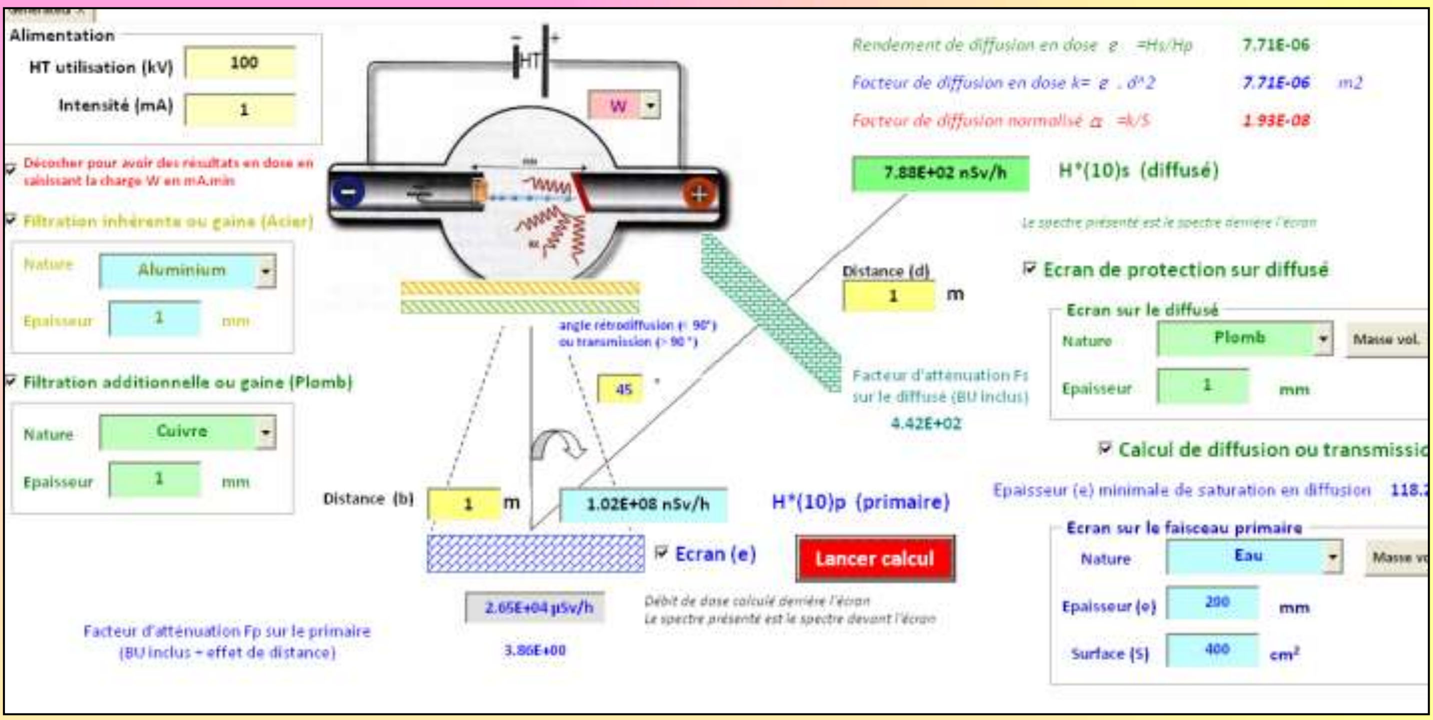
DOSIMEX-GX 3.0

✓ *PHYSICAL MODEL GENERATOR X HAND-BOOK*



Alain VIVIER, Gérald LOPEZ

SEPTEMBER 2019

SUMMARY

I- 1 : PREAMBLE: THE MODELING OF X GENERATORS IN DOSIMEX

In the development of the Dosimex pack, the “X generator” option has continued to gain importance for 2 reasons:

- ✓ On the one hand, the fleet of X generators, all environments combined (medical, industrial, research, security) takes a very large place in the general field of the use of ionizing radiation.
- ✓ On the other hand, the application of the NF C 15-160 standard of March 2011 is likely to cause problems for users, in particular for non-medical applications.

In the defense of the authors of this standard, who have done a remarkable job of synthesis, it is indeed quite difficult to identify in a document not exceeding a few tens of pages all the situations that can be encountered in a radiation protection issues around X generators.

Indeed the number of input parameters is very high, each being likely to affect the final result in high proportions. Essentially these parameters are:

For calculations in the primary beam

- High voltage (kV)
- Intensity (mA)
- The nature of the anode
- The nature and thickness of the filtration (0.1 or 2 screens)
- The distance (b)
- The nature of the screen (or target) on the path of the primary beam

For the calculation on the scattered radiation, in addition to the previous parameters, it is necessary to take into consideration:

- The nature of the diffuser screen
- Its thickness
- Its surface
- Diffusion angle
- The distance (d)
- The nature and thickness of a screen, if any, on the broadcast path

The number of combinations of these various parameters being by nature infinite, we understand that it can be difficult to summarize this by a necessarily limited number of charts. Not to mention the output parameters which can be expressed in various sizes (kerma air, equivalent dose various ...)

The other great difficulty of the calculations around the generators X is related to the fact that one works here not on discrete emissions (monoenergetic) as it is the case with radionuclides, but on continuous X spectra going from 0 until at the maximum energy of the tube electrons (kV).

It is Dosimex's essential strength to take into account a continuous X spectrum, discretized into 270 “thin sections”, each section being managed independently of the others. We therefore do not use, as may be the case in deterministic approaches, the average values of the spectra for the attenuation coefficients, the build-up factors, etc. The taking into account of the full spectrum allows us obtain reliable values on the attenuation factors for example.

The other strong point of Dosimex is that of the calculation of the scattering of X photons by the screen placed on the path of the primary beam. The calculation is a double integral, both on the target volume and on the energy distribution, of the Klein and Nishina formula for taking into account the Compton scattering. In this latest version, we have also succeeded in implementing X-ray fluorescence which in certain cases, with lead for example, is the essential component of the scattered radiation.

Fortunately, we were prompted to do so by a CEA-R report: "Evaluation by Monte-Carlo calculation of the diffusion factors in terms of dose equivalent, of radiation from an X generator, for the calculation of secondary dose equivalents . Creation of a database "(Laurent Bourgois, Stéphanie Ménard,*CEA-R 6452 report 2017*)

This report required, more than 4000 MCNP calculations of diffusion of primary beams X in various materials (5) for various HT (10), angles of diffusion (5) and filtrations (8) (there again a remarkable work). Such reference values were previously sorely lacking. In addition, half of these values are expressed in terms of H * (10).

We were thus able to note that the values calculated with Dosimex presented on the one hand an absence of bias on average as well as an average difference of the order of 16% vs MCNP (*see validation file for details)* We are therefore now able to offer our users a reliable and validated tool, covering an important aspect in this issue of radiation protection around X generators.

In fact, discussions with our users showed us that the most frequent component to be taken into consideration for the radiation protection aspect was the diffused component, the primary component often being screened by the equipment.

To complete this preamble, we have chosen for ease of use to merge the manual and the validation file into a single document. This is all the more true since the validation part, which is now based on around 520 comparison points (vs MCNP or NF c15-160) allows us to better understand certain aspects of the modeling of generator X and its logic of use.

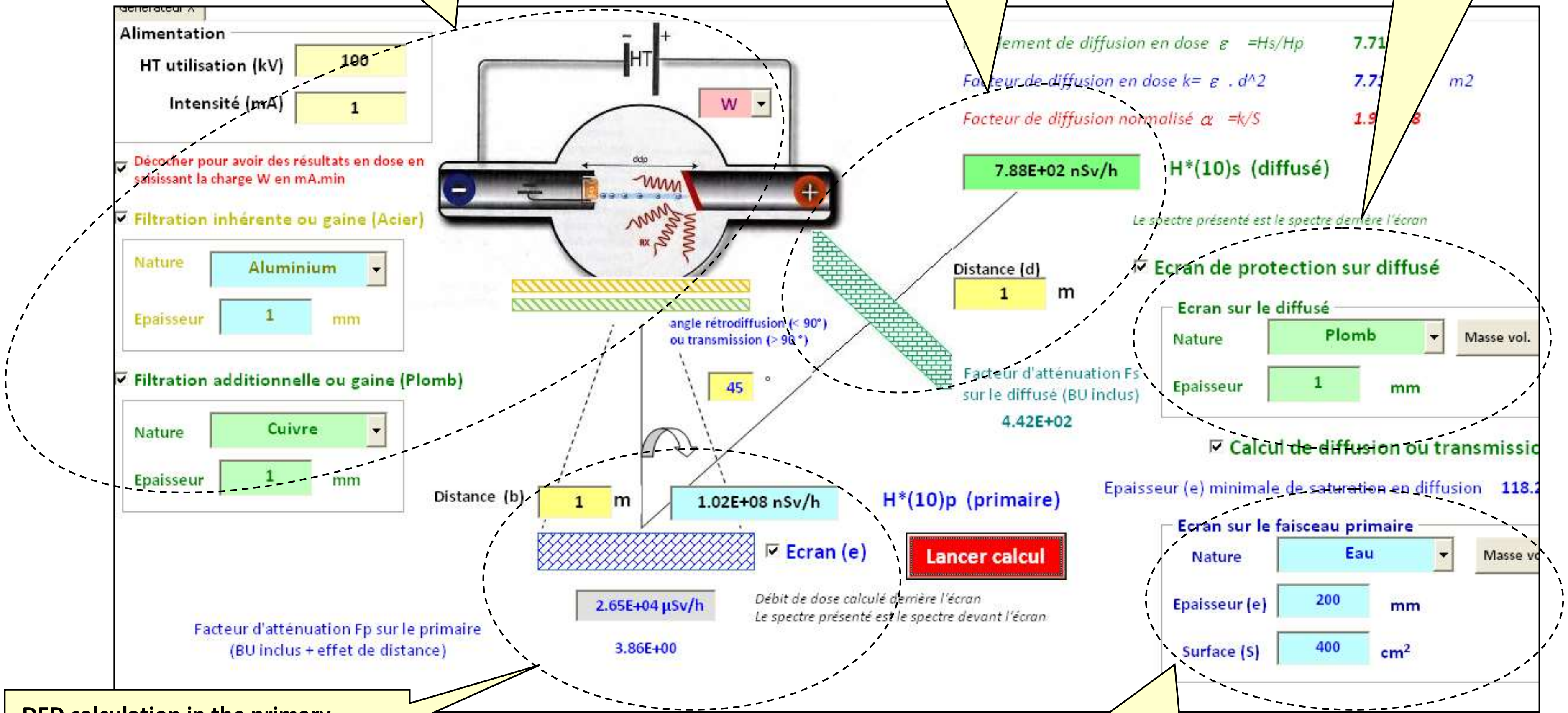
Note: it is possible to directly obtain the dose value and no longer the dose rate by entering the load W in mA.min instead of the intensity in mA. This mode allows you to get into the conditions of use of NF C 15-160 based on weekly doses and loads (p 10)

MAIN FEATURES OF GENERATOR MODELING X

Operating parameters of generator X, anode, filtration (s).

