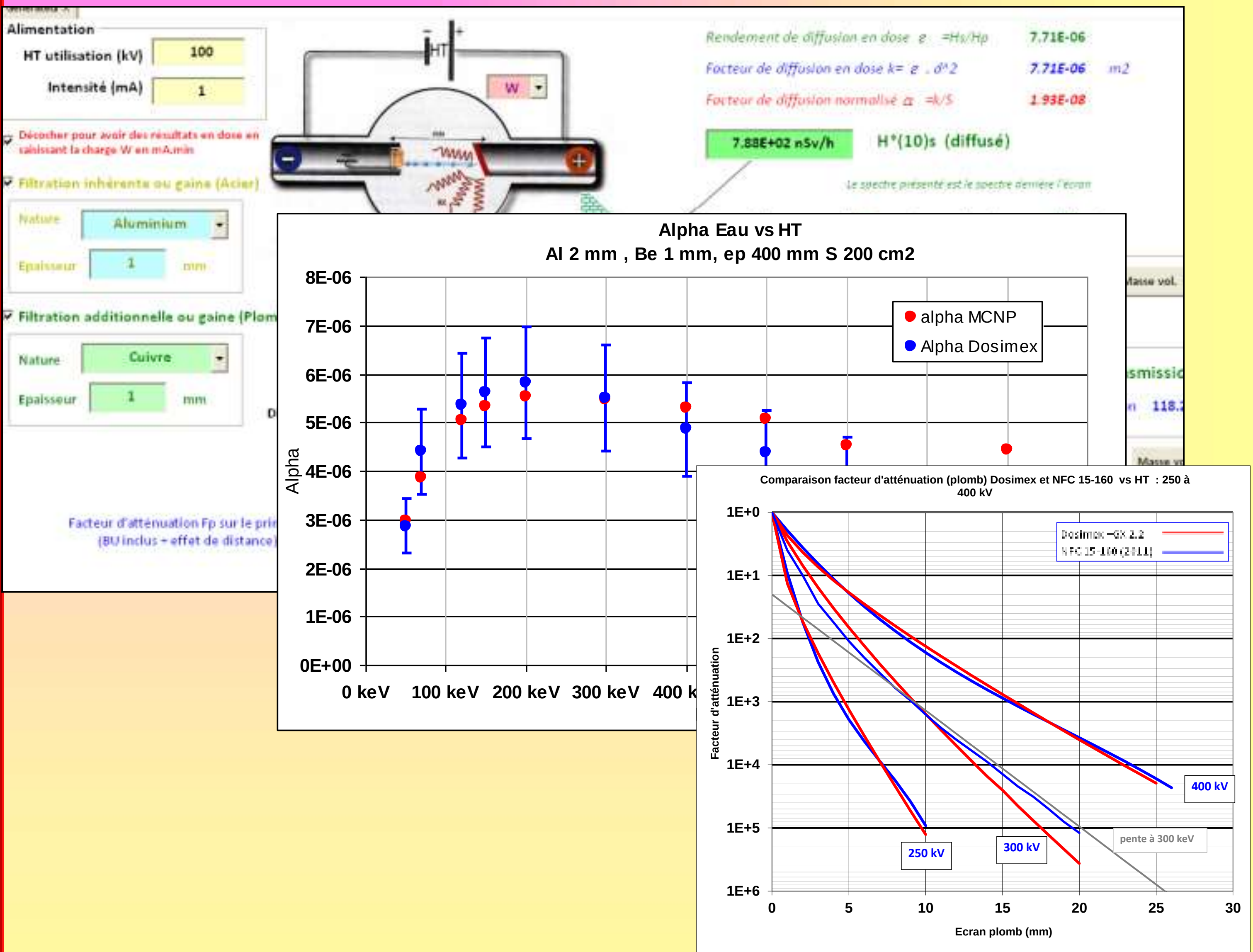
DOSIMEX-GX 3.0

✓ *GENERATOR VALIDATION FILE X*



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SEPTEMBER 2019

SUMMARY

PREAMBLE: GENERAL CONTEXT OF THE VALIDATION OF THE "GENERATOR X" MODEL OF DOSIMEX-GX 3.0

This validation file seeks to demonstrate the reliability of the "generator X" model of Dosimex - GX-3.0. implements 1000 points of comparison on the dose rates on the primary, the scattered radiation and the attenuation factors from 50 to 800 kV.

This file is articulated on 3 axes of validation:

- **Axis 1** : Validation of the dose rate calculation in the primary beam:

The comparison points relate to 154 values in terms of kerma air and as many in terms of dose equivalent H * (10). For this, we benefit from 308 MCNP reference values included in the book Applied Physics of External Radiation Exposure (Rodolphe Antoni and Laurent Bourgois, Springer 2017,https://www.springer.com/gp/book/9783319486581

- **Axis 2** : Validation of the dose equivalent rate calculation in the radiation scattered by a screen:

Again, we recently had access to the CEA-R 6452 report (***Evaluation by Monte-Carlo calculation of the scattering factors in terms of dose equivalent of the radiation from an X generator… ",****Laurent Bourgois, Stéphanie Ménard, 2017*) allowing us to validate our model on 97 comparison points.

- **Axis 3: Validation of the attenuation coefficients in lead and in concrete:**

We relied here on the one hand on values taken from the NFC 15-160 standard of March 2011 but also, for the 2018 version, on the reference article by Laurent Bourgois and Stéphanie Ménard:*Dose equivalent transmission data for shielding industrial x-ray facilities up to 800 kV (journant of radiological protection, 2018)* .

Concerning the comparisons vs MCNP (405 values), the essential result of this validation campaign is as follows: the mean quadratic relative difference, all values combined, is equal to 16%, with 94% of the results having a difference of less than 25 % (*see the details in the final chapter*).

Regarding the attenuation factors, and despite the imprecision of certain reference values (2011), the average difference over 600 points of comparison is around 30%, which, for quantities involving exponentials and attenuation factors up to more than 1011, remains acceptable

IN TOTAL, THIS VALIDATION FILE IMPLEMENTS 980 POINTS OF COMPARISON WITH, IN TERMS OF RATIO, AN AVERAGE OF 0.95 A STANDARD DEVIATION OF AROUND 23%

Partie I. VALIDATION DOSE RATE IN THE PRIMARY

I- 1 : BACKGROUND TO THE COMPARISON

Up to version 2.0 we only had reference values ranging from 50 to 500 kV (110 values). For version 3.0 we were able to benefit from 44 additional points ranging from 600 to 900 keV, still for 11 different filtrations

The values are given in ambient dose equivalent flow in mGy.mn-1 for kerma air and in mSv.mn-1 for H * (10), at1 mof the hearth and an intensity of 1 mA. The values thus obtained correspond to the concept of yield Γ_R defined in standard NF C 15-160 expressed in mSv.m2.mn-1.mA-1.

These comparisons relate to a set of 154 values in kerma air and 154 values in H * (10) for 10 different values of high voltages and 11 different filtrations, for a total of 308 values tested.

Note: the 2011 NFC 15-160 standard expressed the yield in terms of dose equivalents (Sv), but the values actually implicitly correspond to air kerma (Gy). the standard of2018 acorrected this error and the values are now given in terms of H * (10). Version 3.0 gives, in the main dialog, the values in H * (10).

I- 2 : DOSE RATE H * (10) IN THE PRIMARY BEAM:

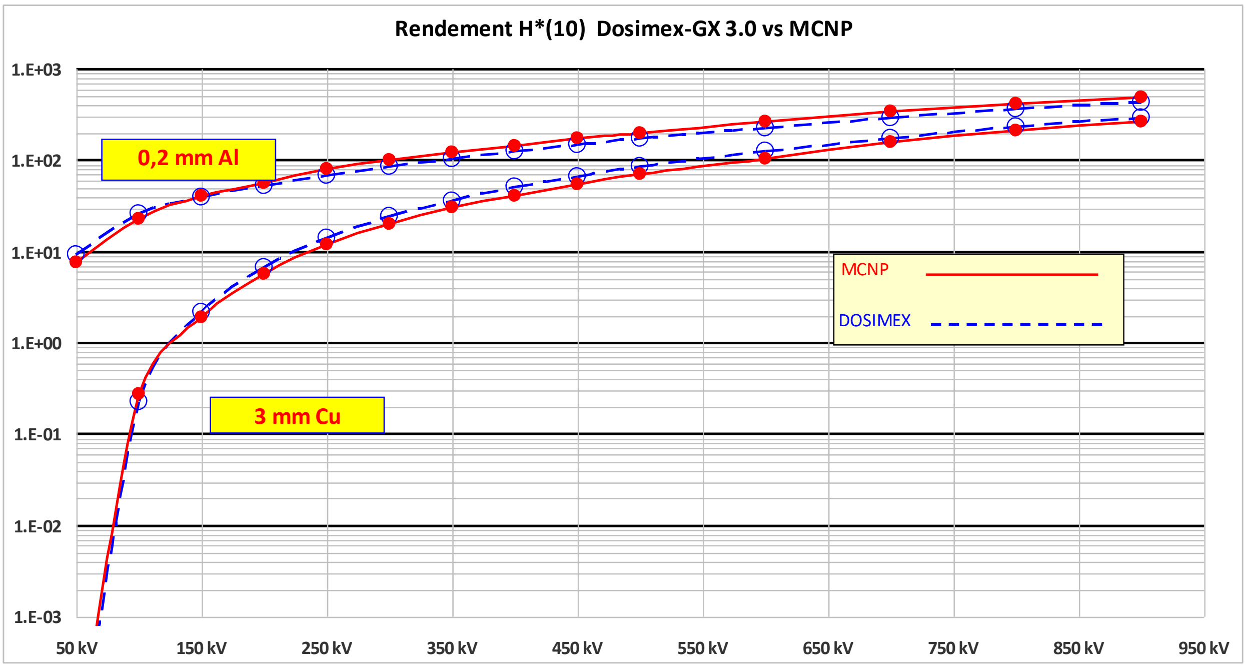
I.2.1 COMPARISON OF YIELDS

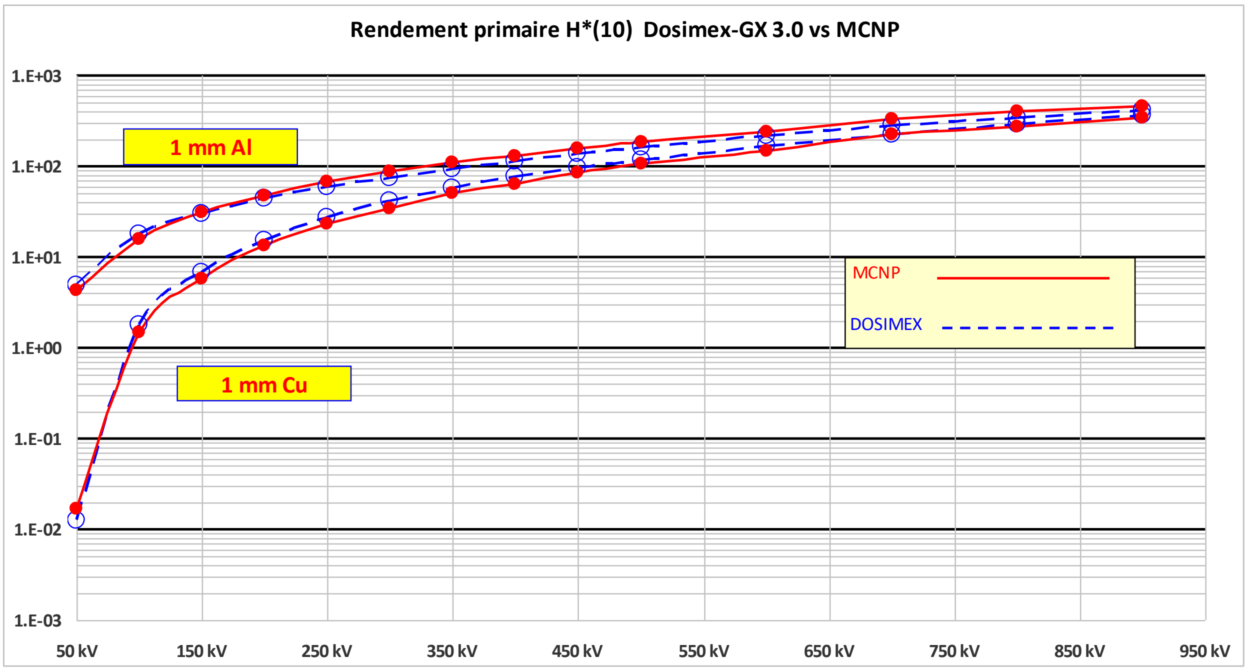
The values obtained (154) below in mSv.mn-1 are calculated at a distance of1 mand an intensity of 1 mA with the corresponding filtrations. Remember that these yields calculated with MCNP are used in the NFC 15-160 version 2018 standard. (*be careful : dose rate are given here per minut*)

Primary yield H * (10) MCNP (mSv / min at 1 m for 1 mA)											
HT (kV)	None	0.2 mm Al	0.5 mm Al	1 mm Al	2 mm Al	3 mm Al	0.2 mm Cu	0.5 mm Cu	1 mm Cu	2 mm Cu	3 mm Cu
	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min
50	1.01E + 01	7.69E + 00	6.00E + 00	4.35E + 00	2.75E + 00	1.87E + 00	6.75E-01	1.28E-01	1.69E-02	5.72E-04	2.92E-05
100	2.73E + 01	2.31E + 01	1.94E + 01	1.59E + 01	1.22E + 01	9.94E + 00	5.97E + 00	3.02E + 00	1.46E + 00	6.41E-01	2.79E-01
150	4.60E + 01	4.07E + 01	3.63E + 01	3.13E + 01	2.53E + 01	2.18E + 01	1.57E + 01	9.50E + 00	5.78E + 00	3.05E + 00	1.89E + 00
200	6.28E + 01	5.74E + 01	5.24E + 01	4.67E + 01	3.97E + 01	3.57E + 01	2.76E + 01	1.90E + 01	1.32E + 01	8.92E + 00	5.63E + 00
250	8.44E + 01	7.95E + 01	7.38E + 01	6.72E + 01	5.82E + 01	5.20E + 01	4.29E + 01	3.11E + 01	2.30E + 01	1.56E + 01	1.20E + 01
300	1.04E + 02	9.97E + 01	9.40E + 01	8.67E + 01	7.68E + 01	7.03E + 01	6.01E + 01	4.56E + 01	3.48E + 01	2.52E + 01	2.02E + 01
350	1.25E + 02	1.23E + 02	1.17E + 02	1.10E + 02	9.93E + 01	9.14E + 01	8.02E + 01	6.28E + 01	5.06E + 01	3.78E + 01	3.08E + 01
400	1.46E + 02	1.44E + 02	1.37E + 02	1.29E + 02	1.18E + 02	1.10E + 02	9.74E + 01	7.86E + 01	6.30E + 01	4.91E + 01	4.12E + 01
450	1.83E + 02	1.74E + 02	1.67E + 02	1.58E + 02	1.46E + 02	1.37E + 02	1.25E + 02	1.02E + 02	8.42E + 01	6.61E + 01	5.52E + 01
500	2.07E + 02	2.02E + 02	1.94E + 02	1.85E + 02	1.72E + 02	1.63E + 02	1.50E + 02	1.26E + 02	1.05E + 02	8.37E + 01	7.09E + 01
600	2.69E + 02	2.62E + 02	2.54E + 02	2.43E + 02	2.30E + 02	2.18E + 02	2.03E + 02	1.73E + 02	1.49E + 02	1.22E + 02	1.05E + 02
700	3.55E + 02	3.48E + 02	3.43E + 02	3.33E + 02	3.17E + 02	3.02E + 02	2.88E + 02	2.54E + 02	2.22E + 02	1.87E + 02	1.61E + 02
800	4.22E + 02	4.15E + 02	4.07E + 02	3.97E + 02	3.79E + 02	3.65E + 02	3.52E + 02	3.13E + 02	2.77E + 02	2.41E + 02	2.14E + 02
900	5.02E + 02	4.91E + 02	4.84E + 02	4.59E + 02	4.59E + 02	4.44E + 02	4.24E + 02	3.81E + 02	3.43E + 02	2.95E + 02	2.66E + 02

Primary yield H * (10) DOSIMEX-GX 3.0 (mSv / min at 1 m for 1 mA)											
HT (kV)	None	0.2 mm Al	0.5 mm Al	1 mm Al	2 mm Al	3 mm Al	0.2 mm Cu	0.5 mm Cu	1 mm Cu	2 mm Cu	3 mm Cu
	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min
50	1.18E + 01	9.34E + 00	7.07E + 00	4.96E + 00	2.95E + 00	1.99E + 00	6.78E-01	1.12E-01	1.27E-02	3.74E-04	1.65E-05
100	2.97E + 01	2.59E + 01	2.21E + 01	1.82E + 01	1.39E + 01	1.14E + 01	7.60E + 00	3.86E + 00	1.82E + 00	5.18E-01	2.30E-01
150	4.38E + 01	3.95E + 01	3.51E + 01	3.05E + 01	2.50E + 01	2.17E + 01	1.70E + 01	1.09E + 01	6.88E + 00	3.57E + 00	2.14E + 00
200	5.81E + 01	5.35E + 01	4.89E + 01	4.38E + 01	3.76E + 01	3.36E + 01	2.90E + 01	2.13E + 01	1.54E + 01	9.74E + 00	6.79E + 00
250	7.35E + 01	6.89E + 01	6.41E + 01	5.88E + 01	5.20E + 01	4.74E + 01	4.33E + 01	3.44E + 01	2.69E + 01	1.89E + 01	1.42E + 01
300	9.09E + 01	8.62E + 01	8.13E + 01	7.56E + 01	6.83E + 01	6.31E + 01	6.00E + 01	4.99E + 01	4.10E + 01	3.07E + 01	2.42E + 01
350	1.11E + 02	1.06E + 02	1.00E + 02	9.45E + 01	8.65E + 01	8.07E + 01	7.87E + 01	6.78E + 01	5.74E + 01	4.48E + 01	3.65E + 01
400	1.31E + 02	1.26E + 02	1.21E + 02	1.15E + 02	1.07E + 02	1.00E + 02	9.95E + 01	8.77E + 01	7.60E + 01	6.11E + 01	5.08E + 01
450	1.54E + 02	1.49E + 02	1.44E + 02	1.38E + 02	1.29E + 02	1.22E + 02	1.22E + 02	1.10E + 02	9.67E + 01	7.95E + 01	6.73E + 01
500	1.79E + 02	1.74E + 02	1.69E + 02	1.62E + 02	1.52E + 02	1.45E + 02	1.47E + 02	1.34E + 02	1.19E + 02	9.99E + 01	8.56E + 01
600	2.35E + 02	2.30E + 02	2.24E + 02	2.17E + 02	2.06E + 02	1.97E + 02	2.02E + 02	1.87E + 02	1.70E + 02	1.46E + 02	1.28E + 02
700	2.98E + 02	2.93E + 02	2.86E + 02	2.78E + 02	2.66E + 02	2.56E + 02	2.65E + 02	2.48E + 02	2.28E + 02	2.28E + 02	1.76E + 02
800	3.68E + 02	3.62E + 02	3.56E + 02	3.47E + 02	3.33E + 02	3.21E + 02	3.34E + 02	3.15E + 02	2.93E + 02	2.93E + 02	2.32E + 02
900	4.44E + 02	4.38E + 02	4.31E + 02	4.22E + 02	4.06E + 02	3.93E + 02	4.09E + 02	3.89E + 02	3.64E + 02	3.64E + 02	2.93E + 02

Below as examples the graphs for 4 different filtrations:

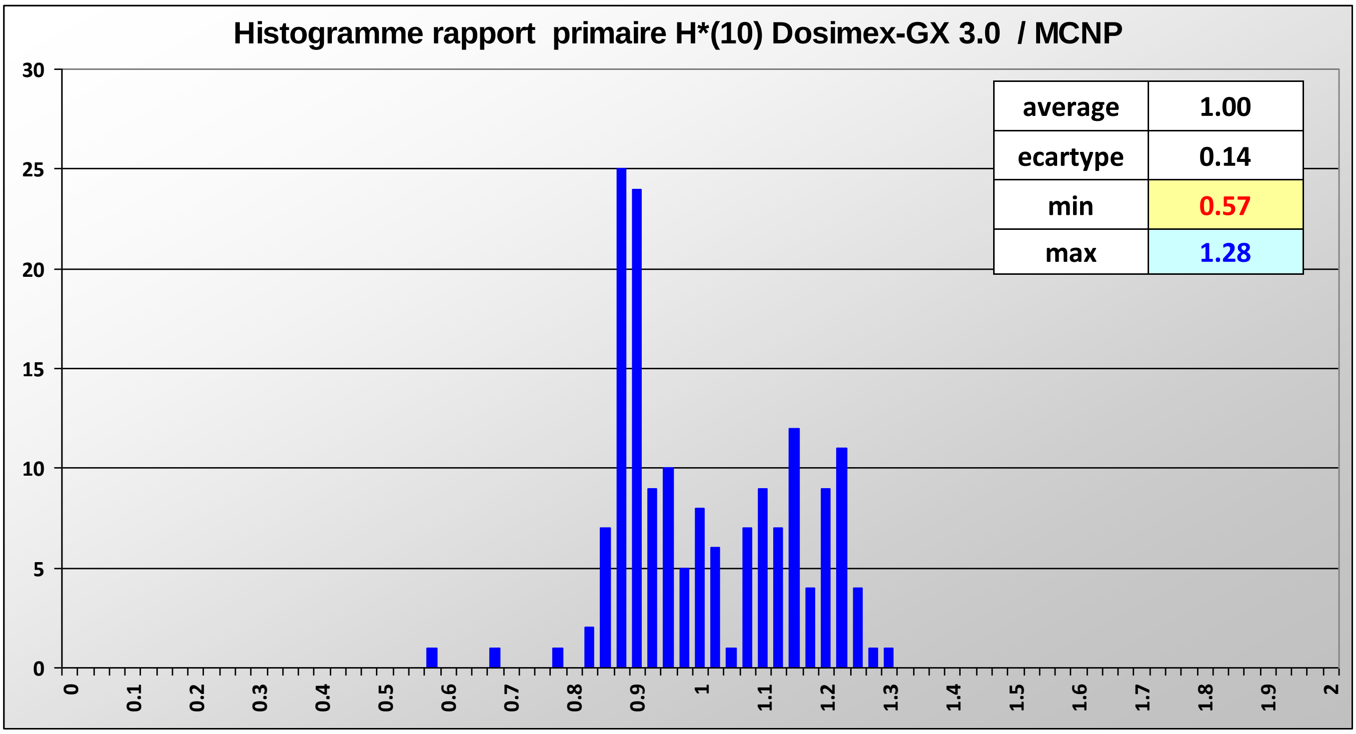




Conclusion: The average quadratic difference over these 154 comparison points is equal to 14%.

