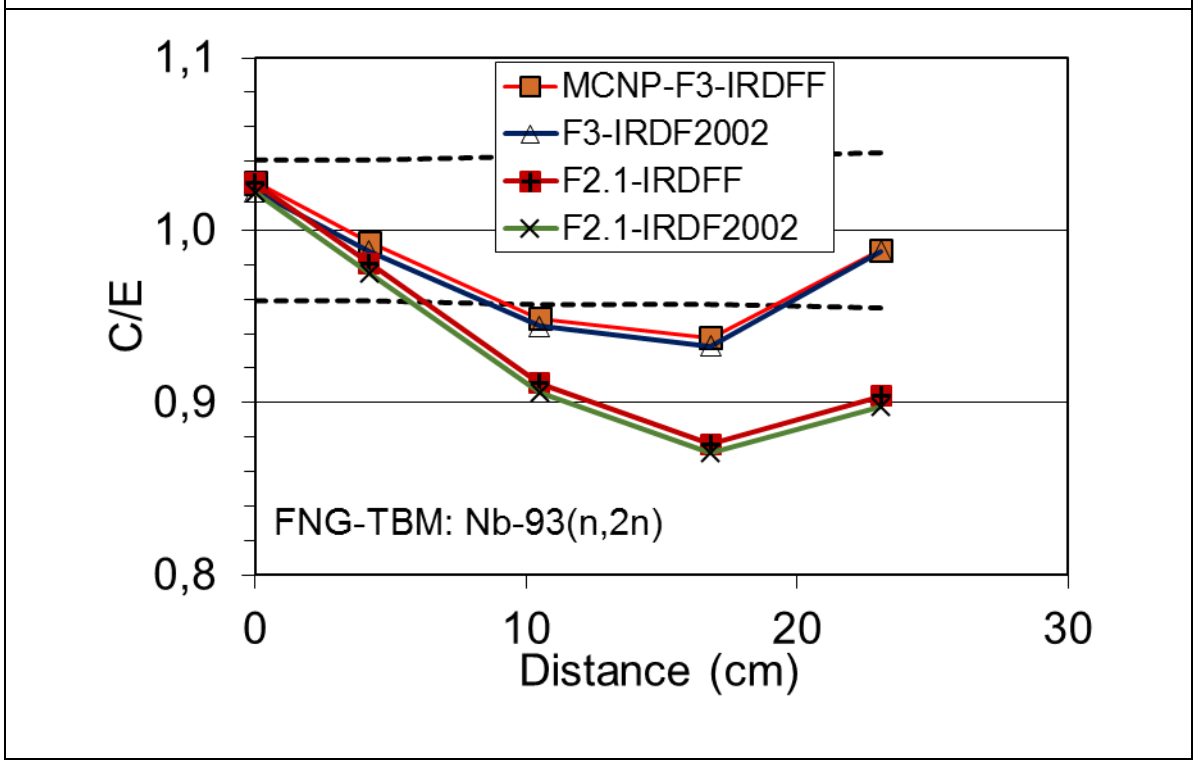


***Fig. 8**: ^{27}Al detector: comparison of measured and calculated ^{27}Al activity at different depths for the benchmarks considered in the analysis; comparison between DORT and MCNP provides an estimate of modelling uncertainties in the deterministic calculation - FENDL-2.1 (F2.1), -3 (F3) and EFF3 cross sections were used in the analyses. Dashed lines delimit the ± 1σ experimental uncertainty bounds.*


1,2
1,1
1,0
0,9
0,8
0,7
0,6
C/E
MCNP-IFDF90
DORT-IRDFF
DORT-IRDF02
Exp.uncert.
FNG Bulk Experiment: Nb-93(n,2n)
0
20
40
60
80
100
Distance (cm)


1,1
1,0
0,9
0,8
C/E
FNG-SiC: Nb-93(n,2n)
DORT/EFF3-IRDFF
DORT-IRDF2002
MCNP/EFF3
Exp.uncertainty
0
10
20
30
40
50
60
Distance (cm)