Calculation DED broadcast and attenuation by a screen on the path of the broadcast

Screen characteristics on the broadcast path

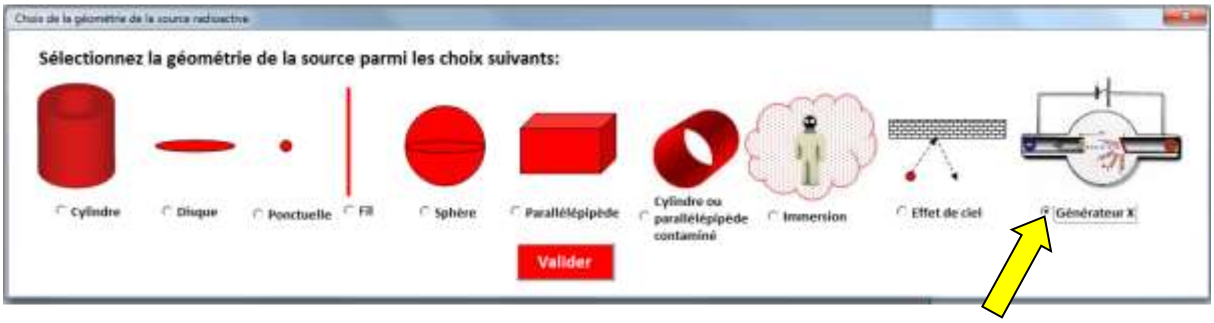


DED calculation in the primary beam in front of and behind a

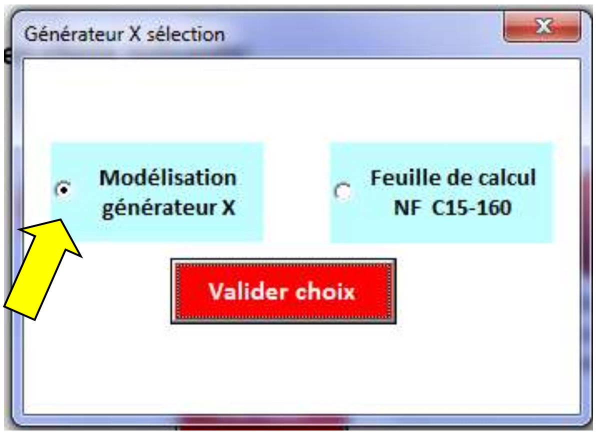
Screen or target characteristic in the primary beam.

I- 2 : CHOICE OF GAMMA SOURCES OR X GENERATOR

The main dialog offers the X generator as sources of radiation:



By validating this choice, a dialog box opens, allowing you to choose between two options:



- **Generator X modeling:** allows to determine the primary and diffused dose rate according to the HT / Intensity / filtration parameters of the X generator as well as the screens set up.

- **NF C15-160 worksheet:**provides all the results requested by standard NF C 15-160 of March 2018 entitled: "Installations for the production and use of X-rays - Radiation protection requirements". The use of this application is given at the end of the manual

I- 3 : CALCULATION IN THE PRIMARY BEAM

I.3.1 POSSIBILITY OF CALCULATIONS

This option calculates the dose rate (H * (10), kerma air, etc.):

1. **In the primary beam**
2. **In the primary beam behind a screen**
3. **In the beam scattered by a screen**
4. **In the beam scattered behind a screen**

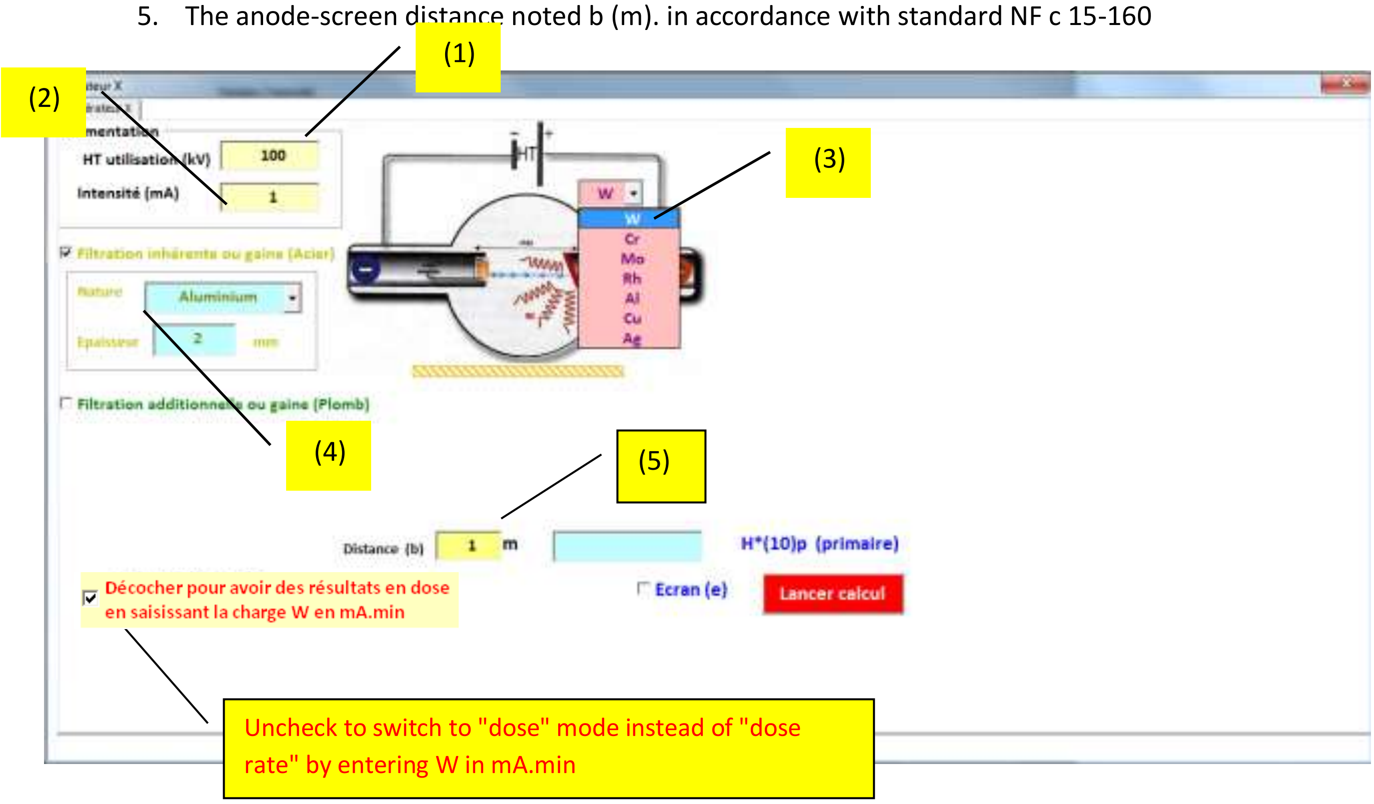
! : From version 2.2, the main quantity displayed in the dialog box is expressed in ambient dose equivalent rate (DED) H * (10), and no longer in kerma air as before for the following 2 reasons:

1. The kerma air is not an operational or protective quantity, but a quantity for metrological use
2. In all likelihood, future standards will also return to operational magnitude

I.3.2 INPUT PARAMETERS

In this mode, it suffices to enter:

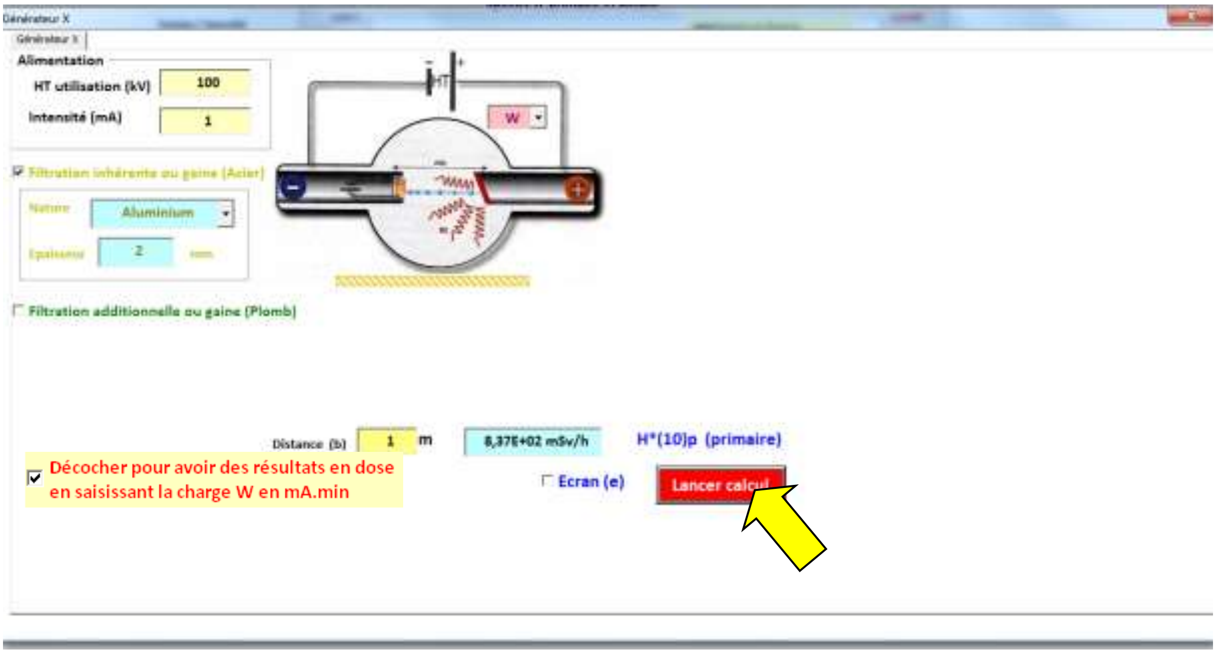
1. The value of high voltage (kV)
2. Electronic intensity (mA) or load W (mA.min) in "dose" mode
3. The nature of the anode (by default the spreadsheet is positioned on a tungsten W anode)
4. Type and thickness of filtration (with the possibility of 2 filtration screens)
5. The anode-screen distance noted b (m). in accordance with standard NF c 15-160