I.2.2 ANALYSIS OF DOSIMEX / MCNP RELATIONSHIPS IN TERMS OF H * (10)

DOSIMEX-GX / MCNP performance report											
HT (kV)	None	0.2 mm Al	0.5 mm Al	1 mm Al	2 mm Al	3 mm Al	0.2 mm Cu	0.5 mm Cu	1 mm Cu	2 mm Cu	3 mm Cu
	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min
50	1.17	1.21	1.18	1.14	1.07	1.06	1.00	0.88	0.75	0.65	0.57
100	1.09	1.12	1.14	1.14	1.14	1.15	1.27	1.28	1.25	0.81	0.82
150	0.95	0.97	0.97	0.97	0.99	1.00	1.08	1.15	1.19	1.17	1.13
200	0.93	0.93	0.93	0.94	0.95	0.94	1.05	1.12	1.17	1.09	1.21
250	0.87	0.87	0.87	0.88	0.89	0.91	1.01	1.11	1.17	1.21	1.18
300	0.87	0.86	0.86	0.87	0.89	0.90	1.00	1.09	1.18	1.22	1.20
350	0.89	0.86	0.85	0.86	0.87	0.88	0.98	1.08	1.13	1.19	1.19
400	0.90	0.88	0.88	0.89	0.91	0.91	1.02	1.12	1.21	1.24	1.23
450	0.84	0.86	0.86	0.87	0.88	0.89	0.98	1.08	1.15	1.20	1.22
500	0.86	0.86	0.87	0.88	0.88	0.89	0.98	1.06	1.13	1.19	1.21
600	0.87	0.88	0.88	0.89	0.90	0.90	1.00	1.08	1.14	1.20	1.22
700	0.84	0.84	0.83	0.83	0.84	0.85	0.92	0.98	1.03	1.22	1.09
800	0.87	0.87	0.87	0.87	0.88	0.88	0.95	1.01	1.06	1.22	1.08
900	0.88	0.89	0.89	0.92	0.88	0.89	0.96	1.02	1.06	1.23	1.10



For these 154 values, the average algebraic deviation is equal to -1.00, which indicates a significant absence of bias, and a standard deviation of 14%. (where we thus find the mean square deviation of 14%)

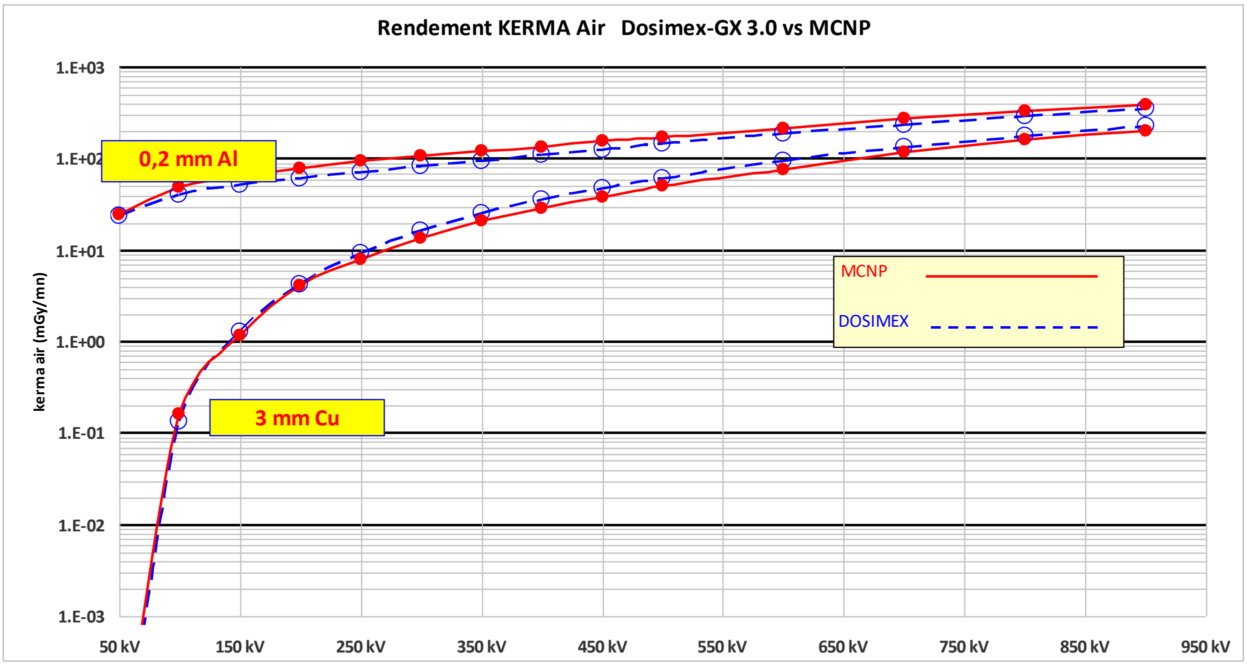
I- 3 : AMBIENT DOSE RATES IN KERMA AIR IN THE PRIMARY BEAM:

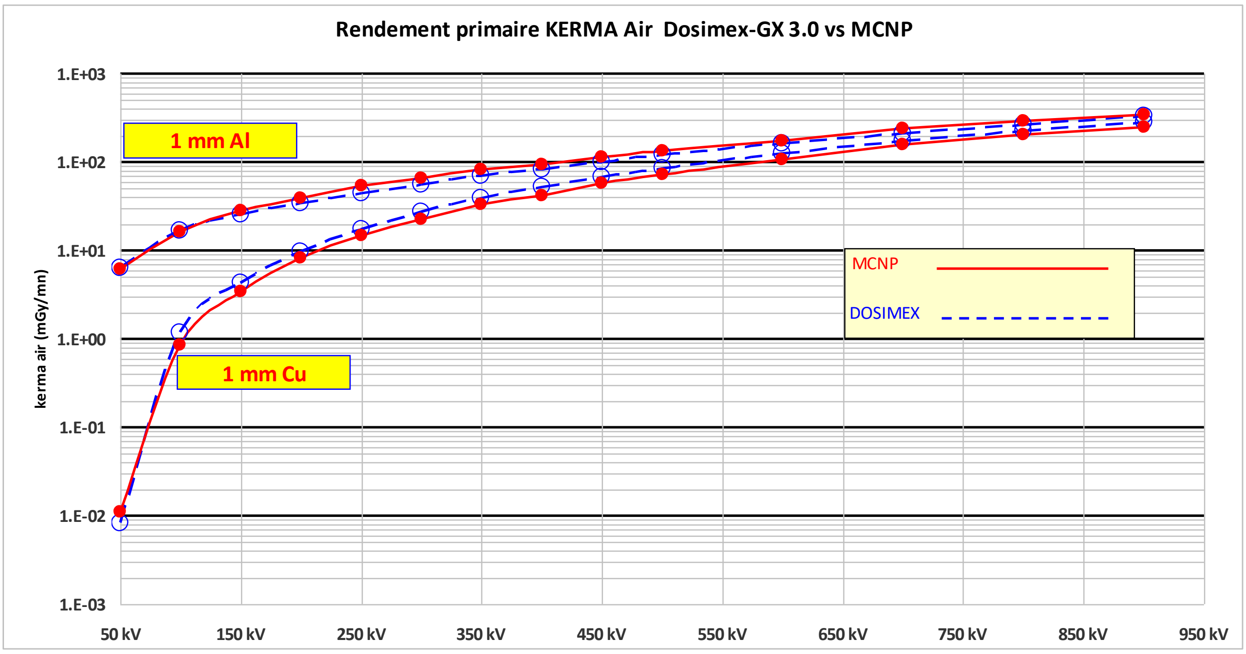
I.3.1 PERFORMANCE COMPARISONS IN KERMA AIR (MGY / MIN)

Kerma air yields were used (wrongly) in the 2011 version of standard NF C 15-160

KERMA Air MCNP primary efficiency (mSv / min at 1 m for 1 mA)											
HT (kV)	None	0.2 mm Al	0.5 mm Al	1 mm Al	2 mm Al	3 mm Al	0.2 mm Cu	0.5 mm Cu	1 mm Cu	2 mm Cu	3 mm Cu
	mGy / min	mGy / min	mGy / min	mGy / min	mGy / min	mGy / min	mGy / min	mGy / min	mGy / min	mGy / min	mGy / min
50	1.48E + 02	2.49E + 01	1.15E + 01	6.08E + 00	3.03E + 00	1.85E + 00	5.62E-01	9.05E-02	1.11E-02	3.62E-04	1.82E-05
100	1.99E + 02	4.89E + 01	2.58E + 01	1.65E + 01	1.04E + 01	7.76E + 00	3.99E + 00	1.82E + 00	8.54E-01	3.73E-01	1.63E-01
150	2.23E + 02	6.61E + 01	4.00E + 01	2.85E + 01	1.97E + 01	1.57E + 01	1.01E + 01	5.76E + 00	3.48E + 00	1.86E + 00	1.16E + 00
200	2.32E + 02	7.85E + 01	5.09E + 01	3.87E + 01	2.93E + 01	2.48E + 01	1.77E + 01	1.17E + 01	8.17E + 00	5.66E + 00	4.05E + 00
250	2.40E + 02	9.50E + 01	6.65E + 01	5.33E + 01	4.19E + 01	3.59E + 01	2.76E + 01	1.96E + 01	1.46E + 01	1.02E + 01	7.86E + 00
300	2.55E + 02	1.08E + 02	8.00E + 01	6.62E + 01	5.43E + 01	4.79E + 01	3.90E + 01	2.93E + 01	2.26E + 01	1.67E + 01	1.36E + 01
350	2.62E + 02	1.23E + 02	9.54E + 01	8.19E + 01	6.97E + 01	6.22E + 01	5.25E + 01	4.09E + 01	3.35E + 01	2.56E + 01	2.11E + 01
400	2.70E + 02	1.36E + 02	1.09E + 02	9.48E + 01	8.21E + 01	7.50E + 01	6.45E + 01	5.19E + 01	4.23E + 01	3.37E + 01	2.87E + 01
450	2.86E + 02	1.56E + 02	1.29E + 02	1.15E + 02	1.01E + 02	9.32E + 01	8.33E + 01	6.84E + 01	5.72E + 01	4.58E + 01	3.87E + 01
500	3.02E + 02	1.74E + 02	1.47E + 02	1.33E + 02	1.20E + 02	1.12E + 02	1.01E + 02	8.54E + 01	7.26E + 01	5.88E + 01	5.04E + 01
600	3.45E + 02	2.17E + 02	1.90E + 02	1.75E + 02	1.61E + 02	1.51E + 02	1.39E + 02	1.20E + 02	1.05E + 02	8.73E + 01	7.63E + 01
700	4.16E + 02	2.80E + 02	2.55E + 02	2.41E + 02	2.25E + 02	2.13E + 02	2.02E + 02	1.79E + 02	1.59E + 02	1.36E + 02	1.19E + 02
800	4.96E + 02	3.32E + 02	3.04E + 02	2.89E + 02	2.72E + 02	2.60E + 02	2.50E + 02	2.25E + 02	2.02E + 02	1.79E + 02	1.60E + 02
900	5.17E + 02	3.85E + 02	3.60E + 02	3.45E + 02	3.31E + 02	3.19E + 02	3.04E + 02	2.77E + 02	2.52E + 02	2.21E + 02	2.00E + 02

KERMA Air DOSIMEX-GX 3.0 primary efficiency (mSv / min at 1 m for 1 mA)											
HT (kV)	None	0.2 mm Al	0.5 mm Al	1 mm Al	2 mm Al	3 mm Al	0.2 mm Cu	0.5 mm Cu	1 mm Cu	2 mm Cu	3 mm Cu
	mGy / min	mGy / min	mGy / min	mGy / min	mGy / min	mGy / min	mGy / min	mGy / min	mGy / min	mGy / min	mGy / min
50	1.71E + 02	2.40E + 01	1.16E + 01	6.30E + 00	3.10E + 00	1.90E + 00	5.31E-01	7.60E-02	8.13E-03	2.30E-04	1.00E-05
100	2.04E + 02	4.10E + 01	2.53E + 01	1.70E + 01	1.13E + 01	8.70E + 00	5.22E + 00	2.55E + 00	1.17E + 00	3.57E-01	1.36E-01
150	2.16E + 02	5.20E + 01	3.50E + 01	2.60E + 01	1.90E + 01	1.50E + 01	1.12E + 01	6.95E + 00	4.28E + 00	2.17E + 00	1.29E + 00
200	2.20E + 02	6.10E + 01	4.40E + 01	3.40E + 01	2.70E + 01	2.30E + 01	1.90E + 01	1.36E + 01	9.73E + 00	6.12E + 00	4.28E + 00
250	2.22E + 02	7.10E + 01	5.40E + 01	4.40E + 01	3.70E + 01	3.20E + 01	2.86E + 01	2.24E + 01	1.74E + 01	1.22E + 01	9.28E + 00
300	2.27E + 02	8.30E + 01	6.60E + 01	5.60E + 01	4.80E + 01	4.30E + 01	4.00E + 01	3.30E + 01	2.71E + 01	2.04E + 01	1.62E + 01
350	2.39E + 02	9.60E + 01	7.90E + 01	7.00E + 01	6.10E + 01	5.60E + 01	6.10E + 01	4.60E + 01	3.88E + 01	3.05E + 01	2.50E + 01
400	2.50E + 02	1.10E + 02	9.30E + 01	8.30E + 01	7.50E + 01	7.00E + 01	6.80E + 01	6.00E + 01	5.20E + 01	4.23E + 01	3.54E + 01
450	2.68E + 02	1.27E + 02	1.11E + 02	1.01E + 02	9.20E + 01	8.60E + 01	8.50E + 01	7.60E + 01	6.75E + 01	5.60E + 01	4.76E + 01
500	2.81E + 02	1.46E + 02	1.30E + 02	1.20E + 02	1.10E + 02	1.03E + 02	1.04E + 02	9.40E + 01	8.46E + 01	7.12E + 01	6.14E + 01
600	3.15E + 02	1.89E + 02	1.72E + 02	1.62E + 02	1.51E + 02	1.44E + 02	1.48E + 02	1.37E + 02	1.26E + 02	1.09E + 02	9.58E + 01
700	3.62E + 02	2.38E + 02	2.22E + 02	2.11E + 02	1.99E + 02	1.91E + 02	1.97E + 02	1.86E + 02	1.72E + 02	1.51E + 02	1.35E + 02
800	4.17E + 02	2.94E + 02	2.77E + 02	2.66E + 02	2.53E + 02	2.44E + 02	2.53E + 02	2.40E + 02	2.24E + 02	2.00E + 02	1.79E + 02
900	4.79E + 02	3.55E + 02	3.39E + 02	3.27E + 02	3.13E + 02	3.02E + 02	3.14E + 02	3.00E + 02	2.82E + 02	2.54E + 02	2.30E + 02

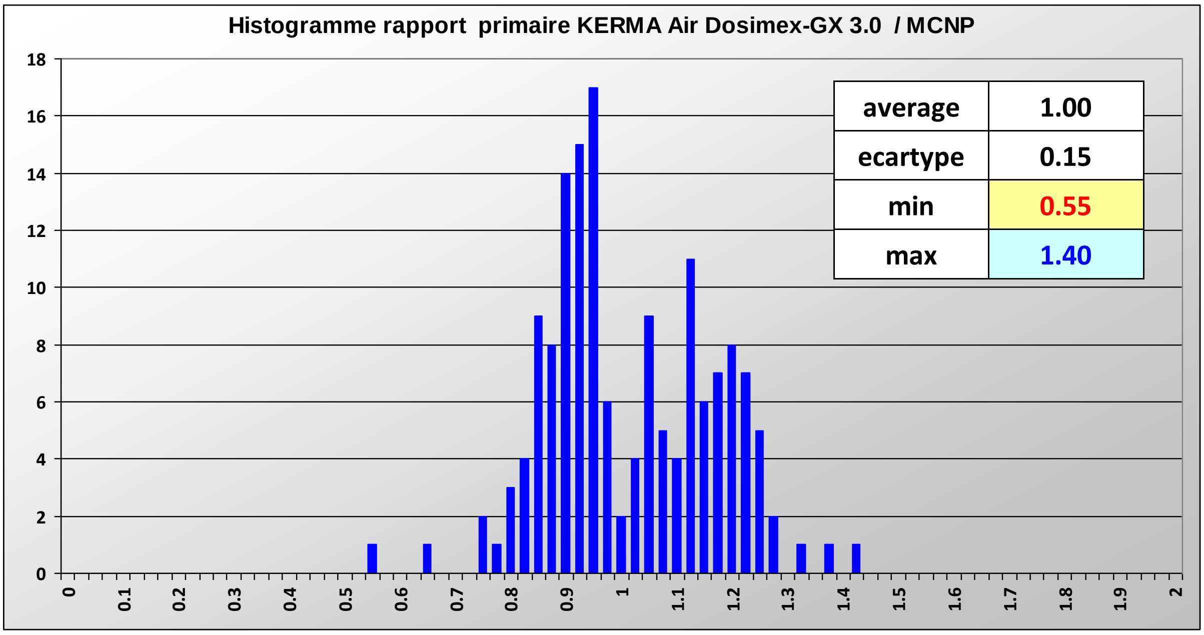




Conclusion: The mean square deviation on these 154 comparison points is equal to 15%

I.3.2 Analysis of DOSIMEX / MCNP reports in Kerma air

DOSIMEX-GX / MCNP performance report											
HT (kV)	None	0.2 mm Al	0.5 mm Al	1 mm Al	2 mm Al	3 mm Al	0.2 mm Cu	0.5 mm Cu	1 mm Cu	2 mm Cu	3 mm Cu
	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min	mSv / min
50	1.16	0.96	1.01	1.04	1.02	1.03	0.94	0.84	0.73	0.64	0.55
100	1.03	0.84	0.98	1.03	1.09	1.12	1.31	1.40	1.37	0.96	0.83
150	0.97	0.79	0.88	0.91	0.96	0.96	1.10	1.21	1.23	1.17	1.11
200	0.95	0.78	0.86	0.88	0.92	0.93	1.07	1.16	1.19	1.08	1.06
250	0.93	0.75	0.81	0.83	0.88	0.89	1.04	1.14	1.19	1.20	1.18
300	0.89	0.77	0.83	0.85	0.88	0.90	1.03	1.13	1.20	1.22	1.19
350	0.91	0.78	0.83	0.85	0.88	0.90	1.16	1.12	1.16	1.19	1.18
400	0.93	0.81	0.85	0.88	0.91	0.93	1.05	1.16	1.23	1.25	1.23
450	0.94	0.81	0.86	0.88	0.91	0.92	1.02	1.11	1.18	1.22	1.23
500	0.93	0.84	0.88	0.90	0.92	0.92	1.03	1.10	1.17	1.21	1.22
600	0.91	0.87	0.91	0.93	0.94	0.95	1.06	1.14	1.20	1.25	1.26
700	0.87	0.85	0.87	0.88	0.88	0.90	0.98	1.04	1.08	1.11	1.13
800	0.84	0.89	0.91	0.92	0.93	0.94	1.01	1.07	1.11	1.12	1.12
900	0.93	0.92	0.94	0.95	0.95	0.95	1.03	1.08	1.12	1.15	1.15



The average algebraic deviation for these 154 values is equal to 1%, and the average absolute deviation to 15%.

As before, we note that the maximum differences are appear with filtration in copper.

I- 4 : COMPARISONS OF YIELDS FOR ANODES OTHER THAN TUNGSTEN:

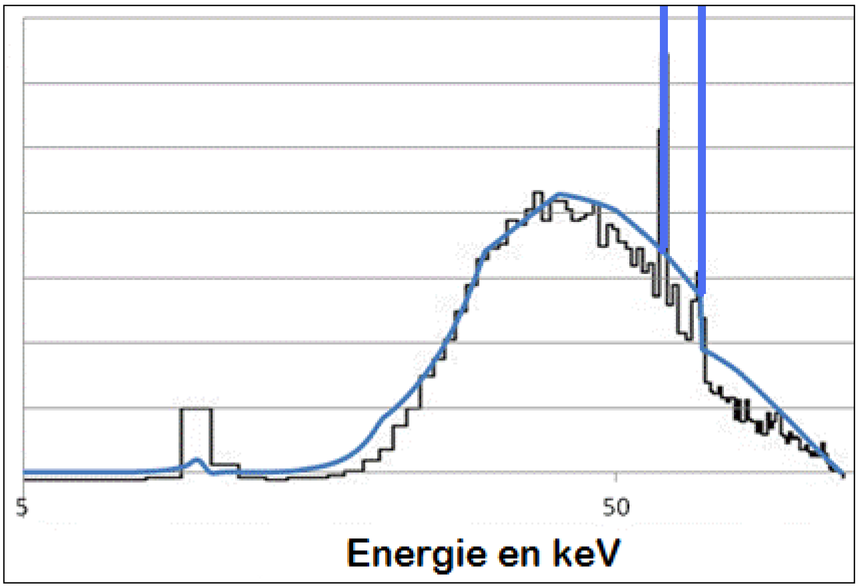
H * (10) at 50 kV without filtration	Dosimex (mGy.m2 / min / mA)	MCNP (mGy.m2 / min / mA)
W	12.23	10
Mo	11.26	13
Rh	11.88	12
Cu	5.9	4.6

For Kerma we have in theory K (Cu) / K (W) = 0.4 and K (Mo) / K (W) = 0.8 between 50 and 200kV.
For Dosimex we have:

	W	Mo	Cu	MB / W (0.8)	Cu / W (0.4)
K at 50kV without filtration	175.6	145.53	111	0.83	0.63
150kV without filtration	220	154	109	0.70	0.50
200kV without filtration	223	152	105	0.68	0.47

I- 5 : COMPARATIVE SPECTER

Tests were carried out to confirm the spectral correspondence of the results obtained with DOSIMEX-GX. The spectrum below (*smoothed blue line*) was obtained for a simulation of 120kV X spectrum without filtration and was confronted with an MCNP result (discretized black spectrum) produced by Laurent Bourgois.