FNG-W: Nb-93(n,2n)
C/E
1,1
1,0
0,9
0,8
0
10
20
30
40
Distance (cm)
DORT-F3-IRDFF
F3-IRDF2002
F2.1-IRDFF
F2.1 IRDF2002
Exp.uncertainty


MCNP-F3-IRDFF
F3-IRDF2002
F2.1-IRDFF
F2.1-IRDF2002
C/E
1,1
1,0
0,9
0,8
FNG-TBM: Nb-93(n,2n)
0
10
20
30
Distance (cm)

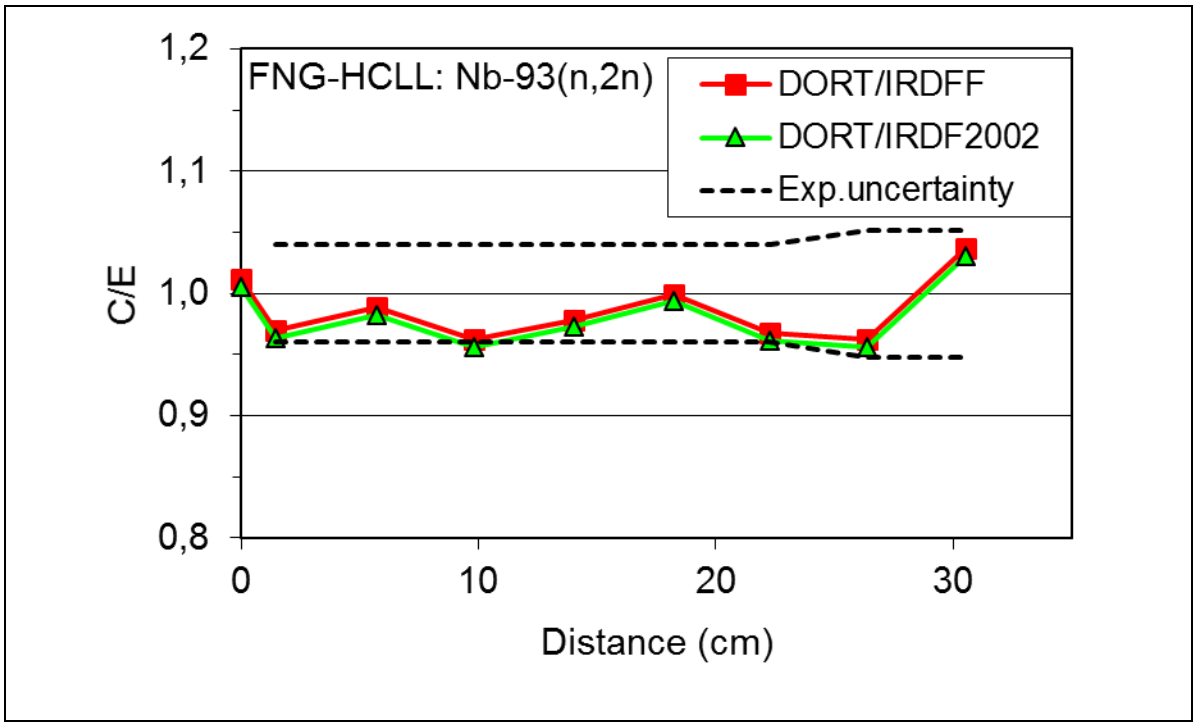


***Fig. 9**: Comparison of measured and calculated ^{93}Nb activity at different depths for the benchmarks considered in the analysis; comparison between DORT and MCNP provides an estimate of modelling uncertainties in the deterministic calculation - FENDL-2.1 (F2.1), -3 (F3) and EFF3 cross sections were used in the analyses. Dashed lines delimit the ± 1 σexperimental uncertainty bounds.*