The high voltages taken into account in this option range from 25 kV to 1000 kV. If exceeded, an alert message appears:

I.3.3 OUTPUT PARAMETERS

After entering the distance between the anode and the dose point marked "b" (see NF C 15-160), you can start the calculation to obtain the DED in the primary beam



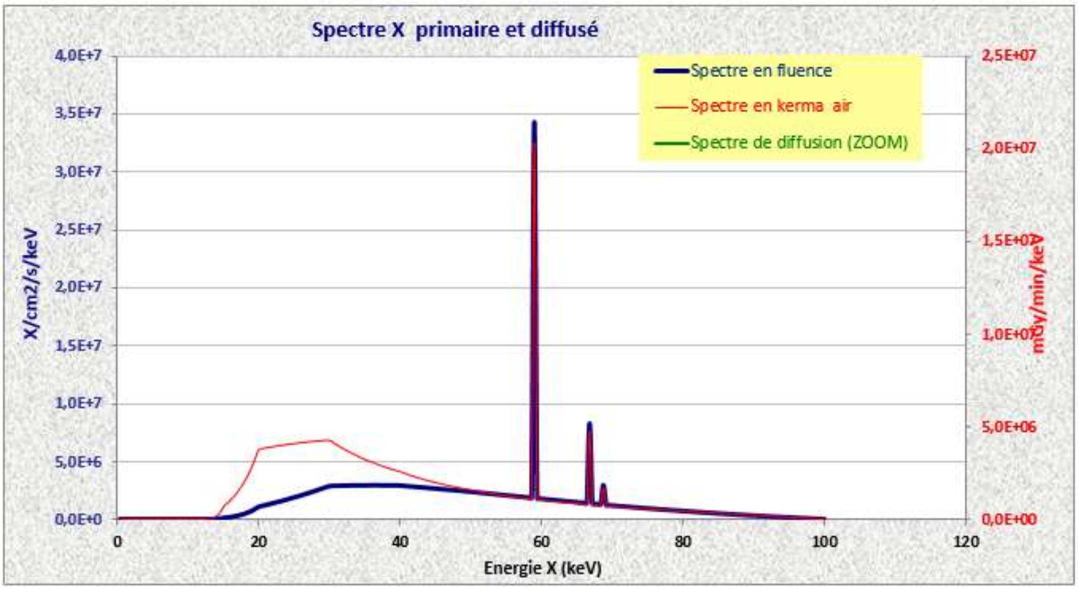
The other operational quantities Hp (10), H '(0.07) and Hp (3), the quantity of protection in effective dose in antero-posterior irradiation E (AP) as well as the air kerma are reported on the summary sheet

		Avec Build-up	Sans Build-up	Build-up moyen
Prim.	Kerma	6,59E+02 mGy/h	6,59E+02 mGy/h	1
	H*(10)	8,37E+02 mSv/h	8,37E+02 mSv/h	
	H'(0,07)	8,85E+02 mSv/h	8,85E+02 mSv/h	
	Hp(10)	8,83E+02 mSv/h	8,83E+02 mSv/h	
	Hp(3)	8,87E+02 mSv/h	8,87E+02 mSv/h	
	E (AP)	4,72E+02 mSv/h	4,72E+02 mSv/h	

Note: in the absence of a screen, the build-up is naturally equal to 1

Other interesting information also appears on the summary sheet:

- the X spectrum in fluence and kerma flow:



- the input parameters used, the average values of the spectrum (average in fluence and average in kerma air)

- The photon fluence rate X (integral of the spectrum) at distance b

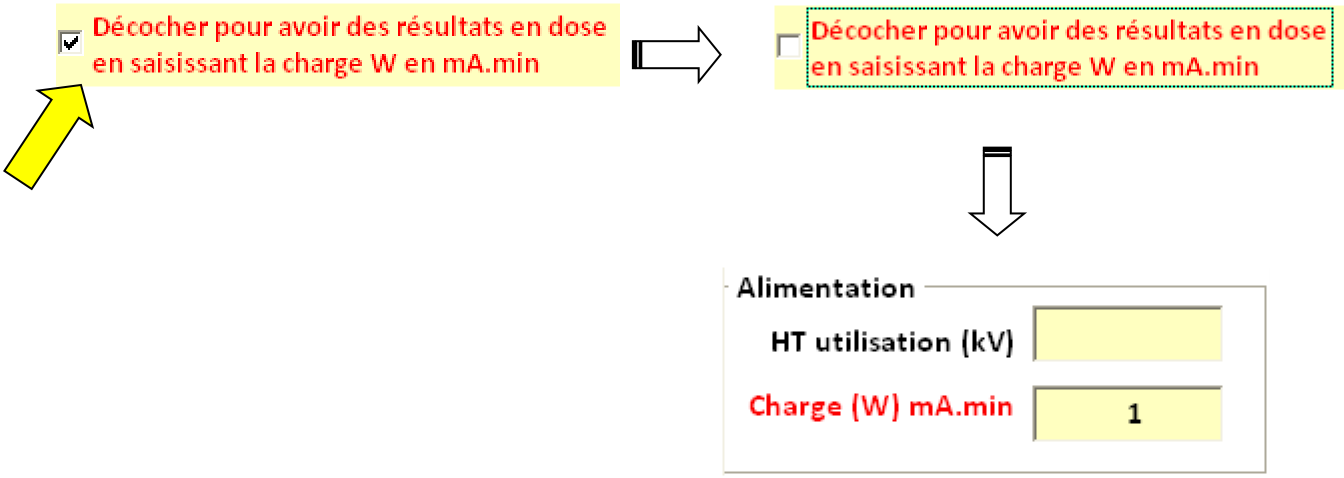
Terme source		
	Source	
	Générateur X	Tension / intensité
Filtre inh. 2mm de Aluminium		100kV / 1mA / Anode W (12°)
	Energie X moyenne (Fluence)	48,83 keV
	Energie X moyenne (Kerma)	40,37 keV
	Fluence X totale au point de mesure	3,68E+08/cm²/s
Distance anode/DED primaire (m)	b= 1	

Recall here that the results appearing on the summary sheet can be easily copied using the “Copy results.xls” sheet, on the express condition of opening it before Dosimex-GX.

I.3.4 "DOSE" MODE AND NF C 15-160

The advantage of the "Dose" mode makes it possible to approach the conditions of application of the NF C15-160 standard based essentially on the limitation of weekly doses for a given load W (mA.min).

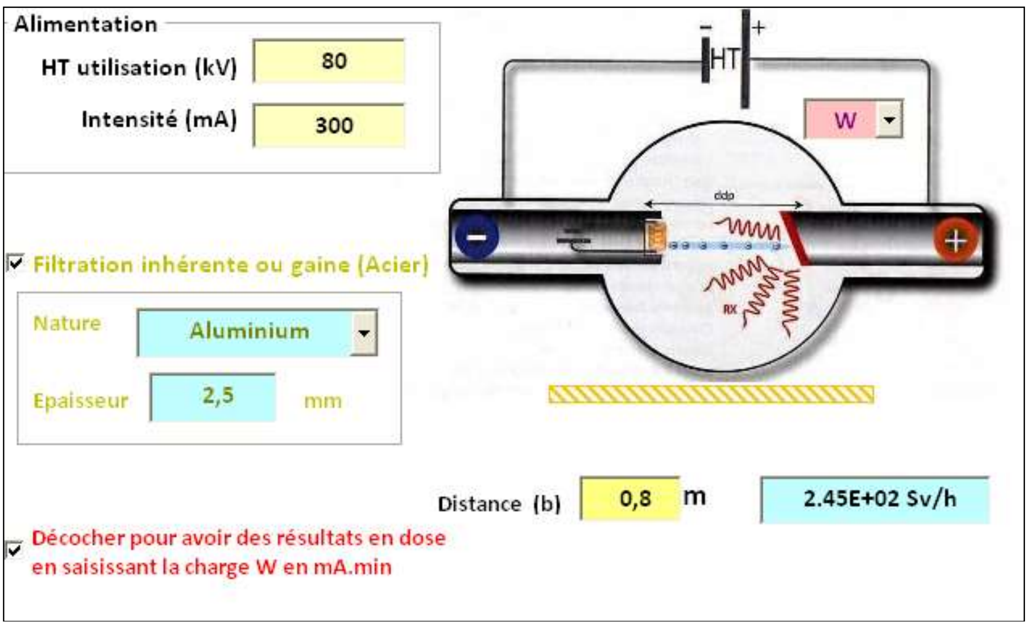
By unchecking the “Uncheck…” option, the intensity input field changes units and switches to load W in mA.min (be careful not to confuse with the load often calculated in mA.s)



The results are then given in terms of dose equivalent corresponding to the load used.
Example with a medical X generator used in an abdomen examination

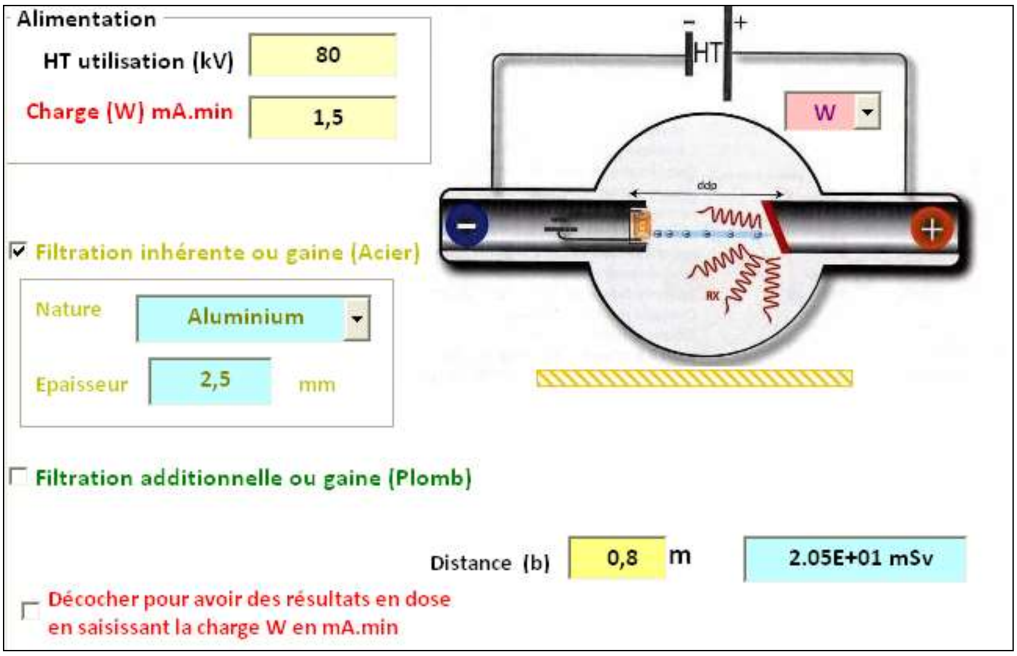
- HT: 80 kV
- I = 300 mA
- Anode: Tungsten
- Filtration: 2.5mm Al
- Exposure time: 0.3 s