The X-ray fluorescence peaks of the tungsten constituting the anode appear larger on the Dosimex-GX spectrum than on the MCNP spectrum. This effect is only an artifact generated by different numerical discretization between these two codes.

Partie II. DIFFUSE RADIATION VALIDATION

II- 1 : GENERAL CONTEXT OF VALIDATION WITH CEA-R 6452 REPORT

The reference values used for the flow equivalent dose rates are taken from the report CEA-R 6452:

"Monte-Carlo calculation evaluation of the diffusion factors in terms of dose equivalent of radiation from an X generator ..."
(Laurent Bourgois, Stéphanie Ménard, 2017)

This report (link) is based on more than 4000 calculations made with MCNP of diffusion on a screen, for various materials, filtration and angles of diffusion!

*For each configuration, the report gives a "diffusion factor α" which is directly calculated, in version 2.2, in terms of H * (10), thus allowing rapid verification for users.*

This diffusion factor is part of a particular model found in the NFC 15-160 standard and which is included in the CEA-R report.

This simplified model requires a prior discussion set out below

*In the report, it is also calculated in terms of the kerma air ratio, but also the dose equivalent H * (10).*

It is in this last quantity that it is calculated in Dosimex

CEA-R-6452

ISSN 0429 - 3460

COMMISSARIAT À L'ÉNERGIE ATOMIQUE ET AUX ÉNERGIES ALTERNATIVES

ÉVALUATION PAR CALCUL MONTE-CARLO DES FACTEURS DE DIFFUSION EN TERMES D'ÉQUIVALENT DE DOSE, DES RAYONNEMENTS ISSUS D'UN GÉNÉRATEUR X, POUR LE CALCUL DES ÉQUIVALENTS DE DOSE SECONDAIRES. CONSTITUTION D'UNE BASE DE DONNÉES.

par

Laurent BOURGOIS
Stéphanie MÉNARD

CEA / DAM ILE DE FRANCE

DIRECTION DES APPLICATIONS MILITAIRES

2017

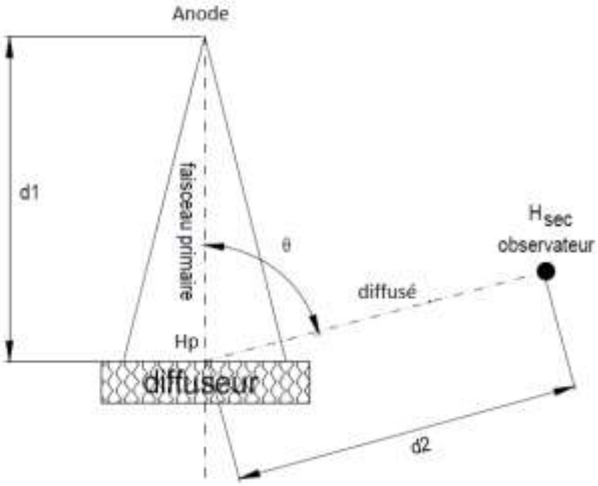
DIRECTION DES SYSTÈMES D'INFORMATION

CEA / SACLAY 91191 GIF-SUR-YVETTE CEDEX FRANCE

RAPPORT CEA-R-6452

II- 2 : SIMPLIFIED DIFFUSION MODEL VS NF C 15-160

For the calculation of the diffusion, the CEA-R 6452 report uses the following diagram proposed in the NFC 15-160 standard:



This diagram is accompanied by a simplified model which can take the form:

$$\dot{H}_S = \frac{\Gamma_R k}{d_1^2 d_2^2} \quad (1)$$

In this model, the quantity $\frac{\Gamma_R}{d_1^2}$ represents the dose equivalent rate $\dot{H}_p$ generated by the primary beam at the entry surface of the screen at the distance d_1, with Γ_R normalized "yield" at a distance of 1 m but above all expressed as it should be in Sv.m2.

The postman k then defines itself as $k = \frac{\dot{H}_S d_2^2}{\dot{H}_p}$ (2)

Equation (1) then shows that the dimension of k is in m2. On the other hand, it has the advantage of not depending on d_2. Indeed, in the case where the calculation distances are large enough to be able to consider the screen as a secondary point source of scattered radiation, the quantity $\dot{H}_S d_2^2$ can be understood as the dose rate at a unit distance of 1 m, taking into account the valid relationship with a point source:

$$\dot{H}_S(d_2) = \frac{\dot{H}_S(1m)}{d_2^2} \quad (3)$$

Note: on the dimensional plane the relation (3) must be understood as $\frac{\dot{H}_S(d_2)}{1(m^2)} = \frac{\dot{H}_S(1m)}{d_2^2}$.

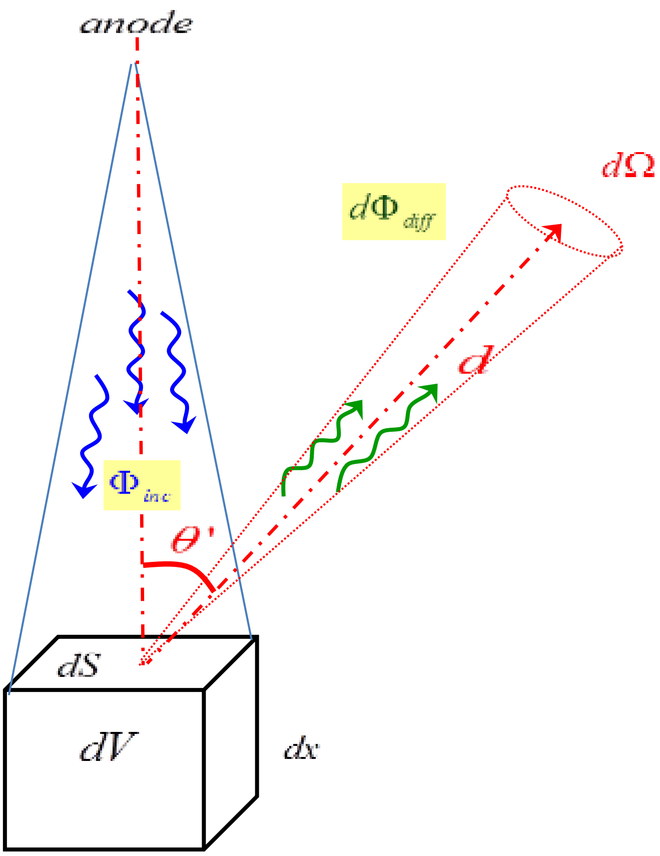
In this acceptance we understand then that k is written $k = \frac{\dot{H}_S d_2^2}{\dot{H}_p} = \frac{\dot{H}_S(1m) \times 1m^2}{\dot{H}_p}$ where we find the dimension of k in m2 but also and above all the fact that in the acceptance of a point model, k is independent of d_2.

Note: the point model (1) implies that the dimensions of the target are small compared to the distance d_2. If this condition is not respected, then the model (1) becomes unsuitable because it does not take into account geometric effects due, for example, to the lateral dimensions of the target, or even to its particular shape.

In Dosimex, as well as in MCNP, the calculation takes into account the dimensions of the target - surface and thickness - considered as a cylinder. So, strictly speaking, k depends (second order) on d_2 and this effect can be noticeable at short distances. The point aspect can be accepted for a distance $d_2 = 1m$ and an illuminated surface of 200 cm2, which corresponds to a disc of 8 cmradius. These are the parameters used for calculations under MCNP and taken up with Dosimex as part of this validation. We will come back to the thickness of the target later which can also influence the result.

II- 3 : Method implemented by DOSIMEX-GX 3.0 for the calculation of the scattered radiation.

II.3.1 Schematic diagram: diffusion in a volume element.



The dimensions of the target being small compared to the average free path, we can consider that the fluence is homogeneous in the target volume of elementary volume $dV = dx\, dS$. Under these conditions, we can show that the number of photons scattered throughout the space is equal to:

$$dN_{diff.} = \mu_{Compt.} \Phi_{inc.} dV \quad (1)$$

With $\mu_{Compt.}$ the Compton linear attenuation coefficient of the material for the energy of incident photons still equal to $\mu_{Compt.} = n\sigma_{Compt.}$ with:

- n : the density of the target in number of nucleus
- $\sigma_{Compt.}$: the Compton cross section (ie all angles combined)

If the scattering was isotropic, the fluence scattered by this target element at a distance d would be equal to:

$$d\Phi_{diff} = \frac{dN_{diff.}}{4\pi d^2} = n\frac{\sigma_{Compt.}}{4\pi d^2}\Phi_{inc.} dV = n\frac{\sigma_{Compt.}}{4\pi}\Phi_{inc.} dV d\Omega \quad (2a)$$

Or again, taking into account that $\frac{1}{d^2}$ equals the solid corner element $d\Omega$ (for a pseudo-dosimeter of 1 cm2):

$$d\Phi_{diff} = n\frac{\sigma_{Compt.}}{4\pi}\Phi_{inc.} dV d\Omega \quad (2b)$$

By taking into account the non-isotropic character of the Compton scattering through the differential cross section of Klein and Nishina, which is a function of the scattering angle and the energy of the photons, we can write:

$$\frac{d\sigma_{e-,Compt.}}{d\Omega}(\theta)=\frac{1}{2}\,r_0^2\,\frac{1+\cos^2\theta}{\left(1+\alpha(1-\cos\theta)\right)^2}\left[1+\frac{\alpha^2(1-\cos\theta)^2}{(1+\cos^2\theta)(1+\alpha(1-\cos\theta))}\right]\quad \text{with } \alpha=\frac{E_\gamma}{m_e c^2}$$

The relation (2b) then becomes:

$$d\Phi_{diff}(\theta)=n\frac{d\sigma_{e-,Compt.}}{d\Omega}(\theta)\Phi_{inc.}d\Omega dV=n\frac{d\sigma_{e-,Compt.}}{d\Omega}(\theta)\Phi_{inc.}d\Omega dx\, dS \quad (3)$$

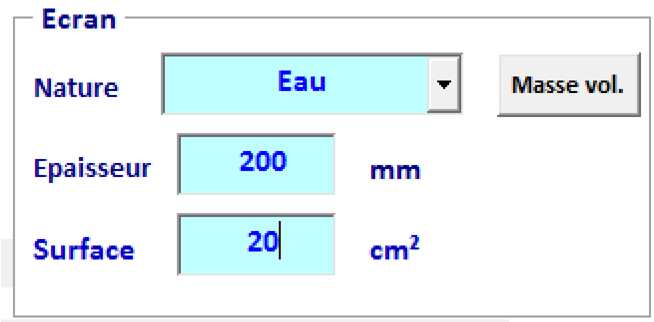
Note: compared to the block diagram above, the angle θ considered in the above formula is equal to $\theta = 180° - \theta'$

The complete calculation of the scattered radiation for a large target (several average free paths) is done by integrating this relationship on all the energies of the X spectrum but especially on the entire surface of the target and all the depth, taking into account the absorption of the incident beam and of the self-absorption of the scattered radiation.

This relation shows, for fairly large distances in front of the dimensions of the target, that the incident fluence is, among other things, proportional to the irradiated surface S of the target.

The DOSIMEX-GX 3.0 Code implements this model, as well as a similar model to take into account X-ray fluorescence, to calculate the energy spectrum and the diffused fluence at a given angle and distance as a function:

- The nature of the target
- Of its thickness
- From its surface



In this context, we can then write as a first approximation $k = \alpha S$, with $\alpha = k/S$ a factor no longer dependent (on the 1st order) on the surface. It is this coefficient α which is introduced and calculated in the CEA-R 6452 report

II.3.2 SEARCH FOR RELEVANT DISSEMINATION FACTORS

If one seeks to establish a fundamental "diffusion factor", one could write, forgetting for the moment the concept of dose, the following elementary relation for a diffusing center:

$$E_{diff} = k' E_{inc}$$

The scattered energy, implied in a given direction, is proportional to the energy incident on the diffuser. It is at this level that we understand that the distance d_1 is not, either, a relevant parameter of the diffusion problem: it does not matter where the energy comes from E_{inc} ! And for the moment we don't care about the distance either d_2

The coefficient k' thus defined is then a pure dimensionless "energy diffusion yield" and better still "universal" (ie independent of distances, but of course dependent on the energies of photons, the nature of the material, its volume, etc.)

To reintroduce the concept of dose while retaining such independence, we can write:
$H_S(d_2) \times d_2^2 = k\ H_p$, equation analogous to equation (1), where we see again that the dimension of k is in m2.

To keep a dimensionless report, we calculate in Dosimex the dimensionless quantity $\dfrac{H_S(d_2)}{H_p(\text{écran})}$, called here "dose diffusion yield" and noted ε_{diff}, with reference to the notation used for the detection yields (effectiveness).

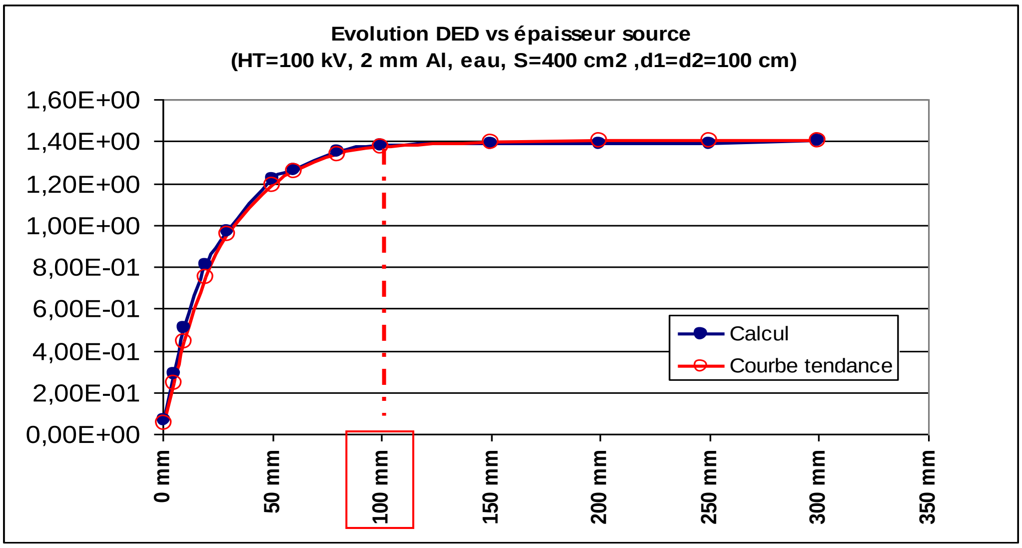
We can thus define 3 diffusion “indicators” implemented in Dosimex:

- ε_{diff} : the dimensionless dose diffusion efficiency, depending on the distance d_2 and the surface of the screen.
- $k = \varepsilon_{diff}\ d_2^2$: the diffusion factor in m^2, independent of d_2 but proportional (1st order) to the screen area. This is the quantity that is used in the NFC 15-160 standard (but applied to kerma air)
- $\alpha = k/S = \varepsilon_{diff} / S\, d_2^2$, the standardized diffusion factor (implied reduced to the unit of surface), without dimension, independent of the surface and the distance d_2. This is the coefficient used in the CEA-R 6452 report and used in the context of validation, subject to saturation.

II.3.3 IMPACT OF TARGET THICKNESS AND SEARCH FOR A SATURATION THICKNESS

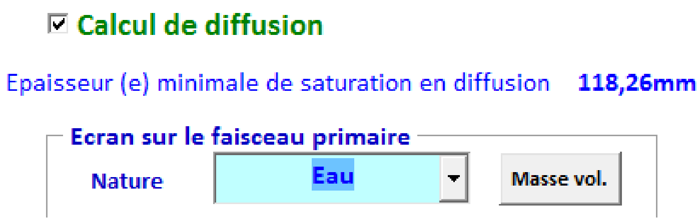
The 3 factors thus defined, and in particular α, depend on the thickness of the target until a saturation thickness is reached. A small study will allow us to define a parameter ensuring the operator that the saturation conditions are reached or not. This study is conducted with a water diffuser for a given HT

When the thickness of the target is gradually increased, a typically exponential saturation curve is obtained. For an HT of 100 kV the coefficient of the exponential, assimilated to a coefficient μ of linear attenuation, then corresponding to a mean free path (lpm) of2.6 cm
With 3 lpm we are at 5% of saturation, a minimum thickness for this assumption of 8 cm about



In water we get a lpm of 2.6 cmfor an energy of 28 keV, or about 1/3 of the max energy. By taking a thickness of10 cm approximately we can consider that saturation is reached, more or less.

A similar study with lead gives a similar result: the attenuation curve corresponds to an average free path of 0.045mmobtained in lead with an energy of 33 keV, again close to 1/3 of the max energy. We can thus easily calculate and offer the user a saturation indicator of the order of magnitude of 3.5 lpm (as a precaution), with an lpm calculated at 1/3 of the maximum energy.
In Dosimex GX 2.2, when choosing a diffusing medium, the code directly calculates the value of 3.5 lpm in the chosen medium for an energy equal to one third of the HT.



Thus for a HV of 800 kV it would be necessary to take at least 32 cm of water and 3 mm of Pb to be close to saturation to within 5%

II- 4 : DOSIMEX VS MCNP DIFFUSION CALCULATIONS

II.4.1 THE CASES STUDIED

- **Cases 1 to 5** : Water, TNT, Concrete, Iron and Lead materials at 45 ° for all 10 HT offered (50, 70, 120, 150, 200, 300, 400, 500, 600, 800 kV) with filtration of2 mm of Al and 1 mm beryllium and an irradiated surface of 200 cm2 (same as MCNP).

- **Case 6**: Idem case 1 for Idem material with an angle of incidence of 60%

- **Case 7**: Same as case 1 for water material with an angle of incidence of 10%

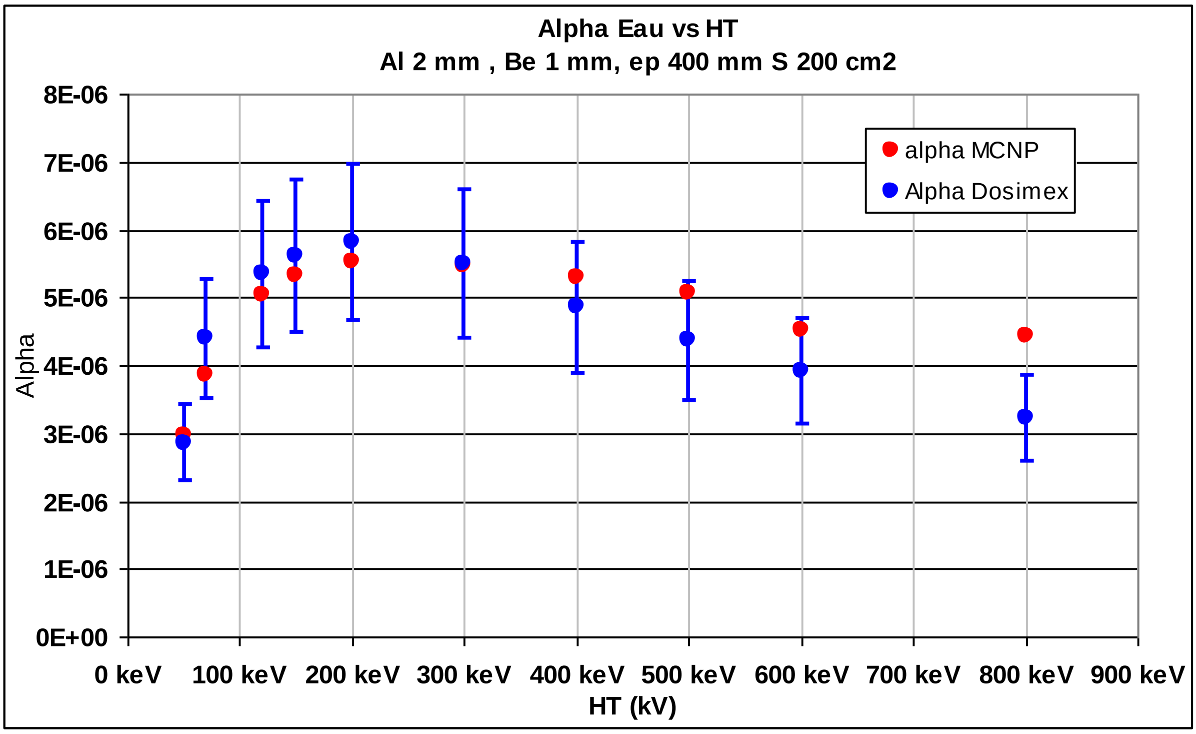
- **Case 8** : Same as case 1 for water material with 3 mm of Al instead of 2 mm

- **Case 9**: water material, HT 50 keV, 45 ° angle with1 mm of Be for thicknesses of Al from 1 to 6 mm

- **Case 10**: lead material,1 mm Be + 2 mm Al, HT = 50kV, for angles from 10 ° to 90 ° (85 ° for Dosimex)

- **Case 11** : Water material 1 mm Be + 2 mm Al for angles from 10 ° to 90 ° (85 ° for Dosimex)