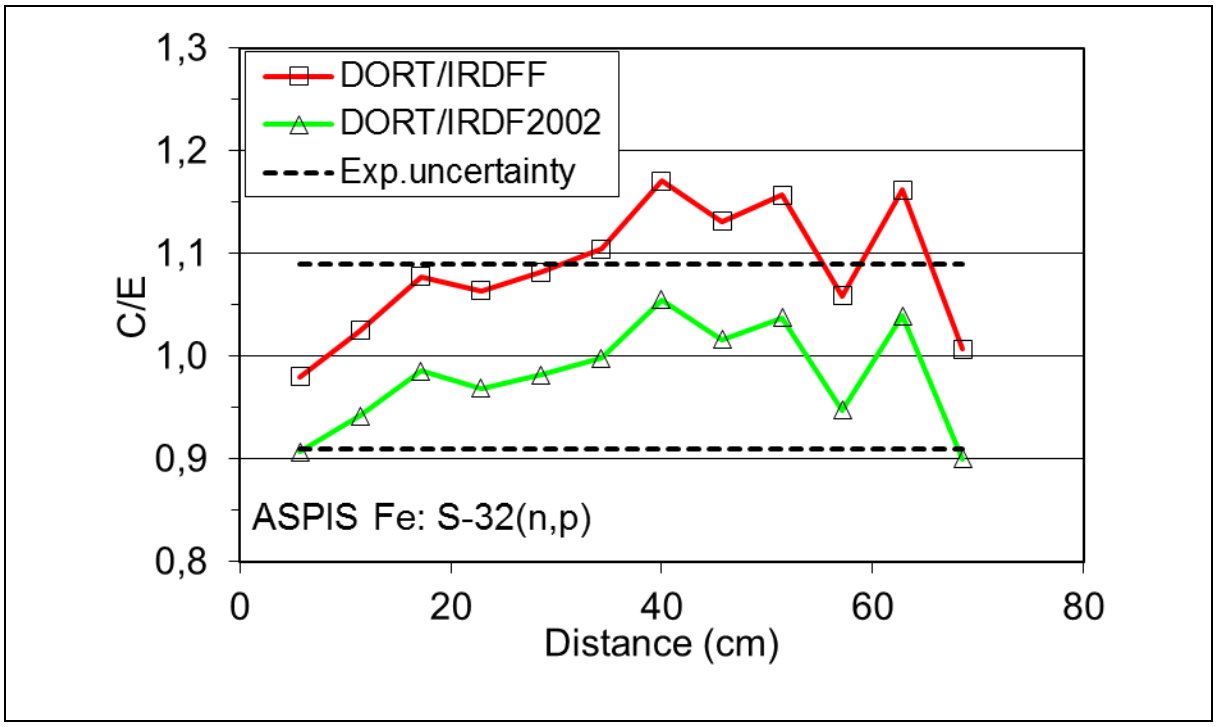


Fig. 10: *^{32}S(n,p) detector: comparison of measured and calculated ^{32}S(n,p) activity at different depths for the ASPIS benchmark. Dashed lines delimit the ± 1σ experimental uncertainty bounds.*