In the “dose rate” mode, we obtain, for a distance of 80 cm:



Going into “Dose” mode and calculating the load for 1 shot (0.3 s):

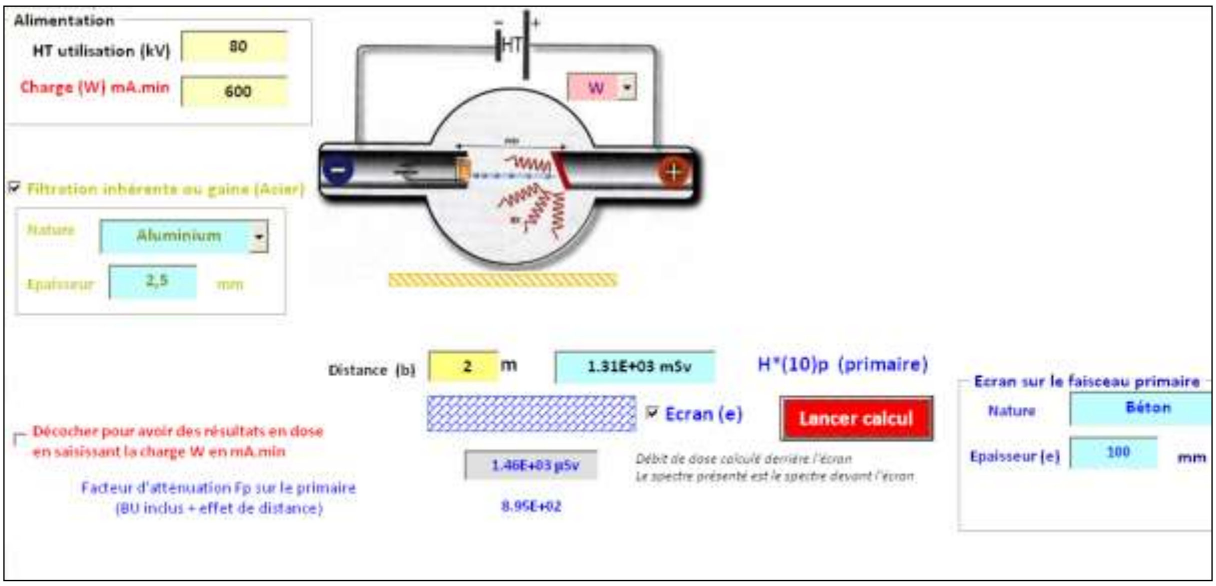
W = 300x 0.3 / 60 = 1.5 mA.min



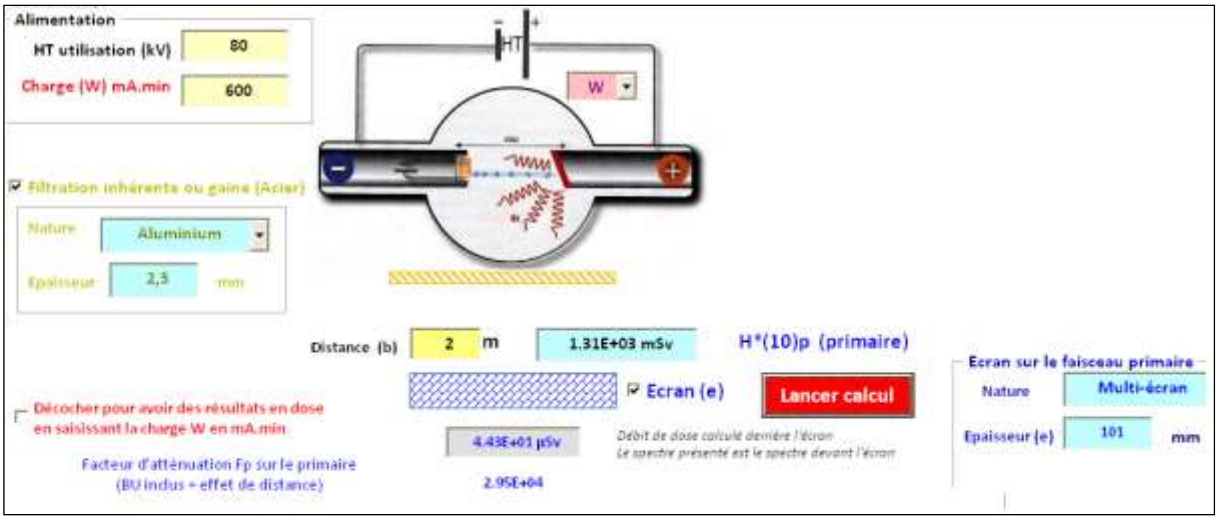
We obtain a dose of 20 mSv for one shot. This information can be interesting in terms of patient radiation protection

For standard NF C 15-160, the weekly load must be used. Considering 400 shots per week, this charge is equal to W = 1.5x400 = 600 mA.min

We can now focus on the protection of an adjacent room located at 2 m behind 10 cm of concrete



A weekly dose of 1.46 mSv is obtained. For an occupancy rate of 1, 80 µSv must be obtained per week. We can then look for the lead overprotection necessary and sufficient to keep this limit (choose multi-screen mode)



With 1 mm of lead, 44 µSv is obtained (lead thicknesses are generally in mm or half-mm of lead at least).

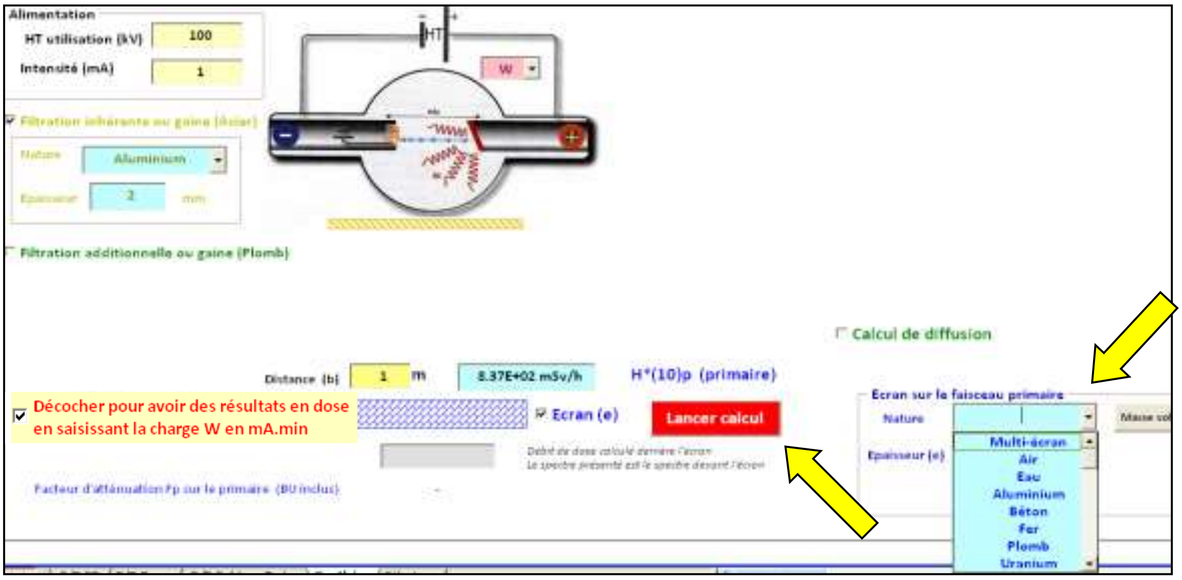
This type of calculation can be repeated for diffusion and sheath leaks.

The "Dose" mode was implemented thanks to a trick found by Dr. Dominique Schiedts

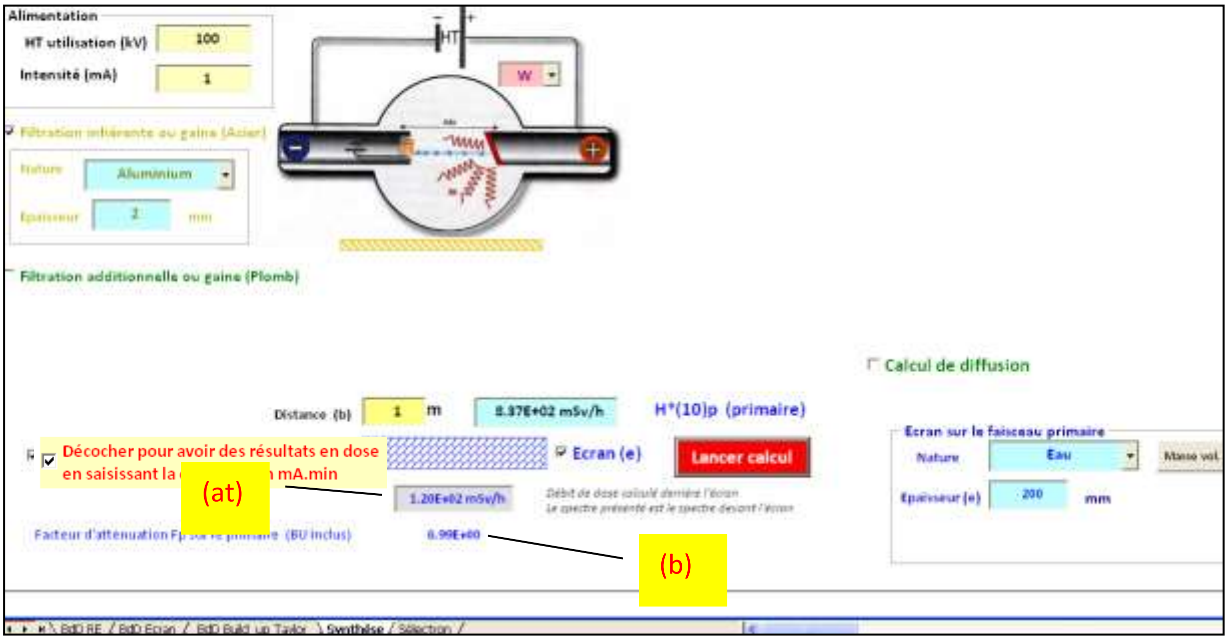
I- 4 : CALCULATION IN THE PRIMARY BEAM BEHIND A SCREEN AND ATTENUATION FACTORS

I.4.1 SCREEN ON THE PRIMARY BEAM PATH

A single screen or a multi-screen can be introduced on the path of the primary beam at distance b, specifying its nature and thickness "e" (! Unit in mm)



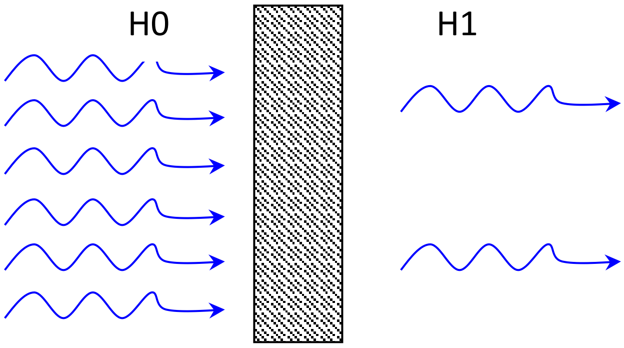
The calculation gives as information:



a) The dose equivalent rate behind the screen
b) The total effective attenuation factor calculated as the ratio of the dose without screen to the dose in the presence of a screen (factor greater than or equal to 1 except in exceptional cases *) behind this same screen. This factor is noted Fp in standard NF C15-160, but it does not have quite the same meaning here (see below)

I.4.2 DEFINITION OF MITIGATION FACTORS

In the classical approach the dose attenuation factor (or transmission factor) is defined as the ratio between the dose rate behind the screen (attenuated beam) and the dose rate before the screen.