CASE 1: WATER, 45 ° FILTRATION 2 MM AL + 1 MM BE, S = 200 CM2VS HT

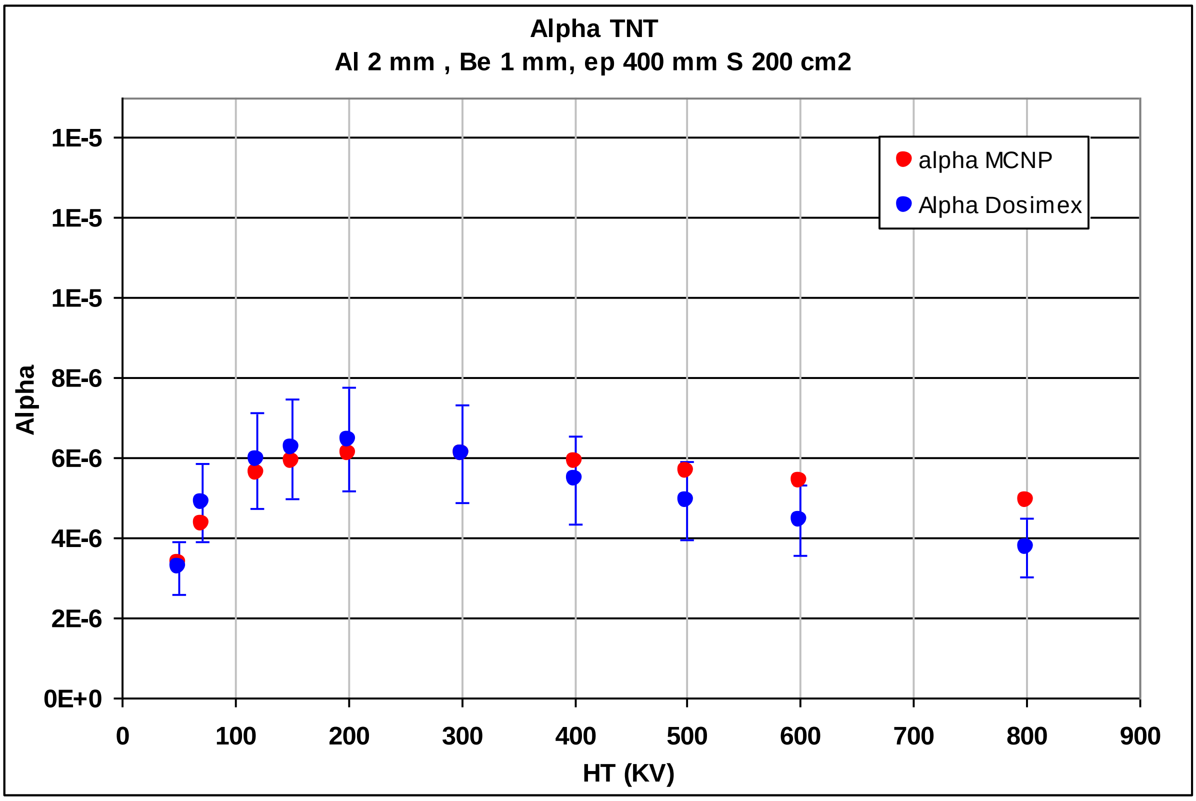


Error bars (+/- 20%) frame the Dosimex values

voltage	α MCNP	α Dosimex	Relative gap
50 keV	2.97E-06	2.86E-06	-4%
70 keV	3.87E-06	4.39E-06	13%
120 keV	5.04E-06	5.34E-06	6%
150 keV	5.31E-06	5.62E-06	6%
200 keV	5.52E-06	5.81E-06	5%
300 keV	5.48E-06	5.49E-06	0%
400 keV	5.30E-06	4.85E-06	-8%
500 keV	5.07E-06	4.36E-06	-14%
600 keV	4.51E-06	3.92E-06	-13%
800 keV	4.42E-06	3.22E-06	-27%
	Mean square deviation		**12%**

Partial conclusion for water : we note a good adequacy between the 2 models, with a good reproduction of the variation of the coefficients alpha vs HT.

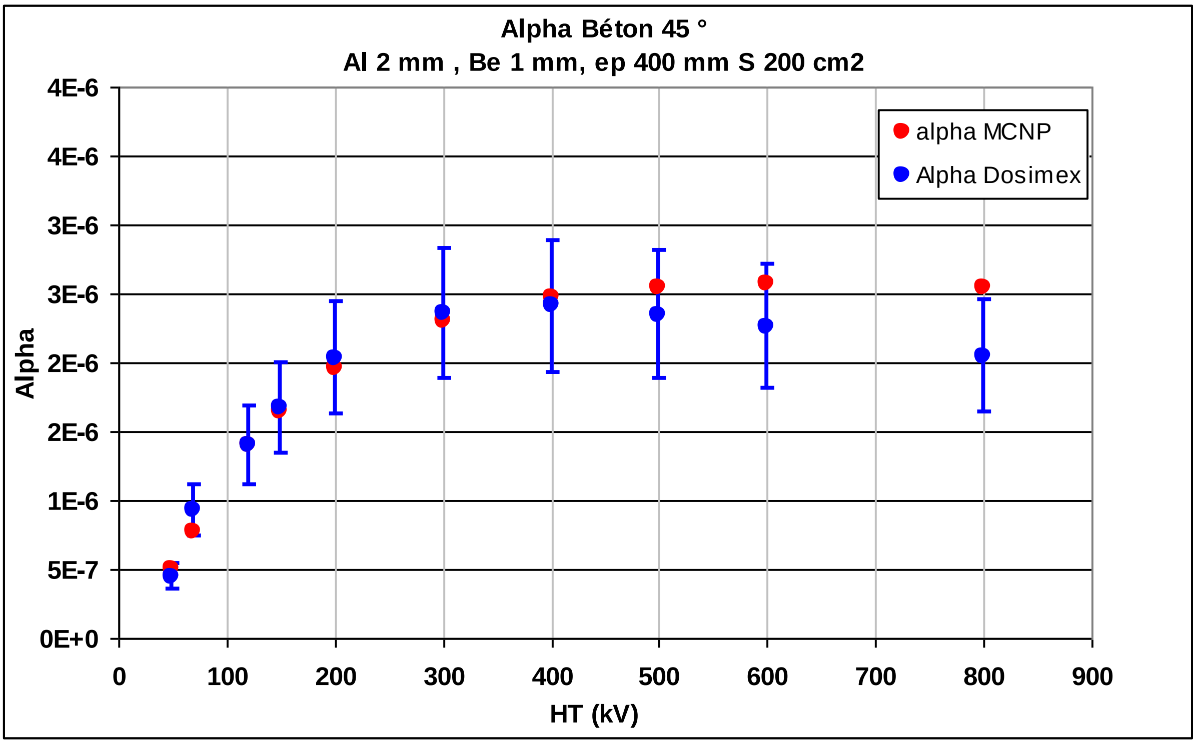
Case 2: TNT, 45 ° filtration 2 mm Al + 1 mm Be, S = 200 cm2vs HT



	voltage	α MCNP	α Dosimex	Relative gap
3.79E-06	50	3.37E-06	3.25E-06	-4%
4.76E-06	70	4.36E-06	4.89E-06	12%
5.03E-06	120	5.63E-06	5.94E-06	6%
4.99E-06	150	5.92E-06	6.25E-06	6%
4.73E-06	200	6.13E-06	6.46E-06	5%
4.08E-06	300	6.12E-06	6.12E-06	0%
3.51E-06	400	5.90E-06	5.45E-06	-8%
3.06E-06	500	5.65E-06	4.92E-06	-13%
2.71E-06	600	5.40E-06	4.45E-06	-18%
2.21E-06	800	4.92E-06	3.76E-06	-24%
		Mean square deviation		**12%**

Partial conclusion for TNT : same as previous case

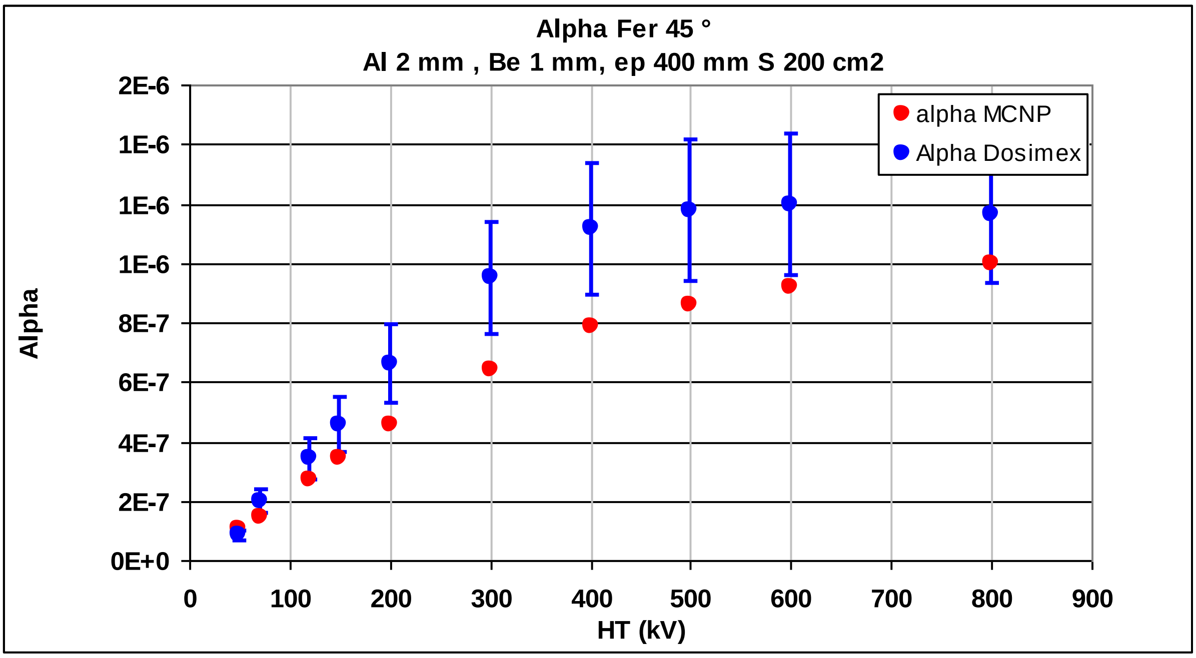
CASE 3: CONCRETE, 45 ° FILTRATION 2 MM AL + 1 MM BE, S = 200 CM2VS HT



voltage	α MCNP	α Dosimex	Relative gap
50	5.04E-07	4.50E-07	-11%
70	7.71E-07	9.27E-07	20%
120	1.40E-06	1.40E-06	0%
150	1.65E-06	1.67E-06	1%
200	1.96E-06	2.03E-06	4%
300	2.30E-06	2.36E-06	3%
400	2.47E-06	2.41E-06	-2%
500	2.54E-06	2.35E-06	-7%
600	2.57E-06	2.26E-06	-12%
800	2.55E-06	2.05E-06	-20%
	Mean square deviation		**11%**

Partial conclusion for concrete: here again we find a good match between the two codes. Concrete is referenced for Taylor build-ups

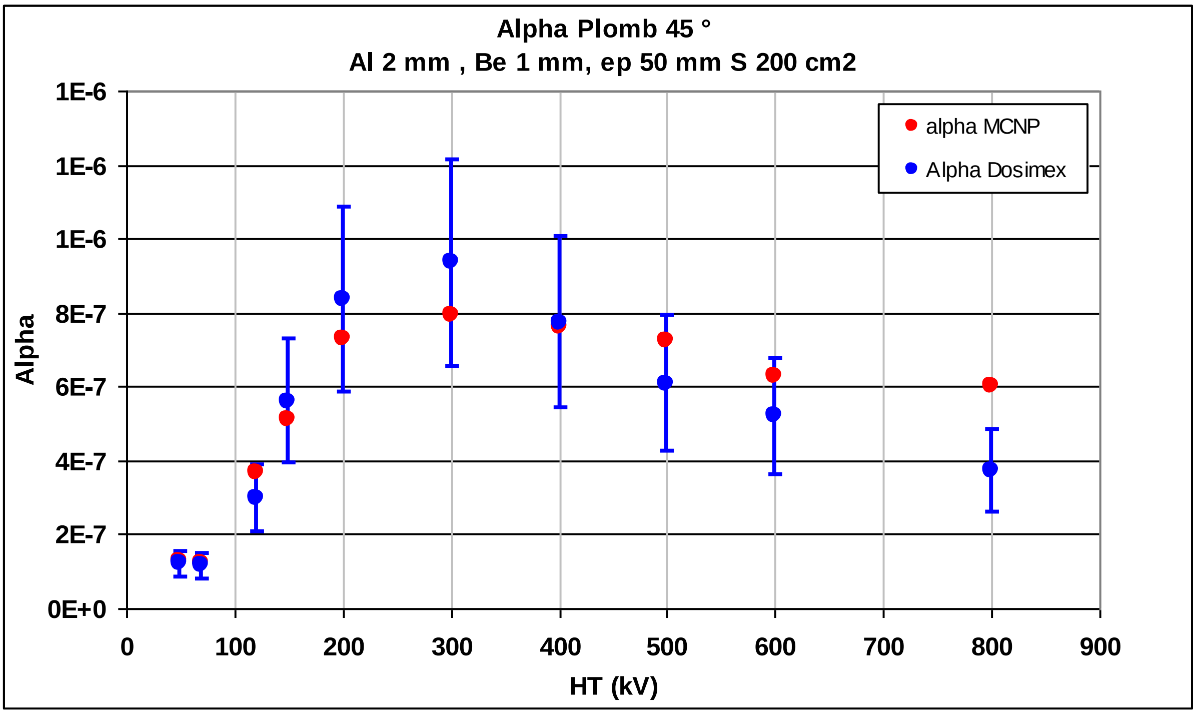
CASE 4: IRON, 45 ° FILTRATION 2 MM AL + 1 MM BE, S = 200 CM2VS HT



voltage	α MCNP	α Dosimex	Relative gap
50	1.08E-07	8.48E-08	-21%
70	1.48E-07	1.96E-07	32%
120	2.70E-07	3.42E-07	27%
150	3.43E-07	4.58E-07	34%
200	4.56E-07	6.63E-07	45%
300	6.43E-07	9.50E-07	48%
400	7.87E-07	1.11E-06	42%
500	8.59E-07	1.18E-06	37%
600	9.22E-07	1.20E-06	30%
800	1.00E-06	1.17E-06	17%
		medium difference	29%

Partial conclusion for iron : there is a slight overestimation for diffusion in iron, while remaining significantly in the order of magnitude

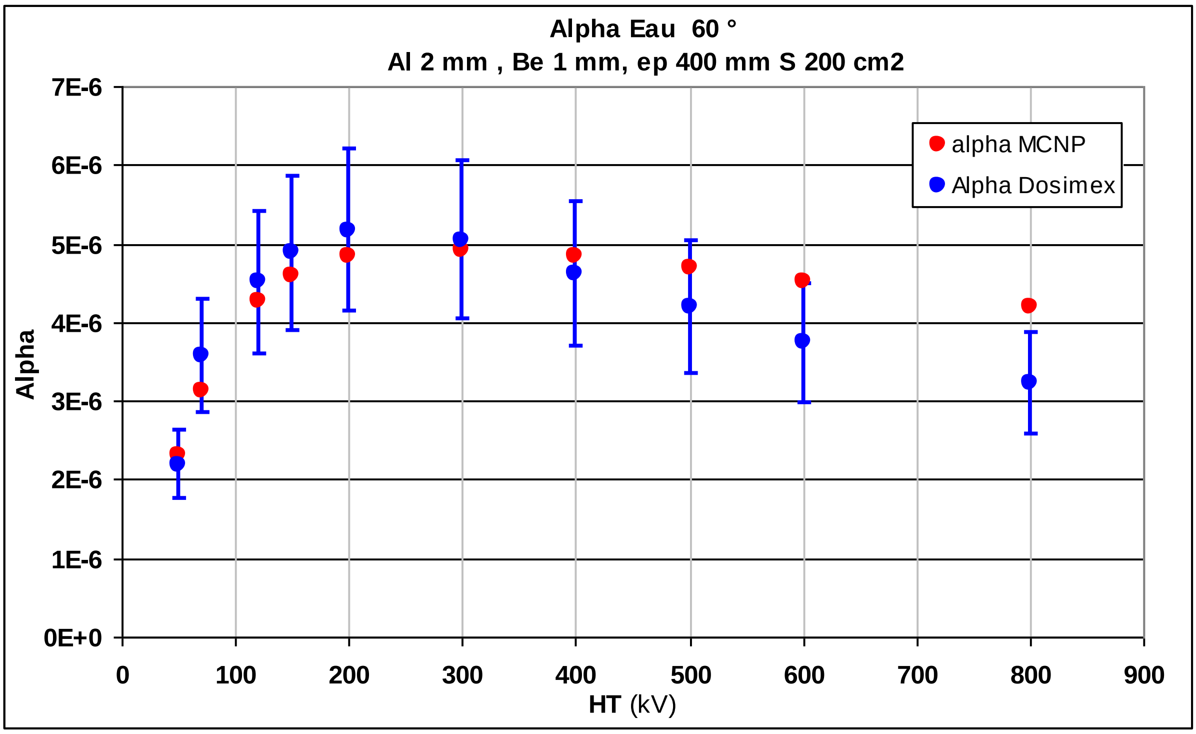
CASE 5: LEAD, 45 ° FILTRATION 2 MM AL + 1 MM BE, S = 200 CM2VS HT



voltage	α MCNP	α Dosimex	Relative gap
50	1.27E-07	1.23E-07	-3%
70	1.25E-07	1.20E-07	-4%
120	3.67E-07	3.14E-07	-14%
150	5.12E-07	5.88E-07	15%
200	7.29E-07	8.76E-07	20%
300	7.92E-07	9.82E-07	24%
400	7.63E-07	8.12E-07	6%
500	7.23E-07	6.39E-07	-12%
600	6.28E-07	5.47E-07	-13%
800	6.01E-07	3.93E-07	-35%
	Mean square deviation		17%

Partial conclusion on lead: there is an excellent match between the 2 codes. Note that the calculation of diffusion in lead required the implementation in Dosimex-GX 3.0 of the X-ray fluorescence mechanism, an essential component of diffusion in such materials (high Z), especially at these relatively low energies.

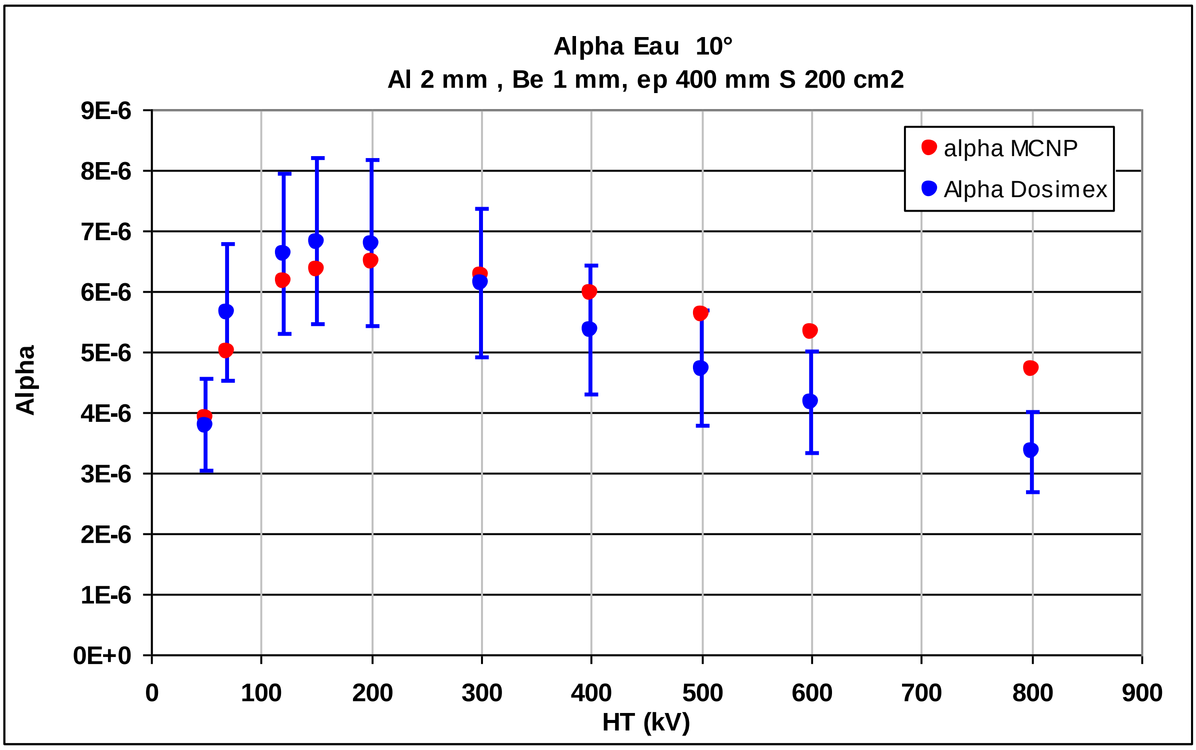
CASE 6: WATER, 60 °, FILTRATION 2 MM AL + 1 MM BE, S = 200 CM2VS HT



voltage	α MCNP	α Dosimex	Relative gap
50	2.32E-06	2.19E-06	-6%
70	3.13E-06	3.57E-06	14%
120	4.28E-06	4.51E-06	5%
150	4.58E-06	4.88E-06	7%
200	4.83E-06	5.17E-06	7%
300	4.91E-06	5.05E-06	3%
400	4.84E-06	4.61E-06	-5%
500	4.68E-06	4.19E-06	-10%
600	4.51E-06	3.74E-06	-17%
800	4.19E-06	3.22E-06	-23%
	Mean square deviation		**11%**

Partial conclusion: oagain finds with water an excellent match with always a slight dropout for high values of HT

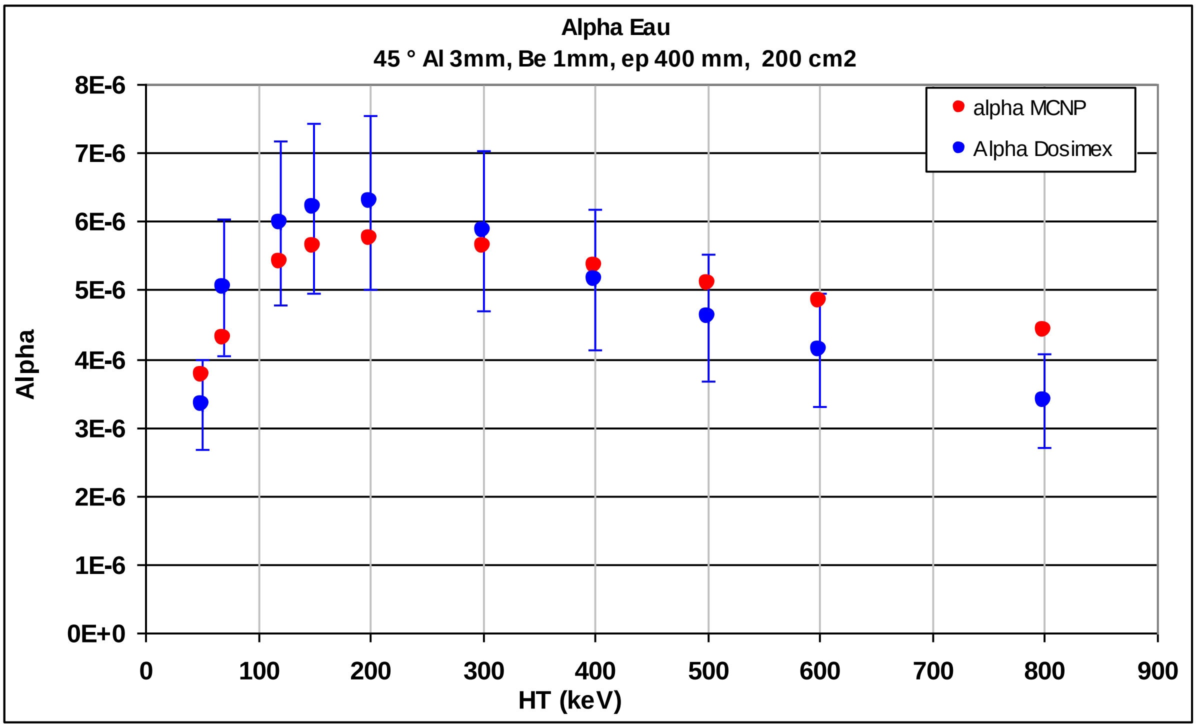
CASE 7: WATER, 10 °, FILTRATION 2 MM AL + 1 MM BE, S = 200 CM2VS HT



voltage	α MCNP	α Dosimex	Relative gap
50	3.89E-06	3.78E-06	-3%
70	4.99E-06	5.64E-06	13%
120	6.15E-06	6.61E-06	7%
150	6.36E-06	6.82E-06	7%
200	6.47E-06	6.79E-06	5%
300	6.27E-06	6.14E-06	-2%
400	5.96E-06	5.36E-06	-10%
500	5.62E-06	4.72E-06	-16%
600	5.31E-06	4.17E-06	-21%
800	4.70E-06	3.34E-06	-29%
	Mean square deviation		**14%**

Partial conclusion :ditto previous case.