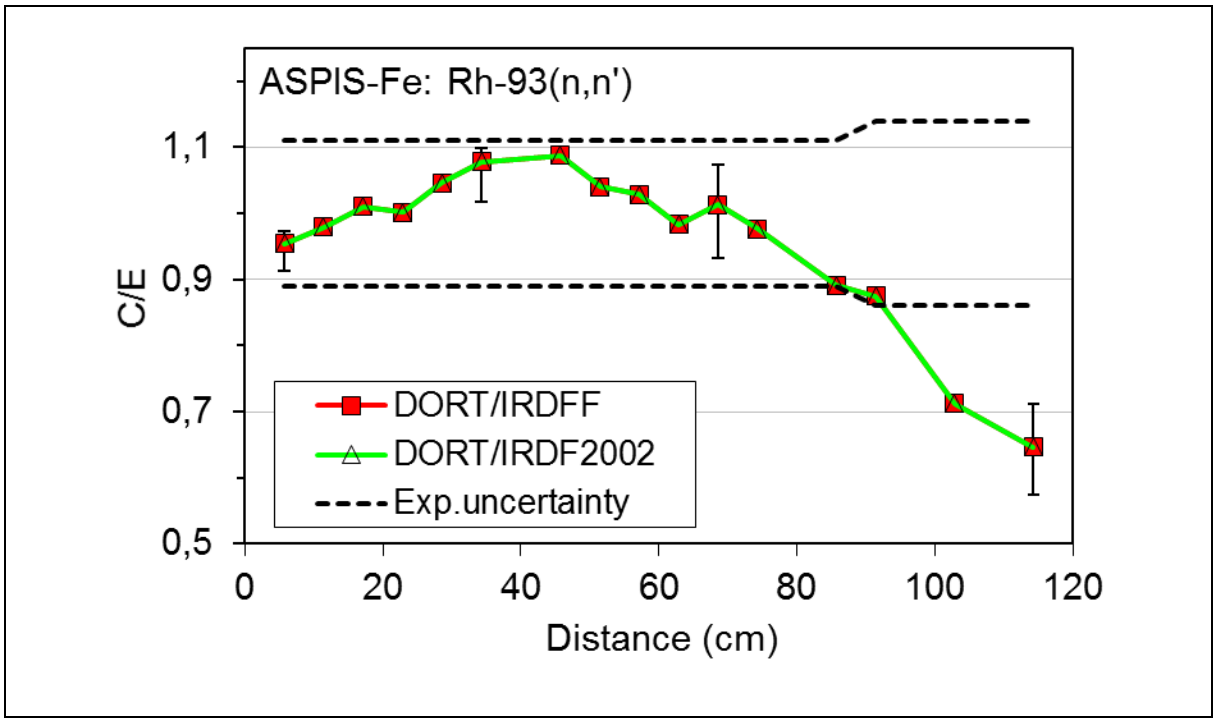


Fig. 11: *^{93}Rh(n,n') detector: comparison of measured and calculated ^{93}Rh activity at different depths for the ASPIS benchmark. Dashed lines delimit the ± 1 σ experimental uncertainty bounds.*