We can write here $f = H_1/H_0 \Rightarrow H_1 = f\ H_0$ with $f < 1$ since in general $H_1 < H_0$ (except very special cases).
As an example, in a straight line attenuation calculation with build-up correction the attenuation f is calculated as $f = BU.e^{-\mu x}$. Without build-up correction we then have $f^* = e^{-\mu x} < f$ since we always have $BU > 1$.

This attenuation factor can be expressed in the form of a quotient of the form $f = 1/F$.

We thus introduce a “divisive” factor of attenuation by considering here not f But F. We will then speak of an attenuation factor of 2 for a half screen, of 10 for a tenth screen, etc. In general, the attenuation factors F will be greater than 1*.

It is in this form that the attenuation factors are presented in the N FC 15-160 standard and this is how we present them in Dosimex, for the sake of consistency but also because this presentation is more "meaningful" in an operational approach.

In this inverse acceptance of the attenuation factor, we obtain for a straight line attenuation with build correction: $F = \dfrac{e^{\mu x}}{BU}$.

The attenuation factor without build-up correction will then be $F^* = e^{\mu x} = BU.F > F$. The attenuation factor excluding build-up will therefore be higher than the included build-up attenuation factor.
This aspect of things is fundamental for the future.

** In certain exceptional cases (for example HT = 100 kV and screen of 100 mm the total attenuation factor can be less than 1. This is related to the fact that the build-up is slightly higher than the straight line attenuation factor.*

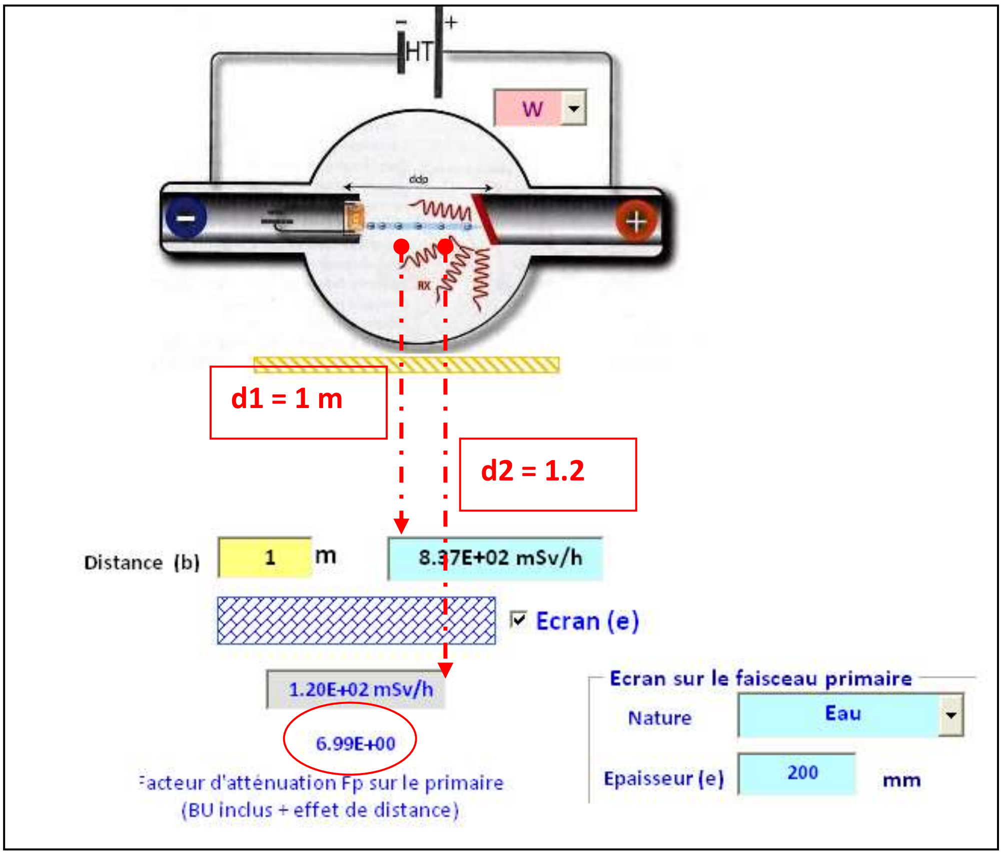
I.4.3 THE DIFFERENT MITIGATION FACTORS

To better conform to the geometry and the ratings of NF C 15-160, and for the sake of simplicity for the user, the distance (b) is the distance between the anode and the front face of the screen, unlike the previous version of Dosimex-GX (see Part III 1.2 for the normative model)

Thus the dose equivalent rate calculated behind the screen is located at the distance b + e / 100 (with regard to the units).

It is therefore important to understand that the attenuation factor given by Dosimex-GX 3.0 now takes into account, by construction, the distance effect between the dose rate at the inlet and the dose rate at the outlet of screen

In the example below the flow at the inlet is calculated at 1 m and the flow after screen is calculated at 1.2m (water screen of 200 mm):

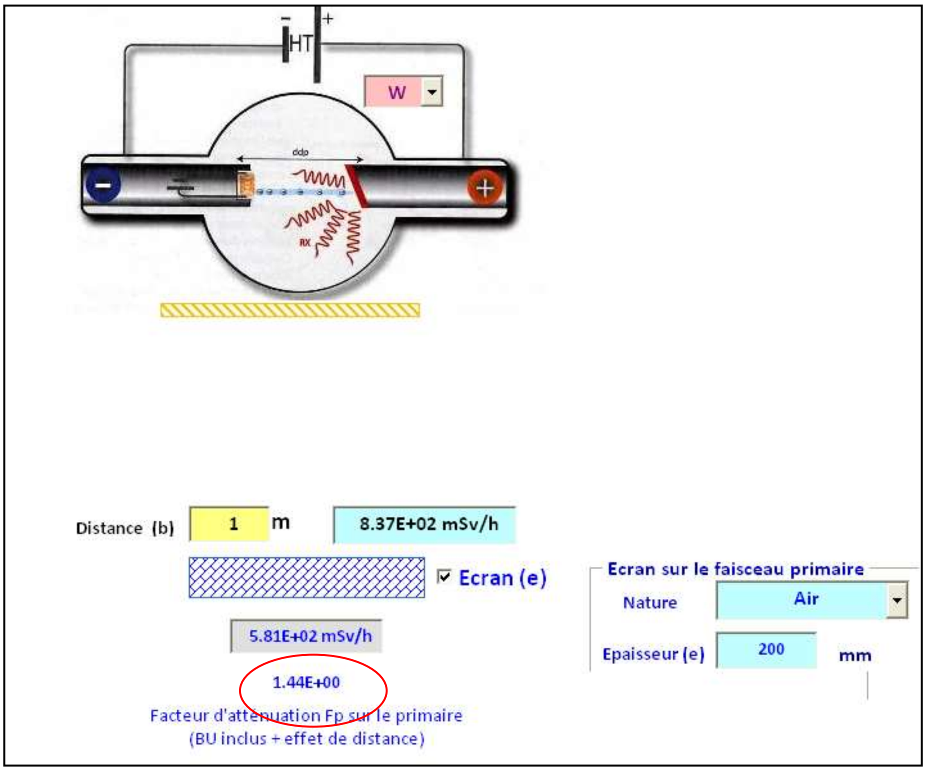


Also in this example, the attenuation factor is 6.99, but it is the product of 2 factors: the intrinsic attenuation Fe du on the screen itself, and the attenuation Fd du at the distance effect with relation:

$$F_p = F_e \; F_d$$

Considering a "point source" type model, the attenuation factor linked only to the distance effect is here equal to $F_d = d_2^2/d_1^2 = 1{,}2^2/1^2 = 1{,}44$, where there is again an attenuation factor greater than 1.

We find this value of 1.44 well by taking an air screen (with a density 100 times lower than normal air, ie a quasi-empty), knowing then that the factor "screen" F_e is then in this case simply equal to 1:

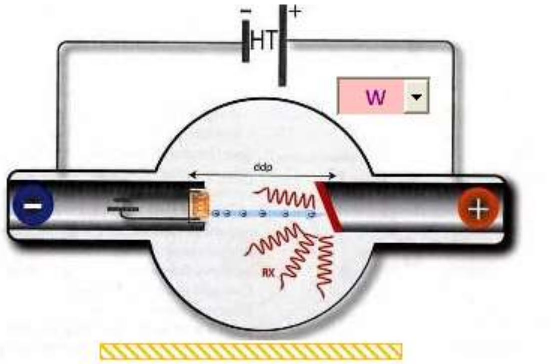


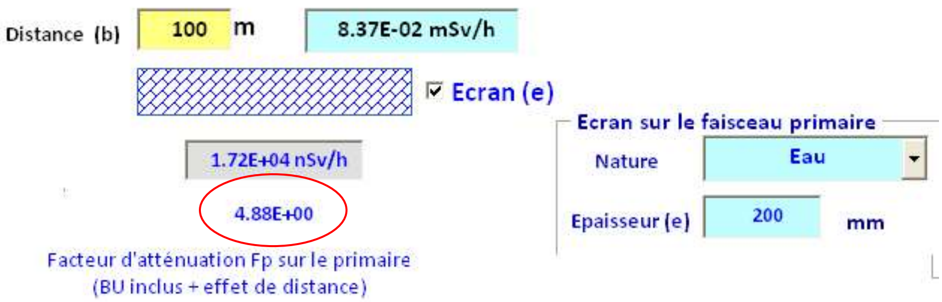
In our example we can then deduce that the attenuation F_e due only to the thickness crossed (in a model with monodirectional photons) should then be equal to $F_e = F_p/F_d = 6{,}99/1{,}44 = 4{,}85$.