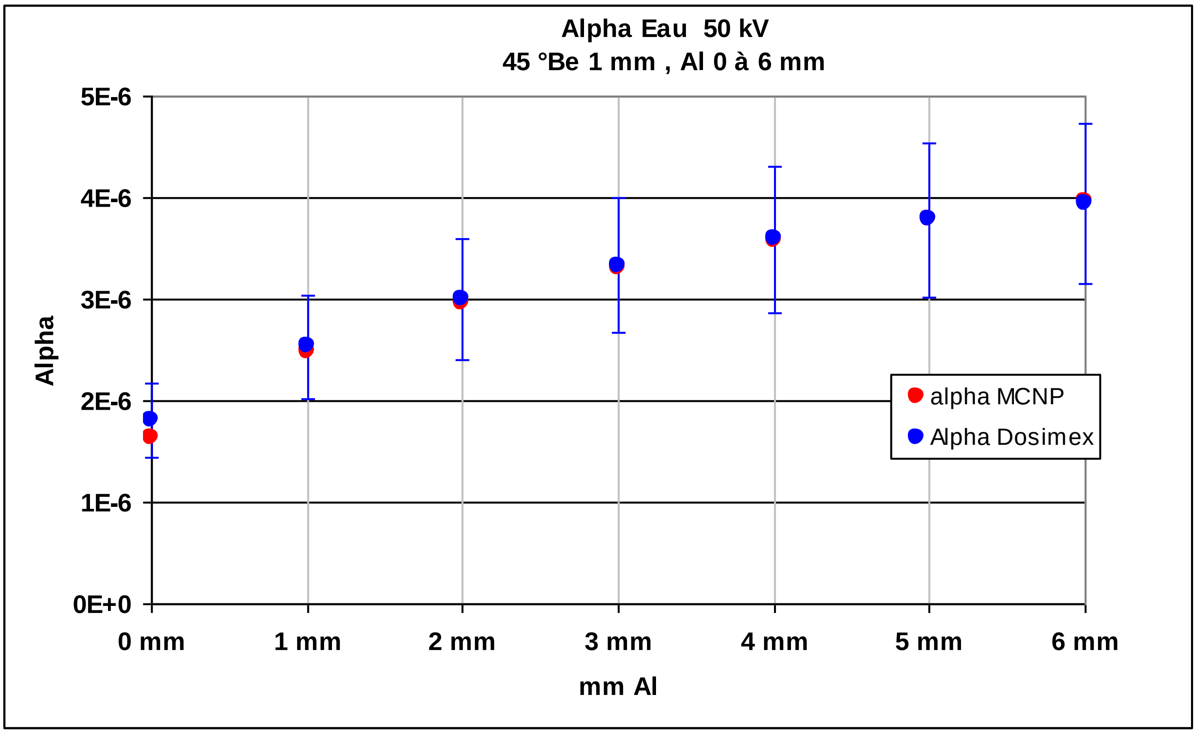
CASE 8: WATER, 45 °, FILTRATION 3 MM AL + 1 MM BE, S = 200 CM2VS



voltage	α MCNP	α Dosimex	Relative gap
50	3.76E-06	3.33E-06	-11%
70	4.29E-06	5.04E-06	17%
120	5.40E-06	5.97E-06	11%
150	5.64E-06	6.20E-06	10%
200	5.76E-06	6.28E-06	9%
300	5.63E-06	5.86E-06	4%
400	5.36E-06	5.16E-06	-4%
500	5.10E-06	4.60E-06	-10%
600	4.85E-06	4.13E-06	-15%
800	4.40E-06	3.39E-06	-23%
	Mean square deviation		13%

Partial conclusion :ditto previous case.

Case 9: water material, HT 50 keV, 45 ° angle with 1 mm from Be for Al thicknesses of 0 to 6 mm

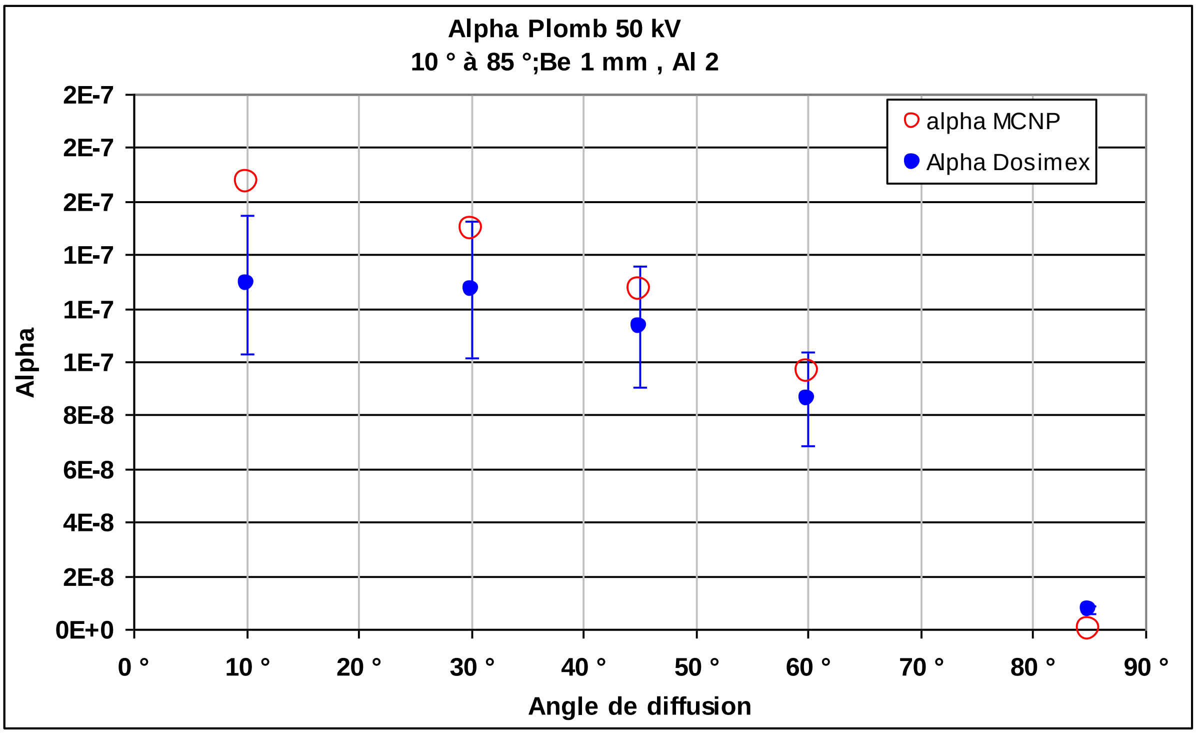


Al	α MCNP	α Dosimex	Relative gap
0	1.63E-06	1.81E-06	11%
1	2.49E-06	2.53E-06	2%
2	2.97E-06	3.00E-06	1%
3	3.31E-06	3.33E-06	1%
4	3.58E-06	3.59E-06	0%
5	3.79E-06	3.78E-06	0%
6	3.97E-06	3.94E-06	-1%
	Mean square deviation		4%

Partial conclusion :good results are obtained depending on the filtering. We can note a ratio equal to 2.4 between the absence of Aluminum and a filtration of6 mm of aluminum, which shows the sensitivity of the results as a function of the incident spectrum, well reproduced by Dosimex.

CASE 10: LEAD MATERIAL, HT = 50 KV,1 MM BE + 2 MM AL FOR ANGLES FROM 10 ° TO 85°

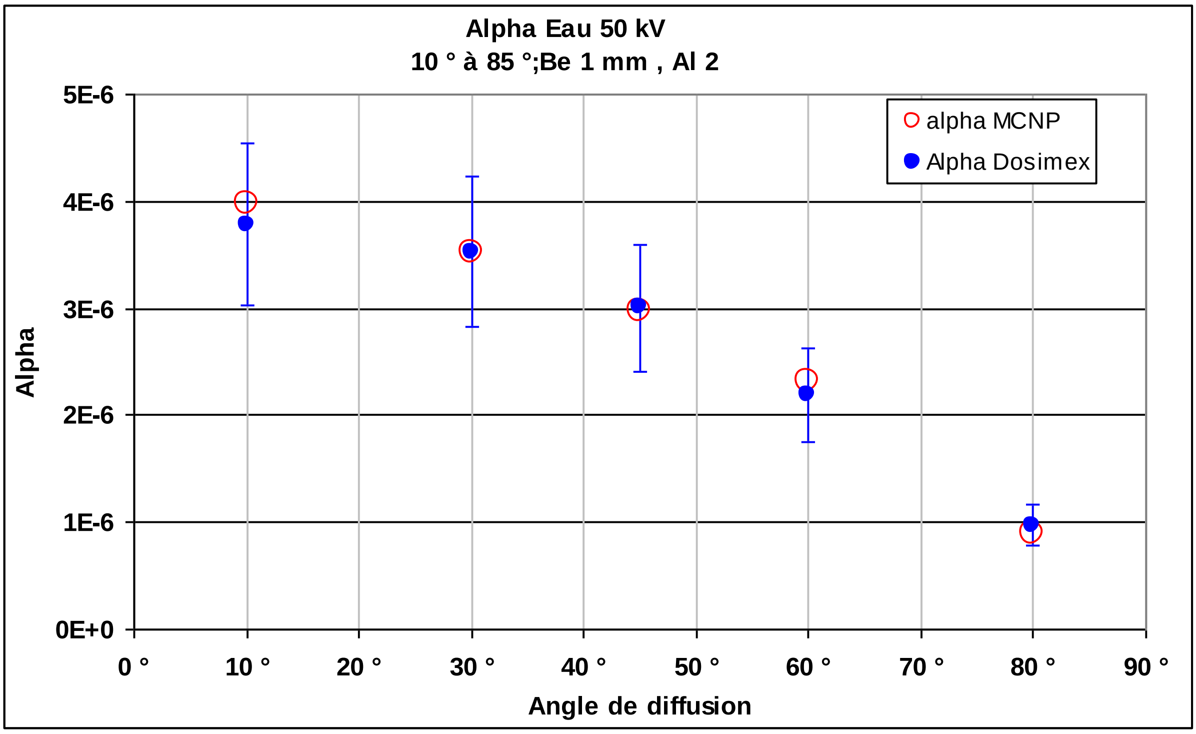
Note: with Dosimex the maximum angle was taken at 85 ° and not 90 °, see § 1.5



Angle	α MCNP	α Dosimex	Relative gap
10 °	1.67E-07	1.44E-07	-14%
30 °	1.50E-07	1.40E-07	-7%
45 °	1.27E-07	1.23E-07	-3%
60 °	9.66E-08	9.27E-08	-4%
85 °	0.00E + 00	7.77E-09	NC
	Mean square deviation		8%

Partial conclusion :the angular evolution is well reproduced, including for high angles. For lead, this is linked to the fact that the emerging component from the side is negligible (see §1.5).

Case 11: material Water, 1 mm Be + 2 mm Al, HT = 50 kV, for angles from 10 ° to 90 °



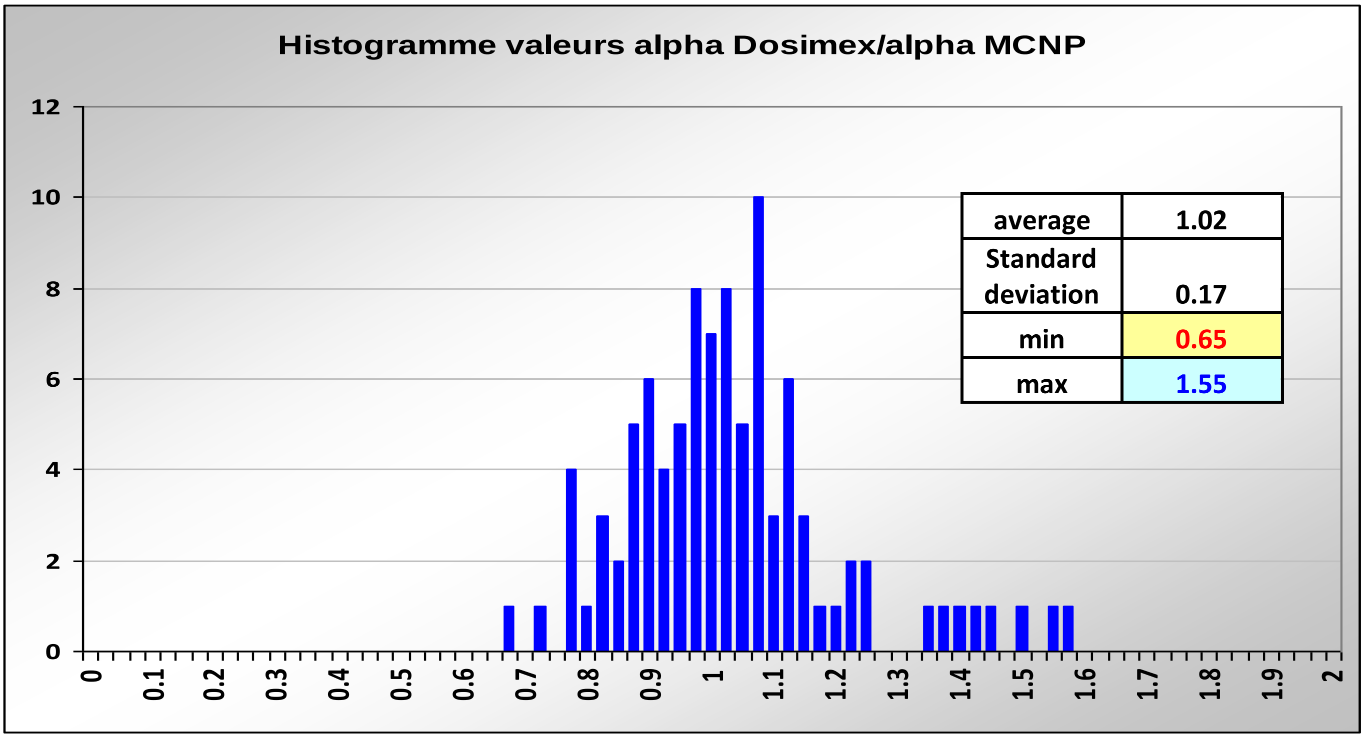
Angle	α MCNP	α Dosimex	Relative gap
10 °	3.98E-06	3.78E-06	-5%
30 °	3.52E-06	3.53E-06	0%
45 °	2.97E-06	3.00E-06	1%
60 °	2.32E-06	2.19E-06	-6%
80 °	8.89E-07	9.76E-07	10%
	Mean square deviation		6%

Partial conclusion :the angular evolution is well reproduced, including at high angles (90 ° for MCNP and 85 ° for Dosimex) where the relative difference is hardly more than 33%.

II.4.2 SUMMARY OF DOSIMEX / MCNP REPORTS FOR ALPHA COEFFICIENTS

For all the previous cases, i.e. 95 calculations of alpha coefficients, we obtain:

	Case 1 Water	Case 2 TNT	Case 3 Concrete	Case 4 Iron	Case 5 Lead	Case 6 Water	Case 7 Water	Case 8 Water	Case 9 Water	Case 10 Water	Case 11 Lead	
	1.01	0.96	0.89	0.82	0.99	0.94	0.97	0.89	1.11	0.86	0.95	
	1.19	1.12	1.2	1.39	0.96	1.14	1.13	1.17	1.02	0.93	1	
	1.11	1.06	1	1.33	0.86	1.05	1.07	1.11	1.01	0.97	1.01	
	1.11	1.06	1.01	1.4	1.15	1.07	1.07	1.1	1.01	0.96	0.94	
	1.11	1.05	1.04	1.53	1.2	1.07	1.05	1.09	1		1.1	
	1.05	1	1.03	1.55	1.24	1.03	0.98	1.04	1			
	0.97	0.92	0.98	1.49	1.06	0.95	0.9	0.96	0.99			
	0.91	0.87	0.93	1.44	0.88	0.9	0.84	0.9				
	0.92	0.82	0.88	1.36	0.87	0.83	0.79	0.85				
	0.77	0.76	0.8	1.23	0.65	0.77	0.71	0.77				Total
Average	1.02	0.96	0.976	1.354	0.986	0.975	0.951	0.988	1.02	0.93	1	1.02
Standard deviation	0.13	0.12	0.11	0.21	0.18	0.12	0.14	0.13	0.04	0.05	0.06	0.17



The average of the reports indicates an absence of systematic deviation for an average deviation of around 17%. all materials combined, and only 13% and 11% respectively with the water and concrete media, the most involved in diffusion (water for the patient and concrete for the walls)

For such a complex deterministic modeling (continuous spectrum, Compton scattering + X-ray fluorescence in a volume), such a result, compared to MCNP, again exceeds our expectations!

The highest negative difference is found with Lead for 800 kV and the highest positive difference with iron (see conclusion case 4).

II- 5 : VALIDATION VS DIFFUSION FACTOR STANDARD NFC 15-160 (2011)

The value of the scattered dose strongly depends on the distances, the nature and dimensions of the diffuser and the illuminated surface, as well as the nature of the filtration. The NFC 15-160 standard is based on diffusion coefficientsk(ratio of the average air kerma diffused to*1 m in air kerma at the level of the object lights up 1m away from the focus*) in terms of the HT.

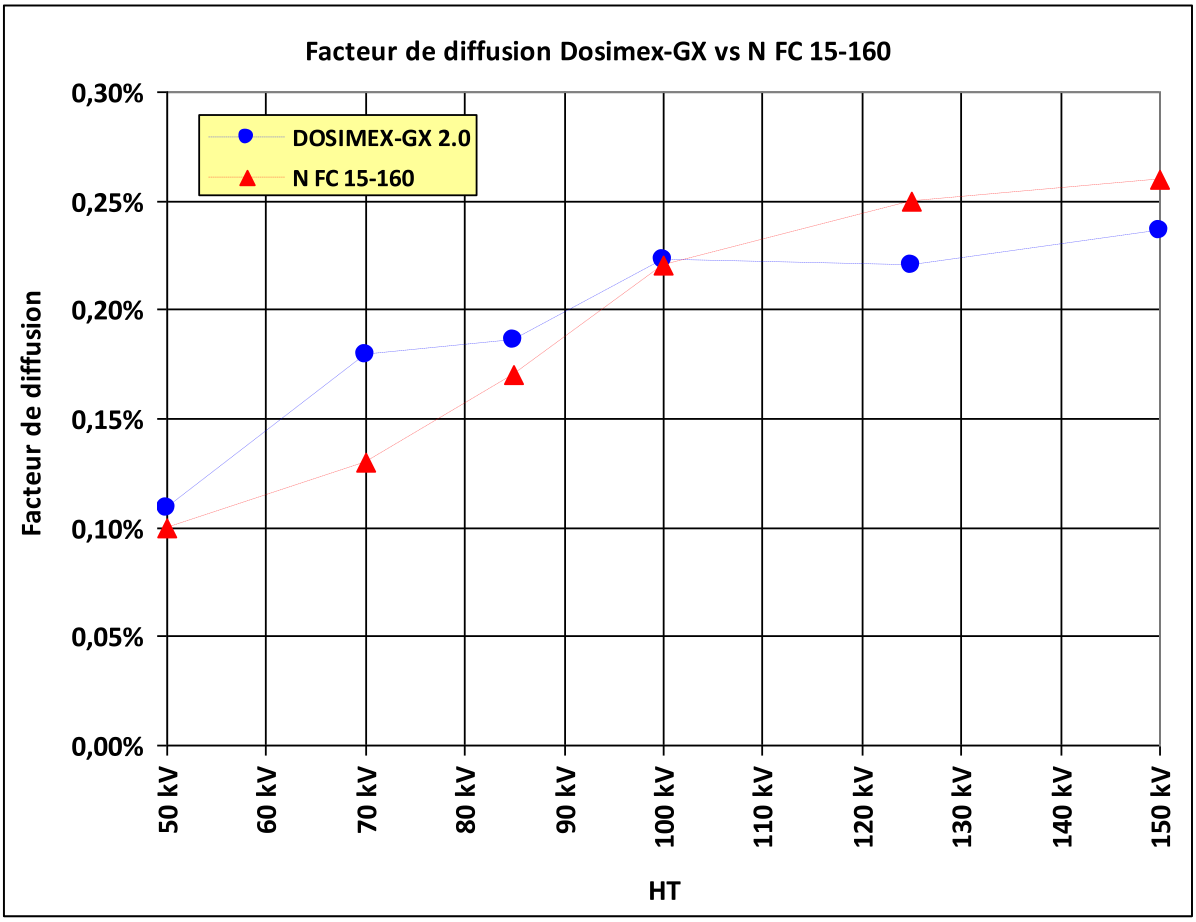
The nature, shape and dimensions of the diffusing object, the illuminated surface and the nature of the filtration are not specified.