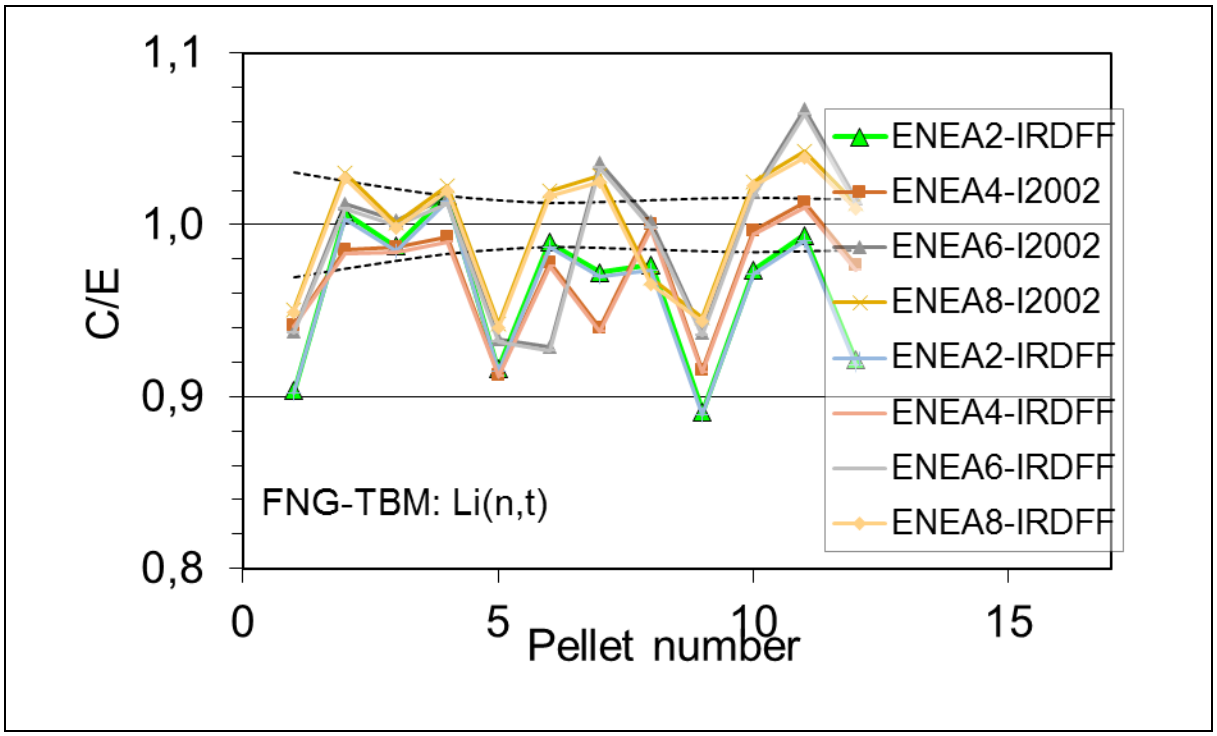


***Fig. 12**: Tritium specific activity: comparison of measured and calculated activity at different pellets measured in the FNG-HCPB benchmark. Dashed lines delimit the ± 1 σ experimental uncertainty bounds.*

4. Conclusions by dosimeter reactions

^{6}Li(n,t), ^{7}Li(n,t)

Large differences in tritium production using IRDF-v1.02 and IRDFF-v1.04 ace files was observed, the IRDFF-v1.04 version not working properly with the MCNP, neither versions 5 nor 6. Different NJOY processing sequences were used at IAEA for the two cases. The bug was finally spotted and corrected by Skip Kahlerto be in NJOY (two numbers defining the interpolation law were swapped). The correction is included in the NJOY99 update up42. After the correction by IAEA this reaction was verified against the tritium specific activity measurements performed at the FNG-HCPB benchmark. Almost no differences were observed between the TPR in ^{6}Li calculated using IRDFF and IRDF2002 (<0.3%, see Table 7).

Also the agreement of the total TPR (in ^{6}Li and ^{7}Li) with the measurements is very good (see Figure 12). Since neither IRDFF nor IRDF-2002 include the ^{7}Li(n,t) cross sections these data were taken from the FENDL-2.1 library. I recommend to consider including the ^{7}Li(n,t) cross sections in a future IRDF evaluation (sum of MT>52).

^{55}Mn(n,γ)

Relatively large differences were observed between IRDFF and IRDF-2002, around 5% for FNG-Bulk Shield, up to 10 % in FNG-W and around 18% in FNG-HCLL benchmarks (see Tables 3, 4 and 8, and Fig. 1). Relatively good C/E agreement was found in the FNG-Bulk Shield experiment mostly sensitivity in the 100-1000 eV energy range where the response function uncertainties are low (~5%). On the other hand relatively large discrepancies between the measured and calculated reaction rates were found for the FNG-W

benchmark where the ^{55}Mn(n,γ) reaction rates are highly sensitive to the response function above 1keV and in the FNG HCLL benchmark. Some systematic errors may though be present in the last two benchmarks, in the FNG-W the exact content of the Mn in the foils needs to be verified and in the case of FNG-HCLL the heterogeneity of Li-6 enrichment in the Li-Pb block was observed. Although the better consistency between the ^{55}Mn(n,γ) and ^{197}Au(n,γ) results seems to indicate better performance of the new data it is at present still difficult to confirm with certitude the progress achieved.

Further verifications are therefore recommended. In particular we expect to have a clearer picture during 2015 after the series of Mn measurements to be performed in spring in new FNG benchmarks. New measurements of the Mn foils were recently performed also in the TRIGA reactor and are under analysis.

^{197}Au(n,γ), ^{58}Ni(n,p), ^{90}Zr(n,2n), ^{115}In(n,n'), ^{56}Fe(n,p), ^{93}Nb(n,2n), ^{103}Rh(n,n')

Comparable or identical results were obtained between the two IRDF dosimetry files, with differences in general below 1% (see Figures 2, 3, 5, 6, 7, 9 and 11, respectively).

^{32}S(n,p), ^{58}Ni(n,2n), ^{27}Al(n,α)

Up to 4% differences were found in the ^{58}Ni(n,2n) (see Tables 3, 4, 5 and 8, Figure 4), around 2% in the ^{27}Al(n,α) (Tables 3 to 6, and 8, Figure 8),and as much as 10% in the ^{32}S(n,p) (Table 9, Figure 10) reaction rates.However, no clear conclusive indications could be drawn concerning eventual improvements due to the uncertainties linked to the modelling of the ASPIS experiment and the uncertainties involved in the modelling and in the transport cross-sections.

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