Note: this attenuation factor F_e can be considered as the intrinsic attenuation provided by the presence of the screen, minus the distance effect.

This intrinsic attenuation can be found either by making a distance correction as above, or by taking a distance (b) large enough for the screen thickness (e) to be considered negligible:

This is the case in this example by taking a distance b = 100 m, i.e. a negligible distance attenuation $\left(F_d = d_2^2/d_1^2 = 100{,}2^2/100^2 = 1{,}004 \approx 1\right)$:





In addition, the attenuation factor given on the dialog box is now given by integrating the build-up, unlike the previous version of Dosimex-GX.

The average build-up is calculated over the entire spectrum and then displayed in the summary sheet, with the total attenuation factor (BU + distance effect)

Primaire Configuration avec écran de Eau de 200mm

		Avec Build-up	Sans Build-up	Build-up moyen
Prim.	Kerma	7.06E+01 mGy/h	4.08E+00 mGy/h	17,3
	H*(10)	1.20E+02 mSv/h	6.92E+00 mSv/h	Fp (BU inclus + effet de distance)
	H'(0,07)	1.11E+02 mSv/h	6.43E+00 mSv/h	6,99E+00
	Hp(10)	1.29E+02 mSv/h	7.48E+00 mSv/h	
	Hp(3)	1.16E+02 mSv/h	6.70E+00 mSv/h	
	E (AP)	9.01E+01 mSv/h	5.21E+00 mSv/h	

The flow values behind the screen are thus given with and without build-up. It is recalled that standard NF C15-160 does not take account of the build-up.

We draw the user's attention here to the fact that we can define a total of 4 different values of the attenuation factor, or more precisely different values for 4 attenuation factor having different meanings depending on the parameters taken in considerations or not.

We can consider the total attenuation factor F_p as being formed by the product of 3 factors:

- The distance attenuation factor: F_d
- The intrinsic screen attenuation factor excluding build-up: F_e^*
- BU build-up factor

We can then define:

1) The total effective attenuation factor $F_p = \frac{1}{BU}.F_e^*.F_d$ that we find only the dialog box and on the summary sheet. This factor takes into account all the real physical effects: attenuation in a straight line by the screen, build-up, distance effect

2) The effective attenuation factor excluding BU F_p^* which can be calculated from F_p :

$$F_p^* = BU.F_p\left(= F_e^*.F_d\right)$$

3) The intrinsic attenuation factor outside BU: F_e^* which can be calculated from F_p^* by correcting the distance effect

$$F_e^* = F_p^* / F_d = F_p^* \frac{b^2}{(b+e)^2} \text{ (watch out for units)}$$

4) The total intrinsic attenuation factor F_e taking into account the build-up effect and corrected for the distance effect: which can be calculated according to $F_e = \frac{1}{BU}F_e^*$

The attenuation factor found on NF C 15-160 conforms in spirit to the intrinsic attenuation factor outside BU noted here F_e^*

Let us insist again on the fact that the same calculation as previously but for a different distance b, for example 3 m, will give a different total attenuation factor: 5.53 instead of 6.99 calculated at1 m.

Distance anode/DED primaire (m) b= 3

	Primaire	Configuration avec écran de Eau de 200mm	
	Avec Build-up	Sans Build-up	Build-up moyen
Kerma	9.93E+03 µGy/h	5.74E+02 µGy/h	17,3
H*(10)	1.68E+04 µSv/h	9.73E+02 µSv/h	Fp (BU + effet de distance)
H'(0,07)	1.56E+04 µSv/h	9.04E+02 µSv/h	5,53E+00
Hp(10)	1.82E+04 µSv/h	1.05E+03 µSv/h	
Hp(3)	1.63E+04 µSv/h	9.42E+02 µSv/h	
E (AP)	1.27E+04 µSv/h	7.32E+02 µSv/h	

Prim.

The previous version did not have this effect because the value was always calculated at the same point. The screen was placed in front of the point at distance b, and not behind it, as it is now.

However, this geometry presented much more difficult interpretation difficulties in calculating the diffusion, and which did not respect the geometry of standard 15-160 included in the CEA-R 6457 report.

I- 5 : CALCULATION IN THE BEAM SCATTERED BY A SCREEN

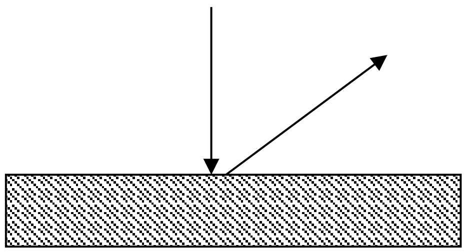
I.5.1 INPUT PARAMETERS

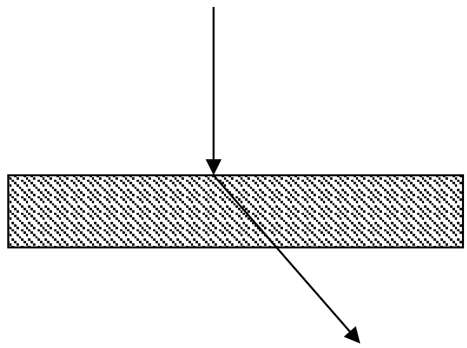
The dose rate generated by the radiation scattered by the screen placed on the path of the primary beam can be calculated. This screen thus becomes a "diffusing medium".

With version 3.0 it is now possible to calculate not only the backscattered radiation, a case which corresponds to the scenario adopted in the NFC 15-160 standard, but also the radiation scattered forward through the screen (transmitted scattering). The possible angles of diffusion are then:

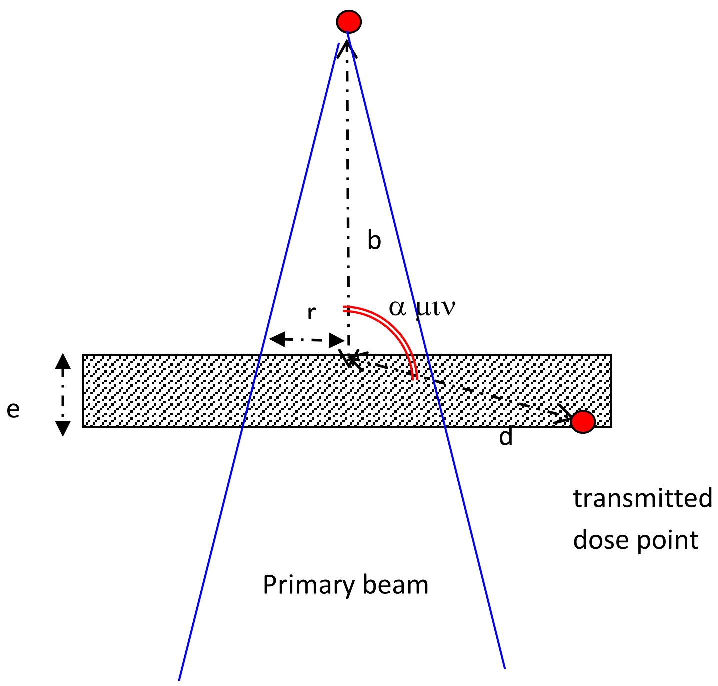
- 0 ° to 90 ° for the backscatter

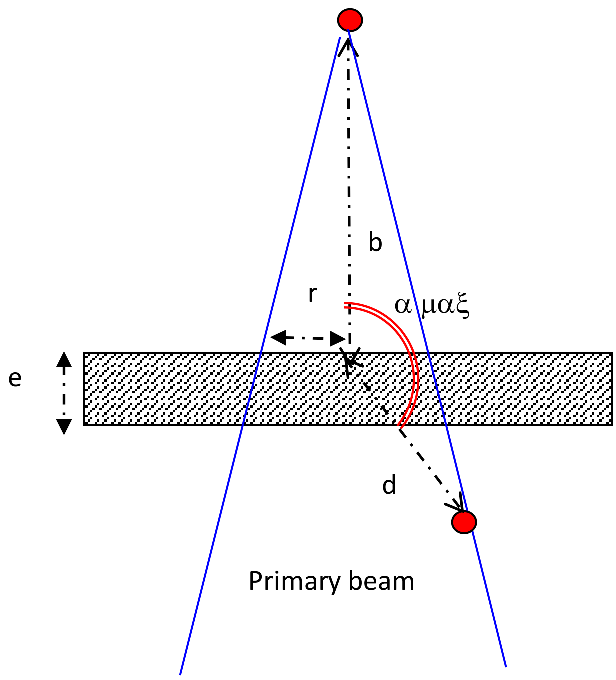
> 90 ° for the broadcast transmitted





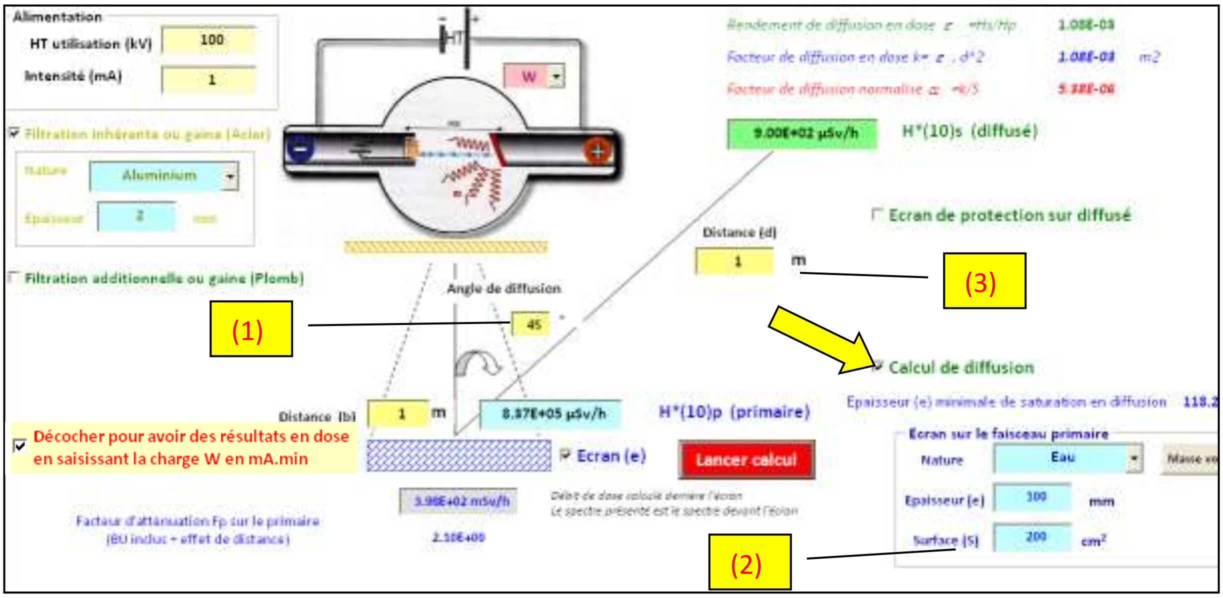
- In the latter case there are constraints on the input parameters to ensure that the calculation point is neither in the screen nor in the primary beam:





After clicking on "Distribution calculation", input fields appear. The additional information requested is:

1) The angle of diffusion, between the axis of incidence and the axis of the scattered photons <90 ° for the backscattered and> 90 ° for the transmitted scattered.
2) The surface (field) of the diffusing medium illuminated by the primary beam
3) The distance d from the center of the front face of the diffuser



Note: according to the diagram, an angle equal to 0 ° corresponds to X-rays backscattered towards the anode.