Assuming that the diffusing medium is an individual and taking the following parameters:

- Middle screen: water (patient)
- Thickness 200 mm
- Illuminated area (field) of 300 cm2
- Filtration of 2 mm Aluminum
- 45 ° angle

The following values are obtained:

	Diffusion coefficient value k (m2)		
High voltage (kV)	**Dosimex-GX 2.0**	**NF C15-160 standard table 3a**	*Relative gap*
50	**0.109%**	**0.10%**	*9%*
70	**0.179%**	**0.13%**	*38%*
85	**0.186%**	**0.17%**	*9%*
100	**0.223%**	**0.22%**	*1%*
125	**0.220%**	**0.25%**	*-12%*
150	**0.236%**	**0.26%**	*-9%*



We obtain, for these few values given in NFC 15-160 (2011), an average algebraic deviation of 6% and an average absolute deviation of 13%.

These results are to be compared with all the results obtained previously.

Partie III. VALIDATION ATTENUATION BY A SCREEN

III- 1 : NOTES ON THE ATTENUATION FACTORS WITH A CONTINUOUS X SPECTRUM

The objective of this part is to compare the attenuation factors in lead screens of various thicknesses and for various HT proposed in standard NFC 15-160.

Several remarks are necessary here:

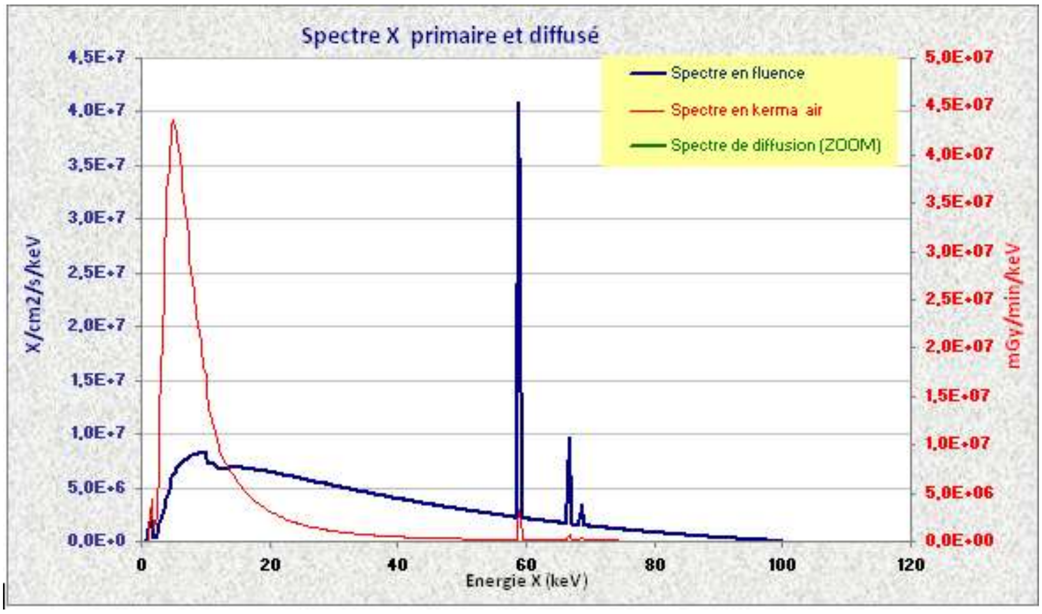
- **Note 1**: to be able to be compared with the values of the standard, these attenuation factors are calculated in terms of kerma air, and not in terms of H * (10) (or fluence). In Dosimex GX 2.2 the main dialog presents coefficients calculated in terms of H * (10).

- **Note 2**: The attenuation coefficients presented in the standard do not take account of the Build-up, which can easily go up to a factor of 2 in lead (120 kV,*2 mm from Pb*) at 15 in concrete (120 kV,*150 mm of concrete*), and which should therefore decrease the diffusion factor accordingly. They therefore correspond to the intrinsic attenuation factor excluding BU F_e^* defined in chapter I.2.2.C. These attenuation factors are tested here, but we must not forget that they are more or less overestimated (and therefore the underestimated speeds behind the screen)

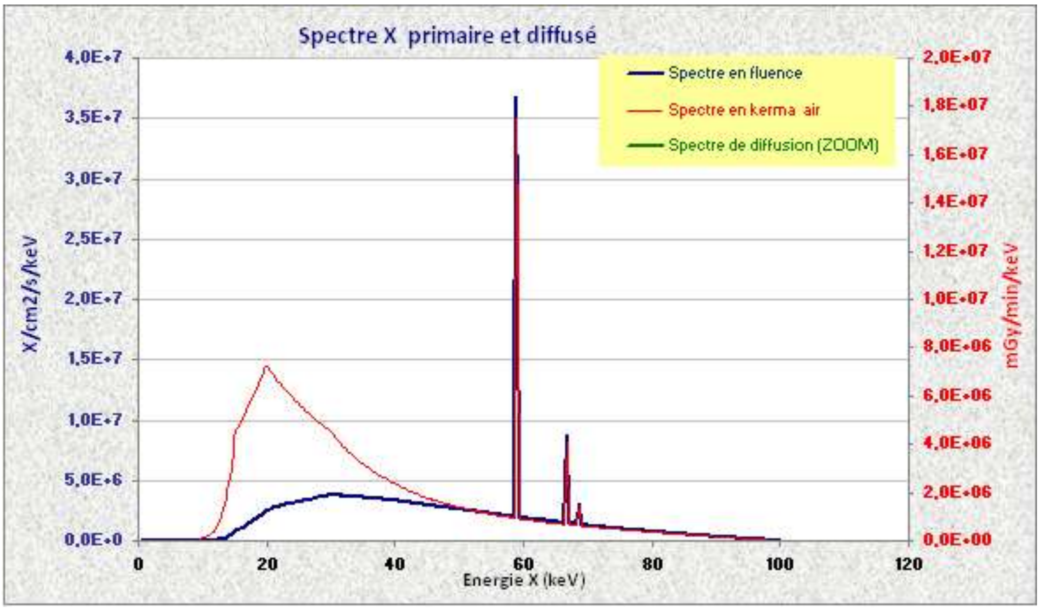
- **Note 3**: the curves proposed in the standard do not specify the filtrations used, which however strongly impact the attenuation factor. The reason is simple: the attenuation factor represents the ratio of the dose without screen to the dose with screen. However, the dose without a screen takes into account low-energy X photons, photons which tend to disappear quickly when the screen thickness increases. The conversion factors fluence / kerma air are moreover very high for these photons of low energies which then strongly contribute to the dose before screen.

Drawing :the graph below, extracted from Dosimex, presents the graph of fluence (blue curve) of X emission for a HT of 100 keV without filtration. The curve in red is the spectrum in kerma air: spectrum in fluence convolved with the conversion coefficient fluence / kerma ICRU 57. We then note the predominant weight of low energies, around 10 keV, in kerma air.

Calculated at 1 m and for 1 mA, the flow of kerma air is equal to 12.5 Gy / h while the dose equivalent flow H * (10) is little more than 1.8 Sv / h.



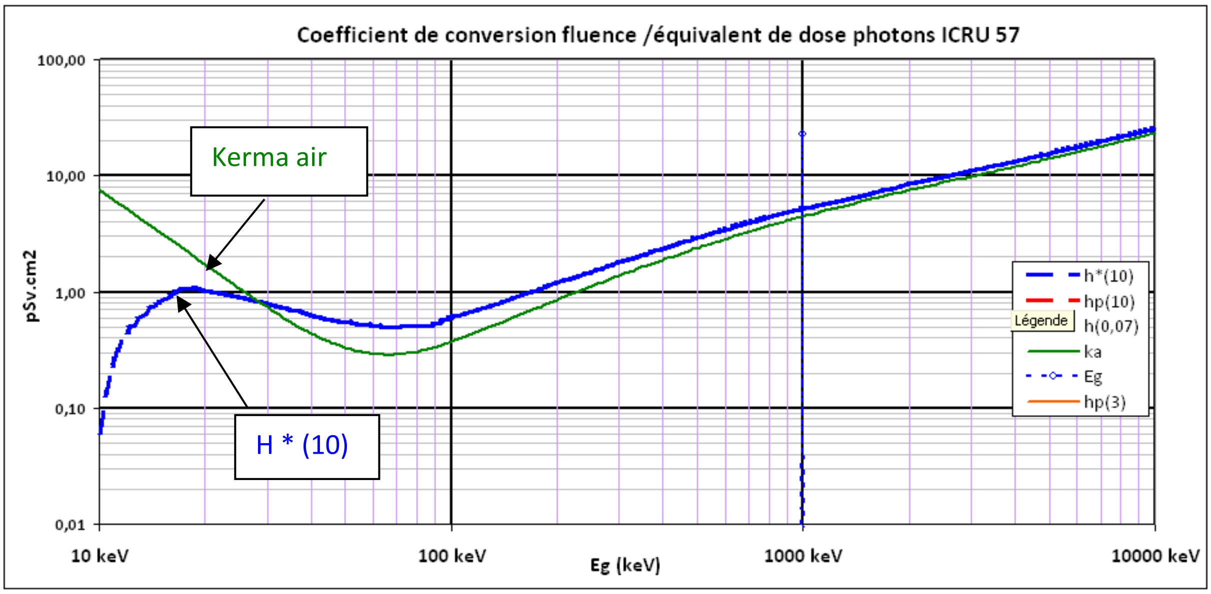
Below, the spectrum obtained by adding a filtration of1 mmAluminum. The presence of this window filters the low energies and the spectrum in kerma air is notably modified. The flow of kerma air thus goes to 0.10 Gy / h only



Thus, in the kerma air attenuation calculations, the attenuation coefficient will be higher, for the same screen, if the value in front of the screen corresponds to an unfiltered spectrum.

Note that for calculations in terms of H * (10), this effect disappears because the fluence / dose equivalent conversion coefficients H * (10) are lower at low energies than for the coefficients in terms of kerma air (effect filtration through the first 10 mm of tissue)

Fluence / kerma air and fluence / H * conversion coefficient graph (10) (Cf "ICRU 57 coefficients" Dosimex educational pack):



In this first example, we note for example that with a filtration of 1 mmof aluminum, H * (10) is then equal to 1.1 Sv / h, for a kerma air very close to 1.0 Gy / h. Whereas without filtration if the air kerma was equal to 12.5 Gy / h, H * (10) was only worth 1.8 Sv / h, which is 7 times lower.

This effect is linked to the fact that H * (10) is calculated under 10 mm of tissue, sufficient thickness to effectively filter low energies: average free path of 10 keV photons in water = 2 mm.

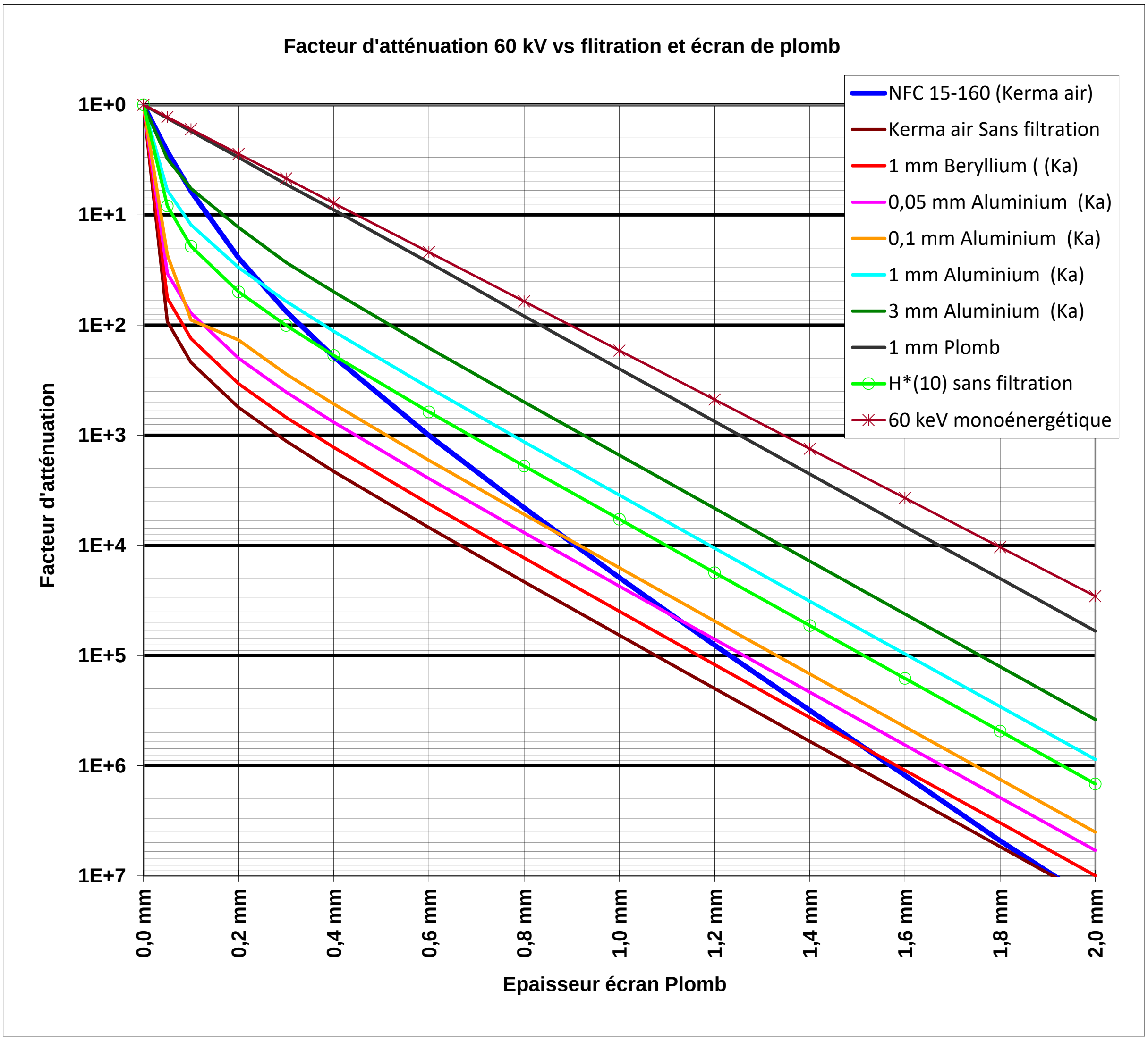
Note: on a practical level of radiation protection in medical imaging X, this low-energy component is on the one hand useless because it does not emerge and therefore does not participate in the construction of the image, and on the other hand is likely to generate very high surface doses. This is the reason for the presence of filtration windows.

III- 2 : VARIABILITY OF THE ATTENUATION FACTOR AS A FUNCTION OF FILTRATION

The curves below, all calculated for an HT of 60 kV, show the great variability of the attenuation factor in lead for various filtrations, going from the case without filtration to a high filtration of1 mmlead, likely to represent the protection provided by the sheath. In the latter case, there is an attenuation almost analogous to the case of monoenergetic photons close to the maximum energy (very hard spectrum):

Note: in the graph below we have plotted the attenuation curve (a perfect straight line on a log-log diagram) for photons of 60 keV in lead according to the classical function $e^{\mu x}$ *(the inverse of the attenuation factor* $e^{-\mu x}$ *) with* $\mu = 51{,}3\ cm^{-1}$ *calculated with X COM / NIST data. It will be noted that the slope thus obtained corresponds, while being slightly lower insofar as the X spectrum, even very hardened, is not perfectly monoenergetic, with the slopes obtained with Dosimex-GX from sufficient screen thicknesses , and conversely departs significantly from the slope given in NFC-15-160. Thus the significant deviations obtained with the latter show that the error is in the camp of the norm*

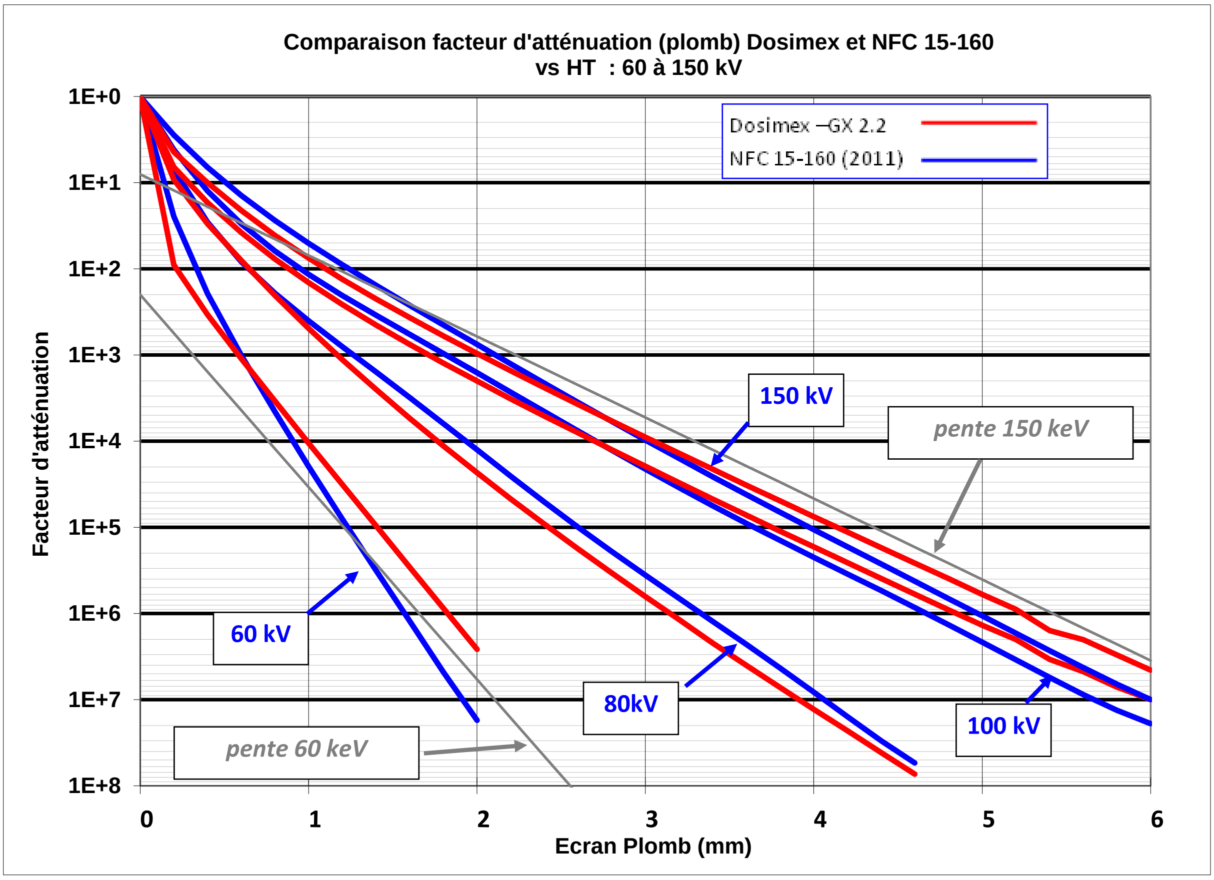
Between the case without filtration and this very hard last filtration, the attenuation coefficients, for the same lead screen, are likely to vary by a factor of around 240. We therefore see the importance of specifying the nature and the thickness of the filtration. What the NFC 15-160 (2011) standard does not do.



Finally, note the attenuation values calculated in terms of H * (10) without initial filtration. We then find a curve close to the curve calculated in terms of kerma air for filtration of1 mm aluminum

III- 3 : COMPARISON OF ATTENUATION FACTORS DOSIMEX-GX 3.0 VS NFC 15-160 VERSION 2011

III.3.1 LOW ENERGIES (SEE FIG 4 NF C 15-160 MARCH 2011)

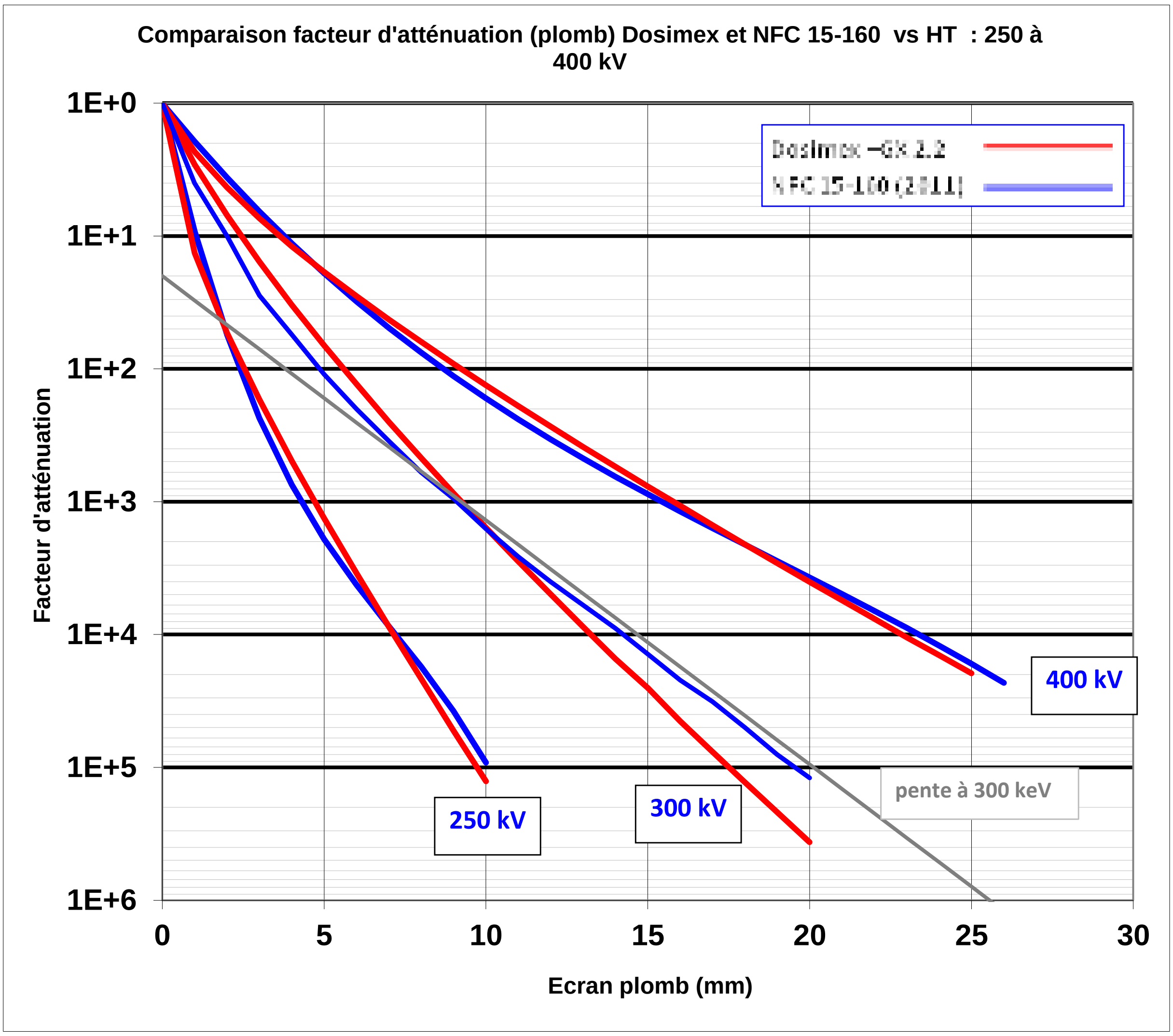


Here we find the good correlation between the slope for 60 keV in monoenergetics vs Dosimex-GX, slope not respected by the standard, which explains the differences observed. Thus the standard overestimates by a factor of 10 the attenuation provided by1 mm lead and ultimately underestimates the dose rate.

The same situation is found, but less marked, for other energies, such as 150 keV for example.

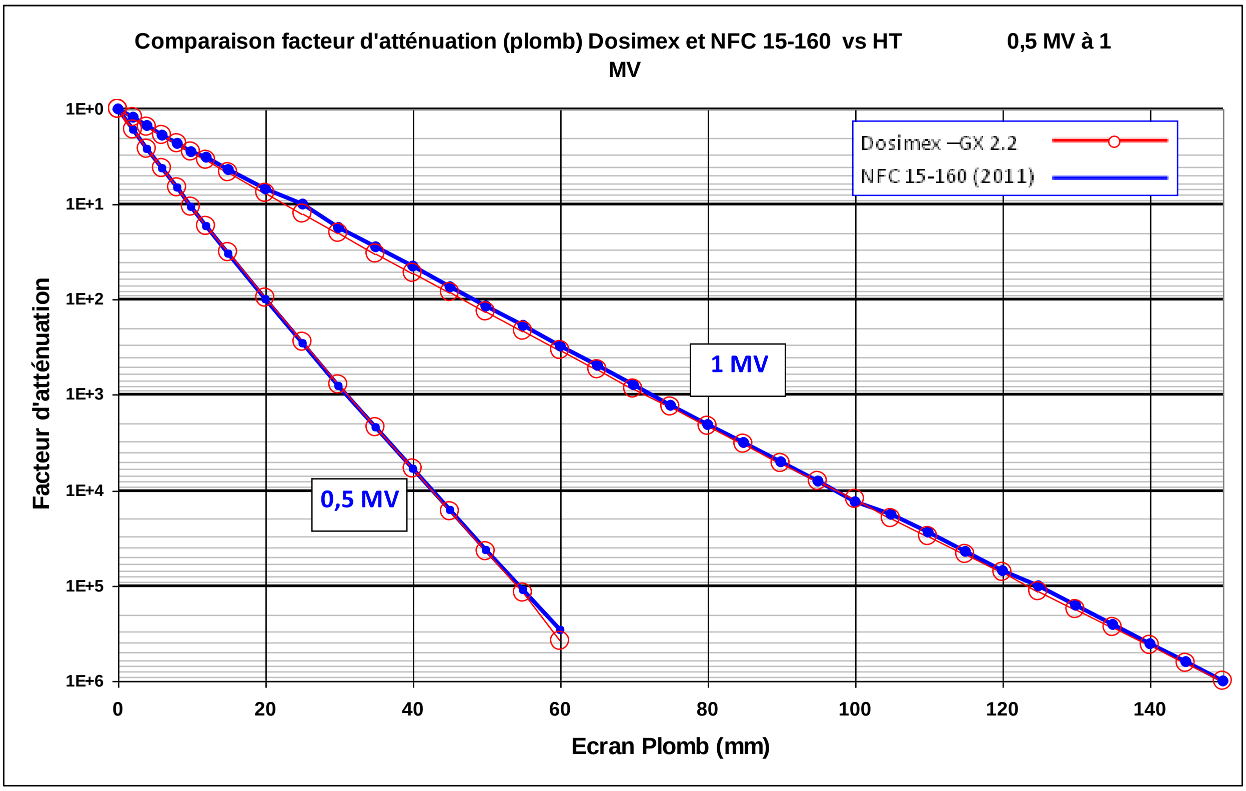
Note: the numerical values are given further in the appendix

III.3.2 Medium energies (see fig 5 NF C 15-160 March 2011)



We find significant differences between Dosimex-GX at 300 kV, which follows the slope at 300 keV well from a sufficiently thick screen (10 mm), and standard 15-160 which does not respect this slope.

III.3.3 High energies (see fig 6 NF C 15-160 March 2011)



Here the adequacy is much better between the NFC standard and Dosimex-GX.

The curve for 500 kV follows a corresponding monoenergetic slope at around 450 kV, and that for 1 MV follows a monoenergetic slope of around 0.9 MeV

III.3.4 DOSIMEX-GX AND N FC ATTENUATION FACTOR TABLES 15_160 (2011)

	60 kV		80 kV		100 kV		150 kV	
mm Pb	NFC 15-160 60 kV	Dosimex 60kV Filt. : 0.1 mm Al	NFC 15-160 80 keV	Dosimex 80 kV filt ..: 3 mm Al	NFC 15-160 100 kV	Dosimex 100 kV Filt. : 3 mm Al	NFC 15-160 150 kV	Dosimex 150 kV Filt. : 3 mm Al
0.0	1.00E + 00	1.00E + 00	1.00E + 00	1.00E + 00	1.00E + 00	1.00E + 00	1.00E + 00	1.00E + 00
0.2	2.46E + 01	9.00E + 01	7.06E + 00	9.20E + 00	4.14E + 00	6.60E + 00	2.79E + 00	4.40E + 00
0.4	1.95 + 02	3.40E + 02	2.88E + 01	3.00E + 01	1.25E + 01	1.70E + 01	6.65 + 00	1.00E + 01
0.6	1.01E + 03	1.10E + 03	8.27E + 01	8.00E + 01	3.01E + 01	3.80E + 01	1.41E + 01	2.10E + 01
0.8	4.56E + 03	3.42E + 03	1.92E + 02	2.04E + 02	6.21E + 01	7.70E + 01	2.74E + 01	4.10E + 01
1.0	1.96E + 04	1.05E + 04	4.01E + 02	4.90E + 02	1.16E + 02	1.44E + 02	5.05E + 01	7.50E + 01
1.2	8.02E + 04	3.17E + 04	7.97E + 02	1.13E + 03	2.03E + 02	2.59E + 02	8.95E + 01	1.32E + 02
1.4	3.14E + 05	9.58E + 04	1.57E + 03	2.50E + 03	3.45 + 02	4.47E + 02	1.55E + 02	2.23E + 02
1.6	1.22E + 06	2.90E + 05	3.11E + 03	5.43E + 03	5.77E + 02	7.51E + 02	2.64E + 02	3.69E + 02
1.8	4.79E + 06	8.69E + 05	6.24E + 03	1.14E + 04	9.62E + 02	1.24E + 03	4.47E + 02	5.99E + 02
2.0	1.74E + 07	2.61E + 06	1.26E + 04	2.33E + 04	1.61E + 03	2.00E + 03	7.54E + 02	9.60E + 02
2.2			2.54E + 04	4.67E + 04	2.70E + 03	3.22E + 03	1.27E + 03	1.52E + 03
2.4			5.08E + 04	9.18E + 04	4.53E + 03	5.11E + 03	2.12E + 03	2.39E + 03
2.6			9.96E + 04	1.78E + 05	7.62E + 03	8.00E + 03	3.54E + 03	3.74E + 03
2.8			1.91E + 05	3.38E + 05	1.27E + 04	1.26E + 04	5.88E + 03	5.81E + 03
3.0			3.60E + 05	6.37E + 05	2.11E + 04	1.96E + 04	9.71E + 03	8.98E + 03
3.2			6.68E + 05	1.18E + 06	3.47E + 04	3.04E + 04	1.59E + 04	1.38E + 04
3.4			1.23E + 06	2.20E + 06	5.62E + 04	4.69E + 04	2.59E + 04	2.12E + 04
3.6			2.29E + 06	4.00E + 06	8.99E + 04	7.21E + 04	4.17E + 04	3.24E + 04
3.8			4.29E + 06	7.22E + 06	1.42E + 05	1.11E + 05	6.68E + 04	4.94E + 04
4.0			8.20E + 06	1.30E + 07	2.23E + 05	1.69E + 05	1.06E + 05	7.52E + 04
4.2			1.58E + 07	2.30E + 07	3.48E + 05	2.58E + 05	1.69E + 05	1.14E + 05
4.4			3.01E + 07	4.13E + 07	5.44E + 05	3.93E + 05	2.67E + 05	1.73E + 05
4.6			5.44E + 07	7.30E + 07	8.53E + 05	5.98E + 05	4.23E + 05	2.61E + 05
4.8					1.35E + 06	9.07E + 05	6.72E + 05	3.94E + 05
5.0					2.15E + 06	1.37E + 06	1.07E + 06	6.00E + 05
5.2					3.45 + 06	2.00E + 06	1.70E + 06	8.95E + 05
5.4					5.53E + 06	3.40E + 06	2.70E + 06	1.58E + 06
5.6					8.74E + 06	4.73E + 06	4.26E + 06	2.02E + 06
5.8					1.33E + 07	7.13E + 06	6.62E + 06	3.03E + 06
6.0					1.90E + 07	1.00E + 07	9.99E + 06	4.54E + 06

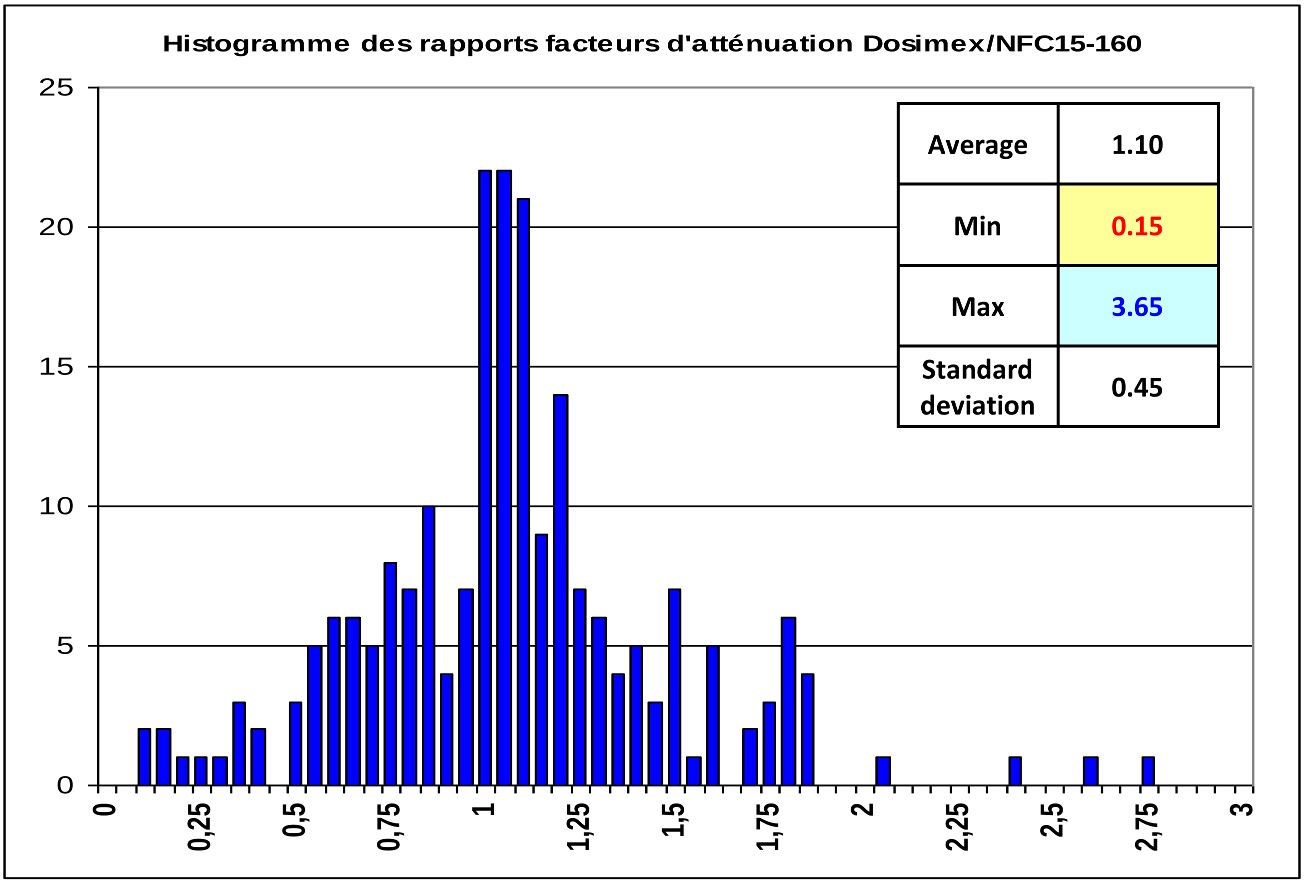
	250 kV		300 kV		400 kV	
mm Pb	NFC 15-160 250 kV	Dosimex250kV Filt. : 3 mm Al	NFC 15-160 300 keV	Dosimex 80 kV filt ..: 1 mm Pb	NFC 15-160 100 kV	Dosimex 100 kV Filt. : 0.5 mm Pb
0	1.00E + 00	1.00E + 00	1.00E + 00	1.00E + 00	1.00E + 00	1.00E + 00
1	9.21E + 00	1.34E + 01	4.00E + 00	2.90E + 00	1.95 + 00	2.32E + 00
2	5.55E + 01	5.40E + 01	1.00E + 01	7.00E + 00	3.64E + 00	4.31E + 00
3	2.35 + 02	1.70E + 02	2.80E + 01	1.56E + 01	6.54E + 00	7.34E + 00
4	7.47E + 02	4.93E + 02	5.50E + 01	3.30E + 01	1.14E + 01	1.20E + 01
5	1.91E + 03	1.33E + 03	1.10E + 02	6.64E + 01	1.91E + 01	1.86E + 01
6	4.23E + 03	3.45 + 03	2.00E + 02	1.30E + 02	3.10E + 01	2.83E + 01
7	8.64E + 03	8.73E + 03	3.50E + 02	2.50E + 02	4.91E + 01	4.25E + 01
8	1.75E + 04	2.16E + 04	6.00E + 02	4.68E + 02	7.55E + 01	6.27E + 01
9	3.76E + 04	5.28E + 04	9.50E + 02	8.63E + 02	1.13E + 02	9.16E + 01
10	9.20E + 04	1.27E + 05	1.60E + 03	1.57E + 03	1.66E + 02	1.33E + 02
11			2.60E + 03	2.81E + 03	2.40E + 02	1.90E + 02
12			4.00E + 03	4.97E + 03	3.39E + 02	2.72E + 02
13			6.00E + 03	8.72E + 03	4.71E + 02	3.86E + 02
14			9.00E + 03	1.52E + 04	6.47E + 02	5.45 + 02
15			1.40E + 04	2.52E + 04	8.79E + 02	7.67E + 02
16			2.20E + 04	4.48E + 04	1.18E + 03	1.07E + 03
17			3.20E + 04	7.63E + 04	1.58E + 03	1.50E + 03
18			5.00E + 04	1.29E + 05	2.10E + 03	2.09E + 03
19			8.00E + 04	2.18E + 05	2.79E + 03	2.90E + 03
20			1.20E + 05	3.65 + 05	3.71E + 03	4.01E + 03
21					4.94E + 03	5.53E + 03
22					6.61E + 03	7.61E + 03
23					8.90E + 03	1.05E + 04
24					1.21E + 04	1.43E + 04
25					1.66E + 04	1.96E + 04
26					2.31E + 04	2.67E + 04
27					3.27E + 04	3.64E + 04
28					4.71E + 04	4.95E + 04

	0.5 MV		1 MV	
mm	NFC 15-160 500 kV	Dosimex 0.5 MV Filt. : 15 mm Pb	NFC 15-160 300 keV	Dosimex 1 MV filt ..: 40 mm Pb
0	1.00E + 00	1.00E + 00	1.00E + 00	1.00E + 00
2	1.63E + 00	1.64E + 00	1.23E + 00	1.23E + 00
4	2.64E + 00	2.65 + 00	1.51E + 00	1.52E + 00
6	4.24E + 00	4.25E + 00	1.86E + 00	1.87E + 00
8	6.76E + 00	6.74E + 00	2.28E + 00	2.29E + 00
10	1.07E + 01	1.06E + 01	2.80E + 00	2.81E + 00
12	1.69E + 01	1.67E + 01	3.21E + 00	3.44E + 00
15	3.31E + 01	3.23E + 01	4.29E + 00	4.65E + 00
20	9.87E + 01	9.55E + 01	7.00E + 00	7.65E + 00
25	2.86E + 02	2.76E + 02	1.00E + 01	1.25E + 01
30	8.05E + 02	7.82E + 02	1.74E + 01	2.03E + 01
35	2.22E + 03	2.18E + 03	2.80E + 01	3.30E + 01
40	6.02E + 03	6.02E + 03	4.51E + 01	5.30E + 01
45	1.61E + 04	1.64E + 04	7.27E + 01	8.40E + 01
50	4.25E + 04	4.44E + 04	1.17E + 02	1.35E + 02
55	1.12E + 05	1.19E + 05	1.88E + 02	2.14E + 02
60	2.94E + 05	3.79E + 05	3.03E + 02	3.40E + 02
65			4.88E + 02	5.38E + 02
70			7.86E + 02	8.50E + 02
75			1.27E + 03	1.34E + 03
80			2.04E + 03	2.10E + 03
85			3.16E + 03	3.29E + 03
90			5.07E + 03	5.14E + 03
95			8.14E + 03	8.03E + 03
100			1.31E + 04	1.25E + 04
105			1.80E + 04	1.95 + 04
110			2.78E + 04	3.03E + 04
115			4.43E + 04	4.70E + 04
120			7.05 + 04	7.29E + 04
125			1.01E + 05	1.13E + 05
130			1.60E + 05	1.75E + 05
135			2.53E + 05	2.70E + 05
140			4.02E + 05	4.16E + 05
145			6.37E + 05	6.41E + 05
150			1.01E + 06	9.87E + 05

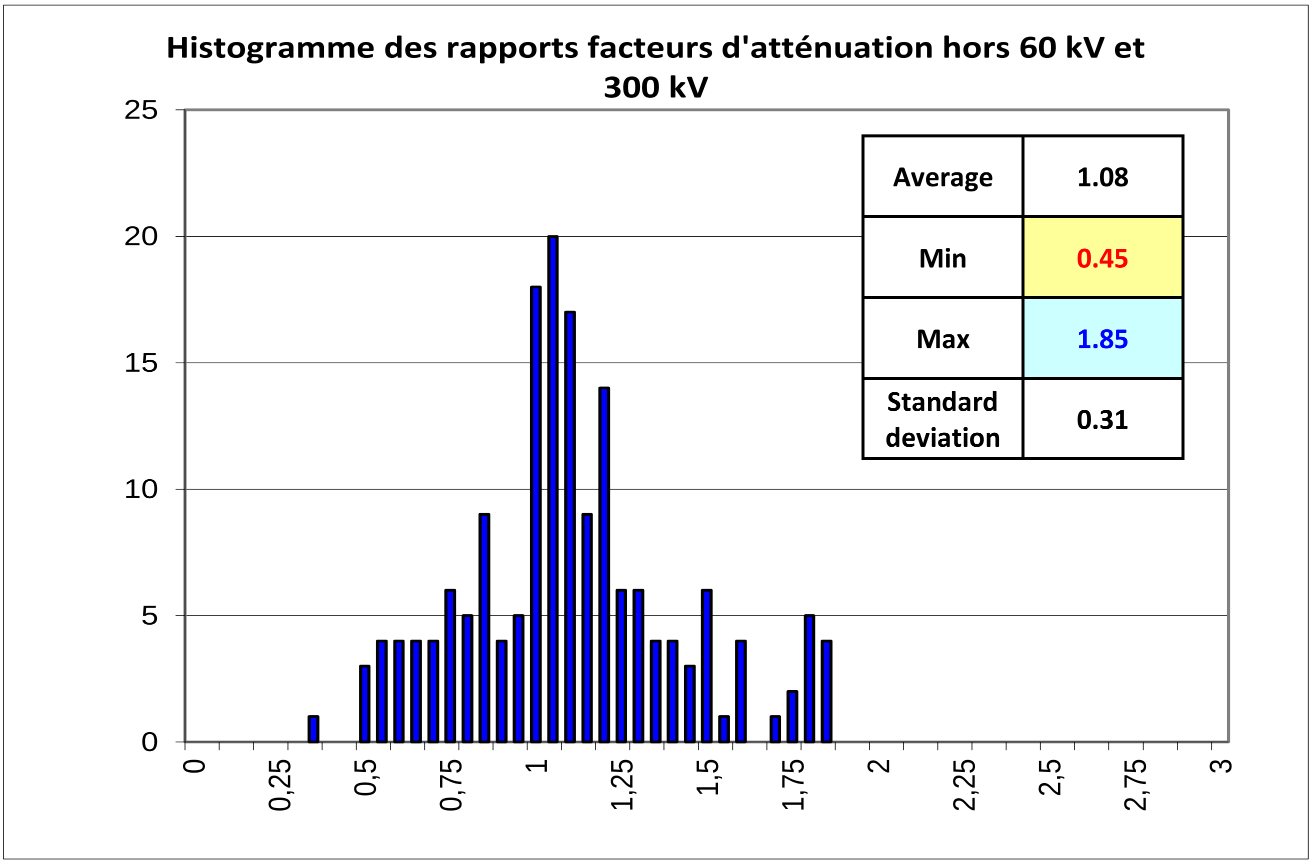
III.3.5 Analysis of the results for the 2011 version