When the user chooses the nature of the diffuser screen, for a given HT, additional information appears:

Epaisseur (e) minimale de saturation en diffusion **118.26mm**

This screen thickness indicates that for lower values the dose rate broadcast may be lower, while it should hardly increase for higher values (see validation file)

Please note: the broadcast calculation does not work if the screen chosen is multi-screen

I.5.2 RESULTS OBTAINED ON THE DIFFUSION CALCULATION

I.5.3 IN THE ABSENCE OF A SCREEN ON THE BROADCAST PATH

The essential results obtained on the broadcast are:

- The dose equivalent rate at distance d:

9.00E+02 µSv/h	H*(10)s (diffusé)

- Broadcast parameters:

Rendement de diffusion en dose ε =Hs/Hp	1.08E-03	
Facteur de diffusion en dose k= ε . d^2	1.08E-03	m2
Facteur de diffusion normalisé α =k/S	5.38E-06	

These various parameters and their respective interests are explained in § III.2.2. The main thing is to know that they are related to the CEA-R 6452 report and the NF C15-160 standard.

Essentially these three parameters are defined by:

- 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)
- $\alpha = k/S = \varepsilon_{diff} \big/ S\, d_2^2$, 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.

See explanations in part III.

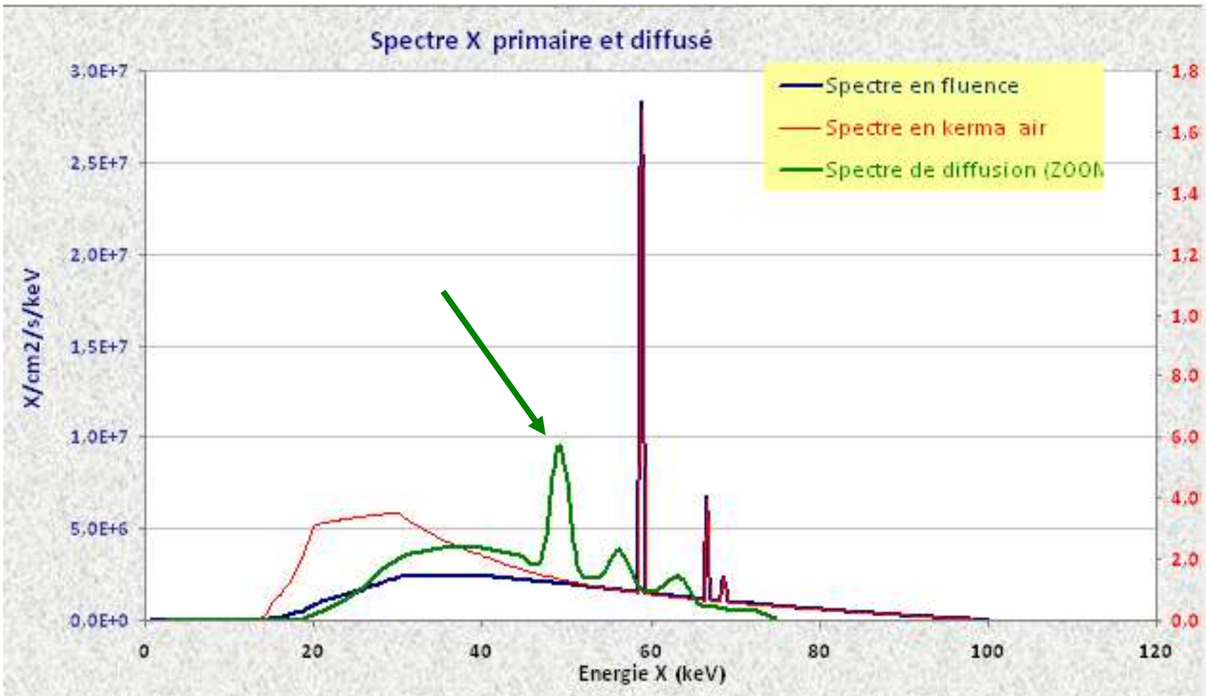
We find on the summary sheet:

- the other radiometric quantities for the scattered component as well as the 3 scattering parameters mentioned above:

		Avec Build-up	Sans Build-up	Build-up moyen	
Prim.	Kerma	2.43E+02 mGy/h	4.00E+01 mGy/h	6.07	
	H*(10)	3.98E+02 mSv/h	6.56E+01 mSv/h	Fp (BU + eff. dist.)	
	H'(0,07)	3.74E+02 mSv/h	6.16E+01 mSv/h	2.10E+00	
	Hp(10)	4.26E+02 mSv/h	7.02E+01 mSv/h		
	Hp(3)	3.88E+02 mSv/h	6.39E+01 mSv/h		
	E (AP)	2.84E+02 mSv/h	4.68E+01 mSv/h	BU diff. (1)	
Diff.	*Kerma*	6.48E+02 µGy/h	*3.86E+02 µGy/h*	1.68	Rend. diff.
	H(10)*	9.00E+02 µSv/h	*5.35E+02 µSv/h*	Fs	1.08E-03
	H'(0,07)	9.02E+02 µSv/h	*5.36E+02 µSv/h*		k (m^2)
	Hp(10)	9.39E+02 µSv/h	*5.59E+02 µSv/h*		1.08E-03
	Hp(3)	9.20E+02 nSv/h	*5.47E+02 µSv/h*		alpha
	E (AP).	5.17E+02 nSv/h	*3.07E+02 µSv/h*		5.38E-06

- The spectrum of the scattered component.

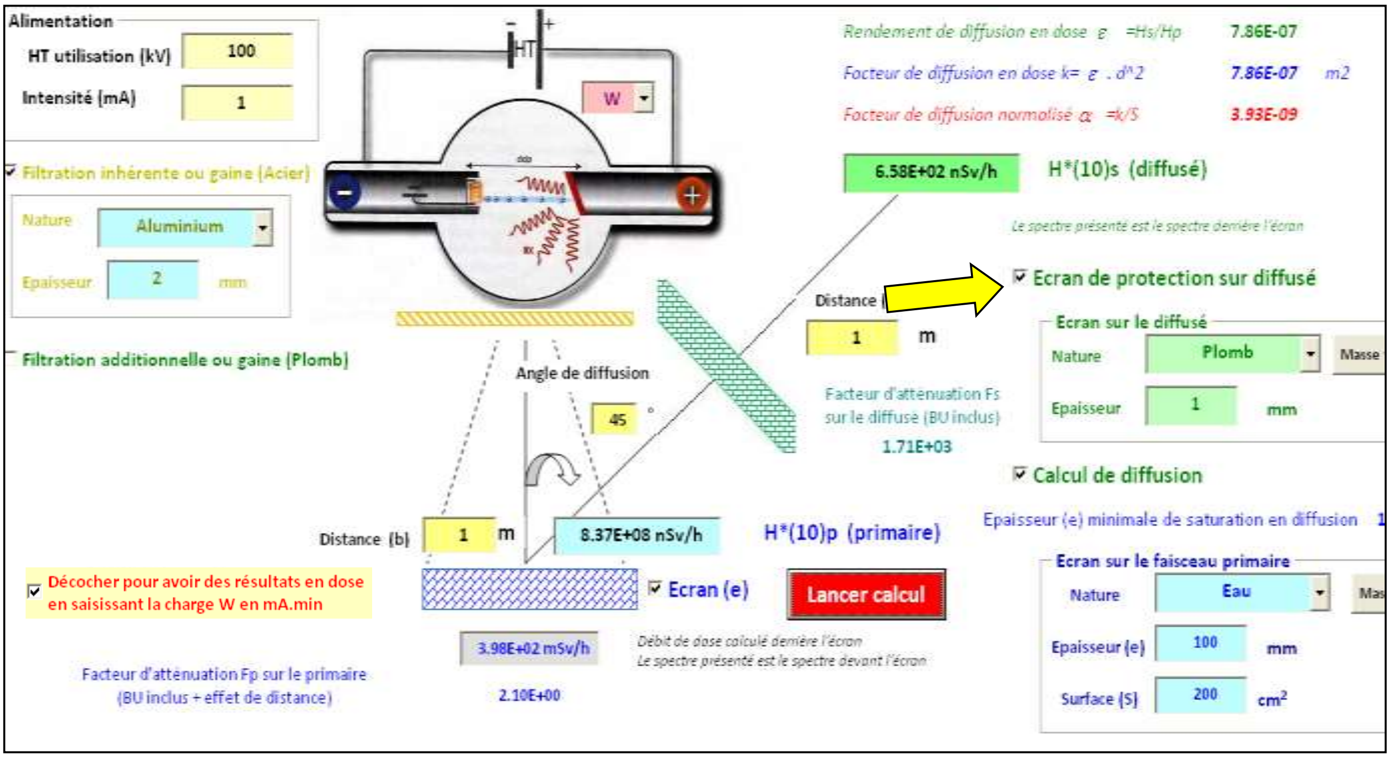
The height (or surface) of this spectrum is not in real proportion of the scattered component compared to the spectrum of the primary component. Here it is normalized (zoomed in) to be visible.