For 202 Dosimex / Nf C 15160 attenuation factor reports obtained from the previous tables:

	60 kV	80 kV	100 kV	150 kV	250 kV	300 kV	400 kV	0.5 MV	1 MV
	3.65	1.30	1.60	1.58	1.46	0.73	1.19	1.00	1.00
	1.74	1.04	1.36	1.50	0.97	0.70	1.19	1.01	1.01
	1.09	0.97	1.26	1.49	0.72	0.56	1.12	1.01	1.01
	0.75	1.06	1.24	1.49	0.66	0.60	1.06	1.00	1.00
	0.54	1.22	1.24	1.48	0.70	0.60	0.98	1.00	1.00
	0.40	1.42	1.27	1.47	0.82	0.65	0.91	0.99	1.07
	0.30	1.59	1.30	1.44	1.01	0.71	0.87	0.99	1.08
	0.24	1.74	1.30	1.40	1.23	0.78	0.83	0.98	1.09
	0.18	1.83	1.29	1.34	1.40	0.91	0.81	0.97	1.25
	0.15	1.85	1.24	1.27	1.38	0.98	0.80	0.97	1.17
		1.84	1.19	1.20		1.08	0.79	0.97	1.18
		1.81	1.13	1.13		1.24	0.80	0.98	1.17
		1.79	1.05	1.06		1.45	0.82	1.00	1.16
		1.77	0.99	0.99		1.69	0.84	1.02	1.15
		1.77	0.93	0.92		1.80	0.87	1.04	1.14
		1.77	0.88	0.87		2.04	0.90	1.06	1.12
		1.78	0.84	0.82		2.38	0.95	1.29	1.10
		1.75	0.80	0.78		2.58	0.99		1.08
		1.68	0.78	0.74		2.73	1.04		1.06
		1.59	0.76	0.71		3.04	1.08		1.03
		1.45	0.74	0.67			1.12		1.04
		1.37	0.72	0.65			1.15		1.01
		1.34	0.70	0.62			1.18		0.99
			0.67	0.59			1.18		0.96
			0.64	0.56			1.18		1.08
			0.58	0.53			1.16		1.09
			0.61	0.58			1.11		1.06
			0.54	0.47			1.05		1.03
			0.54	0.46					1.12
			0.53	0.45					1.10
									1.07
									1.04
									1.01
									0.98
Average	**0.90**	**1.55**	**0.96**	**0.98**	**1.04**	**1.36**	**1.00**	**1.02**	**1.08**
Standard deviation	**1.09**	**0.28**	**0.31**	**0.39**	**0.31**	**0.81**	**0.15**	**0.08**	**0.07**



By not taking into account the results at 60 keV and at 300 keV where the reference values do not follow, generally from high lead thicknesses, the reference slopes in monoenergetics, the following results are obtained for 172 points comparisons:



III- 4 : COMPARISON OF ATTENUATION FACTORS DOSIMEX-GX 3.0 VS NFC 15-160 VERSION 2018

PREAMBLE:

The reference values are taken from the article by Laurent Bourgois and Stéphanie Ménard and correspond to the charts in the NFC standard 15-160 version 2018. In fact, these attenuations are now calculated in terms of dose equivalent H * (10). Another novelty is the dataset for attenuation in concrete.

IOP Publishing | Society for Radiological Protection — Journal of Radiological Protection

J. Radiol. Prot. 38 (2018) 471–479 (9pp) https://doi.org/10.1088/1361-6498/aaae20

Dose equivalent transmission data for shielding industrial x-ray facilities up to 800 kV

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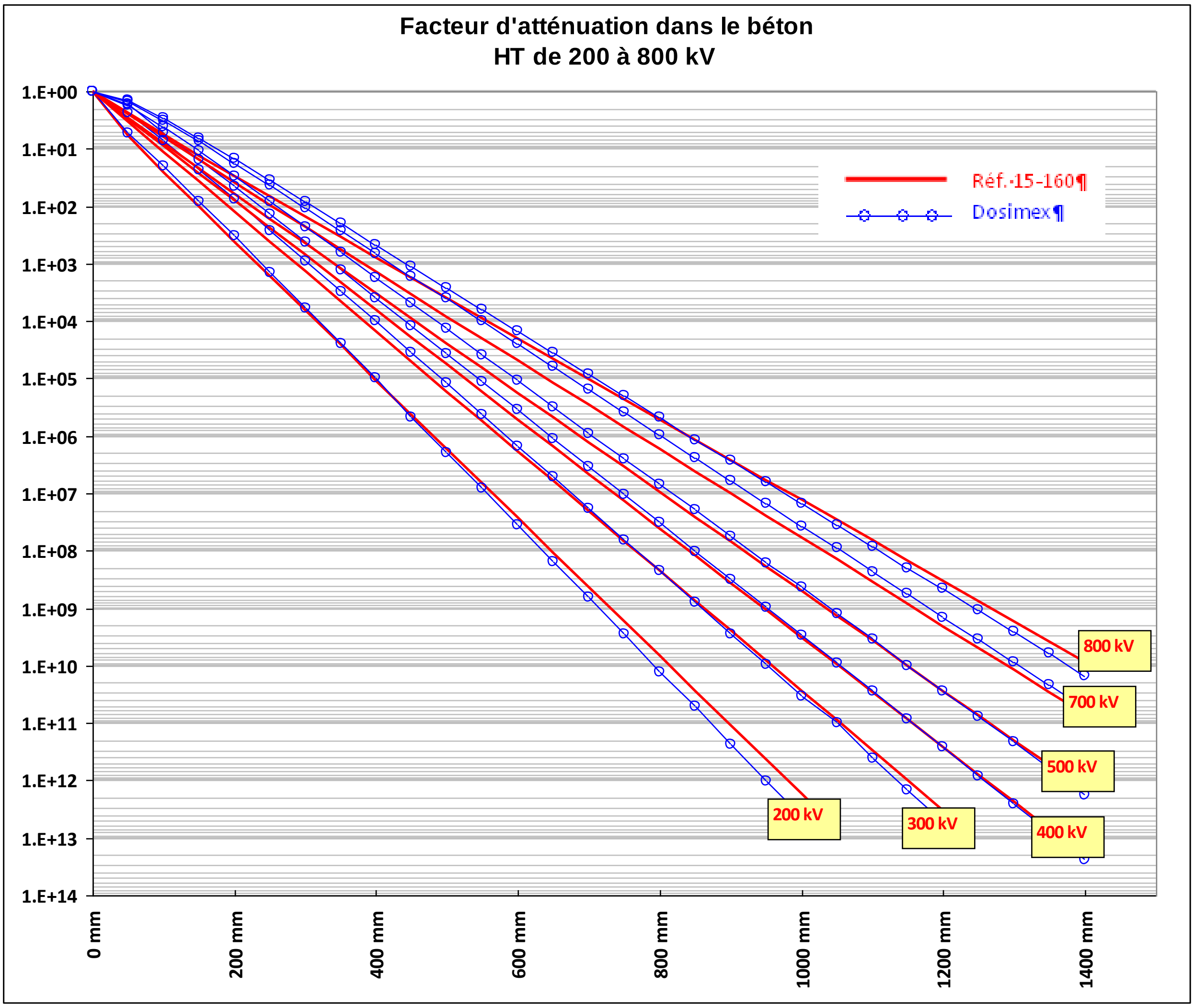
Received 10 November 2017, revised 24 January 2018
Accepted for publication 9 February 2018
Published 13 March 2018

CrossMark

Abstract

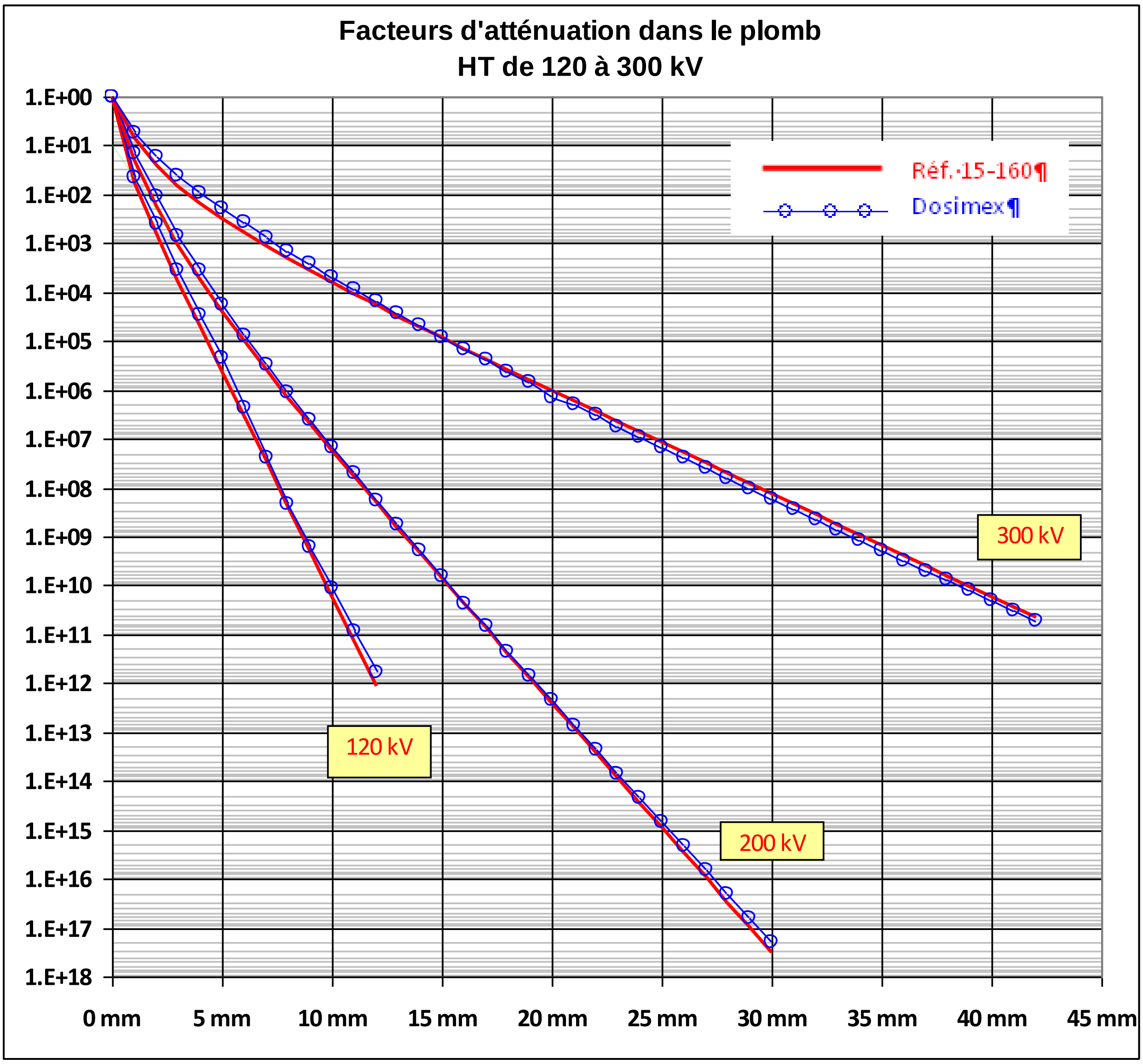
The transmission factors used to calculate radiation shielding around an industrial x-ray device are determined using the MCNP6 code. The transmission factors are given for high voltages ranging between 120 and 800 kV for lead and between 200 and 800 kV for concrete. In view of the high usage intensity of industrial devices, the transmission factors are evaluated up to 1.10^{-10}. The parameters used in the classic equation of Archer *et al* are derived from the transmission data calculated here. This type of data exists in the literature, but only for voltages lower than 150 kV to meet the design demands for facilities used in the medical field. In addition, this study markedly supplements the existing data, in particular for industrial and research installations.

III.4.1 ATTENUATION FACTORS IN CONCRETE (NF C 15-160 2018)



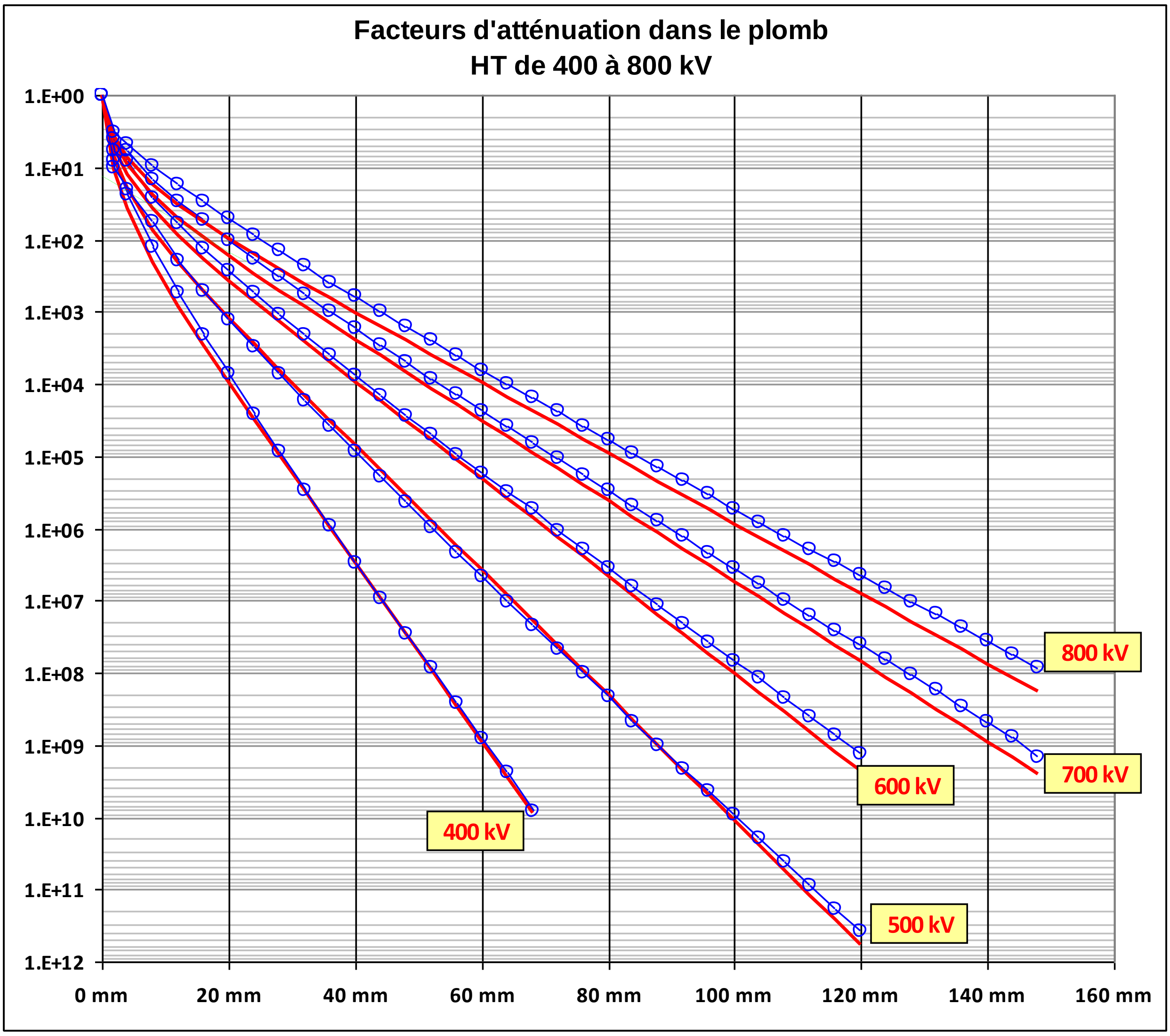
Despite attenuations calculated on continuous spectra and for thicknesses which may exceed 1 mof concrete, the suitability is excellent. The mean squared deviation over 185 values is only 35%.

III.4.2 ATTENUATION FACTORS IN LEAD 120 TO 300 KV (NF C 15-160, 2018)



The mean quadratic deviation over 83 values is equal to 26%.

III.4.3 Attenuation factors in lead 400 to 800 kV (NF C 15-160 2018)



The mean squared deviation over 161 values is equal to 29%.

III.4.4 Analysis of the results for the 2018 version

Statistics on 202 Dosimex / Nf C 15160 mitigation factor reports:

Dosimex / NF C 15-160 attenuation factor ratio for Concrete						Dosimex / NF C 15-160 attenuation factor ratio for Lead							
200 kV	300 kV	400 kV	500 kV	700 kV	800 kV	120 kV	200 kV	300 kV	400 kV	500 kV	600 kV	700 kV	800 kV
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.88	0.69	0.54	0.61	0.60	0.61	0.79	0.76	0.77	0.77	1.43	1.12	0.95	0.87
0.79	0.63	0.59	0.52	0.51	0.52	0.62	0.61	0.66	0.65	1.08	0.66	0.65	0.68
0.79	0.62	0.57	0.49	0.48	0.50	0.64	0.63	0.62	0.61	0.79	0.70	0.61	0.56
0.81	0.62	0.56	0.48	0.46	0.50	0.59	0.66	0.61	0.65	0.94	0.69	0.58	0.53
0.88	0.63	0.58	0.50	0.46	0.52	0.56	0.71	0.61	0.71	0.98	0.70	0.59	0.53
0.92	0.65	0.59	0.51	0.46	0.54	0.68	0.76	0.63	0.78	1.03	0.71	0.60	0.54
0.92	0.67	0.60	0.52	0.47	0.57	0.83	0.79	0.65	0.85	1.09	0.75	0.62	0.55
0.94	0.67	0.61	0.54	0.47	0.60	0.90	0.82	0.68	0.91	1.13	0.77	0.64	0.57
1.13	0.70	0.62	0.55	0.48	0.63	0.81	0.82	0.72	0.96	1.17	0.79	0.66	0.58
1.14	0.74	0.64	0.57	0.49	0.66	0.70	0.85	0.76	0.99	1.20	0.82	0.69	0.60
1.18	0.79	0.67	0.59	0.50	0.70	0.61	0.88	0.80	1.02	1.24	0.83	0.69	0.61
1.36	0.81	0.70	0.62	0.51	0.73	0.51	0.91	0.84	1.00	1.24	0.84	0.71	0.62
1.48	0.85	0.72	0.65	0.52	0.77		0.91	0.88	0.96	1.24	0.85	0.72	0.63
1.49	0.91	0.74	0.69	0.54	0.82		0.89	0.92	0.93	1.24	0.85	0.73	0.64
1.69	0.96	0.77	0.71	0.55	0.87		0.93	0.96	0.91	1.25	0.85	0.73	0.65
1.90	1.00	0.79	0.73	0.56	0.92		1.05	1.00	0.91	1.24	0.86	0.74	0.66
1.87	1.07	0.83	0.77	0.59	1.00		0.93	1.04	0.84	1.20	0.83	0.73	0.65
2.10	1.13	0.85	0.81	0.60	1.02		0.91	1.07	0.95	1.16	0.77	0.72	0.65
2.39	1.19	0.88	0.85	0.62	1.07		0.86	1.10		1.12	0.80	0.73	0.66
2.44	1.25	0.90	0.86	0.63	1.13		0.87	1.38		1.08	0.79	0.74	0.66
	1.08	0.95	0.90	0.64	1.18		0.86	1.15		1.05	0.77	0.71	0.65
	1.40	0.97	0.93	0.68	1.29		0.83	1.18		1.04	0.76	0.69	0.64
	1.48	0.99	1.00	0.65	1.36		0.79	1.26		1.01	0.74	0.68	0.63
	1.55	1.02	1.02	0.70	1.35		0.78	1.22		0.95	0.71	0.68	0.62
		1.07	1.05	0.71	1.43		0.77	1.23		0.89	0.68	0.67	0.62
		1.10	1.09	0.72	1.49		0.75	1.23		0.84	0.65	0.67	0.62
		1.11	1.14	0.74	1.59		0.72	1.24		0.79	0.63	0.66	0.62
		1.15	1.22	0.77	1.72		0.67	1.25		0.76	0.62	0.65	0.60
							0.66	1.25		0.73	0.61	0.65	0.59
							0.64	1.25		0.71	0.60	0.62	0.57
								1.26		0.66	0.58	0.59	0.55
								1.26				0.57	0.54
								1.26				0.55	0.52
								1.27				0.54	0.51
								1.26				0.53	0.49
								1.25				0.53	0.48
								1.24				0.52	0.48
								1.22				0.61	0.47

In blue the ratios greater than 1.5 (8 cases), in red the ratios less than 0.5 (12 cases)

For all the cases the average is equal to 0.83, showing a tendency to slightly underestimate the attenuation factors with Dosimex, which goes in the direction of radiation protection since the DED behind the screen are then slightly overestimated