We observe, from the tungsten fluorescence peaks, a downward sliding of the energies of the scattered photons, in accordance with the Compton scattering phenomenon (see MRI photon gamma Compton tab). This sliding depends on the angle of diffusion chosen.
This effect is not without consequence in particular on the attenuation factors and the build-up coefficients which will then be different for the same screen on the primary and on the broadcast

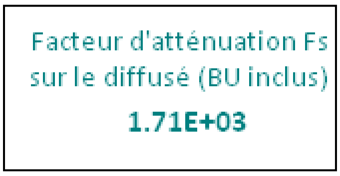
I.5.4 IF THERE IS A SCREEN ON THE BROADCAST PATH

You can place a screen on the broadcast path:



Contrary to the case of the screen on the primary, the dose equivalent flow is taken here at the same distance with or without screen. Thus the attenuation calculation does not take into account the effect of distance.

The attenuation factor given in the dialog box is therefore an intrinsic attenuation factor taking into account the build-up note Fs:



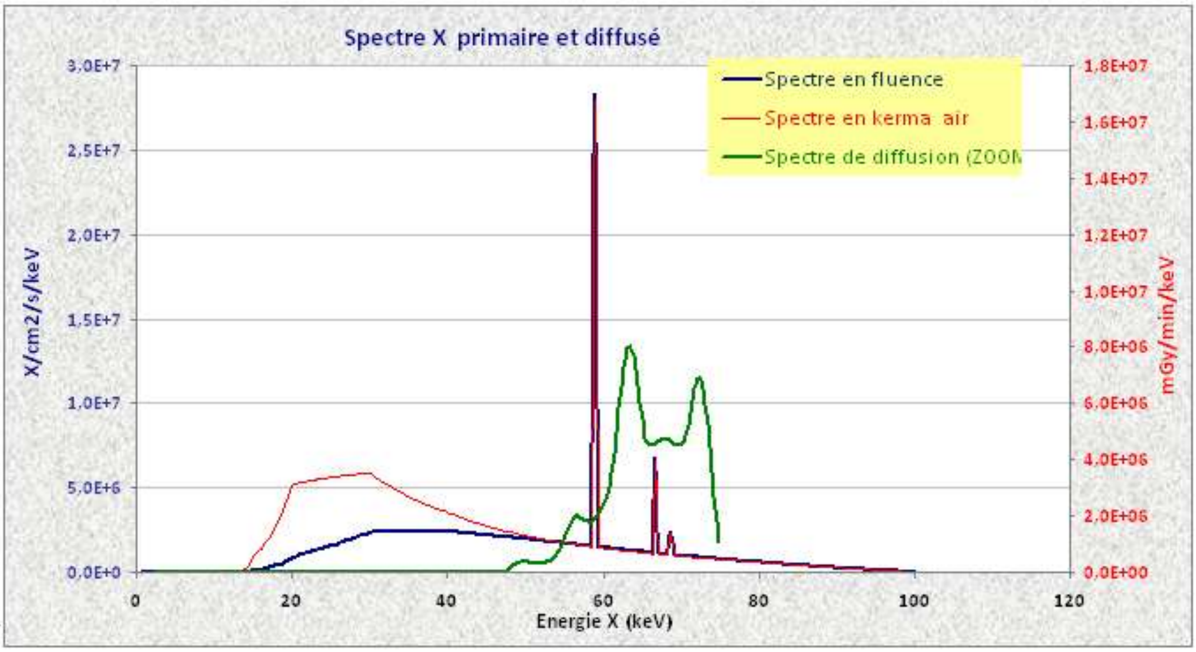
This attenuation factor as well as the build-up factor are given in the summary sheet:

		Avec Build-up	Sans Build-up	Build-up moyen	
Prim.	Kerma	2.94E+02 mGy/h	5.09E+01 mGy/h	5.78	
	H*(10)	4.76E+02 mSv/h	8.23E+01 mSv/h	Fp (BU + eff. dist.)	
	H'(0,07)	4.49E+02 mSv/h	7.77E+01 mSv/h	3.75E+00	
	Hp(10)	5.08E+02 mSv/h	8.79E+01 mSv/h		
	Hp(3)	4.66E+02 mSv/h	8.06E+01 mSv/h		
	E (AP)	3.33E+02 mSv/h	5.76E+01 mSv/h	BU diff. (1+2)	
Diff.	*Kerma*	4.35E+02 nGy/h	*4.02E+02 nGy/h*	1.08	Rend. diff.
	H(10)*	7.56E+02 nSv/h	*6.99E+02 nSv/h*	Fs	4.23E-07
	H'(0,07)	7.04E+02 nSv/h	*6.51E+02 nSv/h*	2.77E+03	k (m^2)
	Hp(10)	8.17E+02 nSv/h	*7.56E+02 nSv/h*		4.23E-07
	Hp(3)	7.30E+02 nSv/h	*6.76E+02 nSv/h*		alpha
	E (AP).	5.91E+02 nSv/h	*5.47E+02 nSv/h*		2.12E-09

For the build-up values in this particular case of the diffusion in a first screen and the attenuation in a second, see next chapter.

The spectrum of the scattered radiation is then the spectrum behind the screen, unlike the primary spectrum which is always the one before the screen.

On the present example, we note the strong hardening of the spectrum behind 1 mm lead.



Here again, the height of the spectrum is not, for obvious reasons of readability, in proportion to its real value compared to the primary spectrum or to the previous spectrum without a screen.

I- 6 : BUILD-UP MANAGEMENT

I.6.1 BUILD –UP ON THE PRIMARY SCREEN

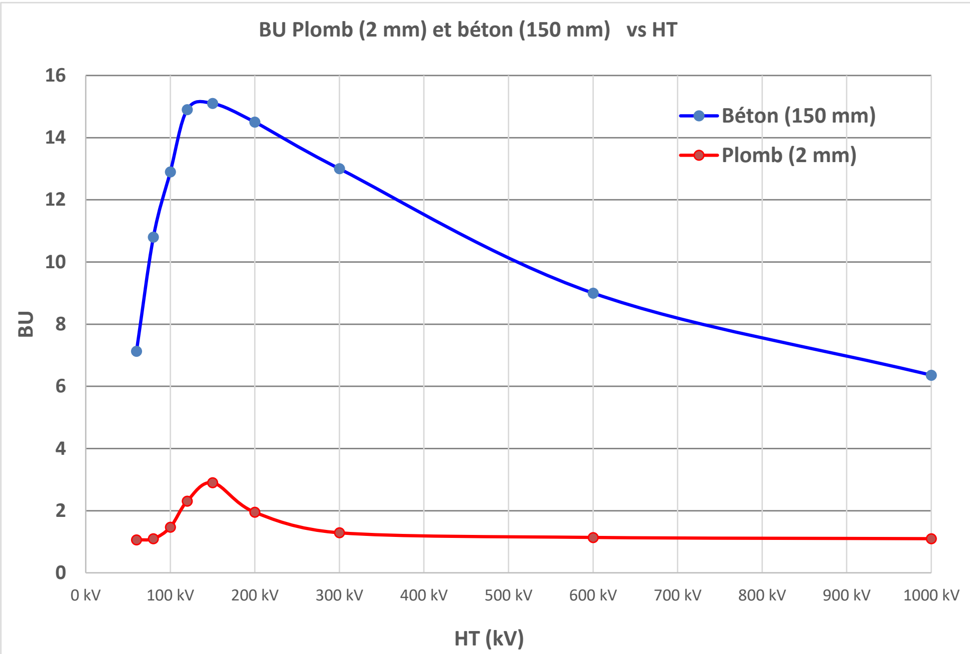
We give below some build up values calculated in concrete and lead, for information. We also remind here that the standard NF C 15-160 does not take account of the build-up.

For more information on the build-up concept see "Dose calculation…" § 6.1.6.3 p 258 and appendix N.

Note: the build-up given here is a dose-average build-up obtained on the continuous spectrum. It is obtained by first calculating the build-up for each energy of the discretized spectrum in the same way as on the monoenergetic calculations for the gamma. The average value is calculated as an average of all of these build-ups weighted by the corresponding dose for each energy (concept of dose average)

Build-up values in a concrete wall 150 mm thick and in a lead screen of 2 mm thickness:

HT	Concrete 150 mm	Lead 2 mm
60 kV	7.13	1.06
80 kV	10.8	1.1
100 kV	12.9	1.47
120 kV	14.9	2.31
150 kV	15.1	2.9
200 kV	14.5	1.95
300 kV	13	1.29
600 kV	9	1.14
1000 kV	6.36	1.1

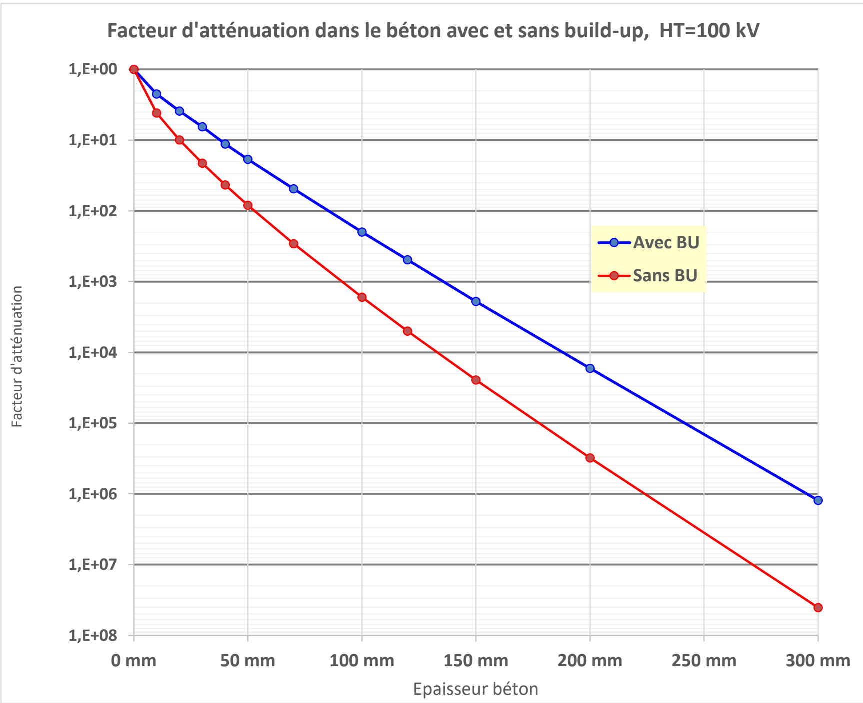


The build-up remains modest in lead, but for all that it is not always negligible and can go up to a factor of 3, and even more if one increases the thickness of lead of course

In concrete, more diffusing environments, the build-up is high and largely significant

Still for information, we give below the attenuation curves in concrete for a HT of 100 kV, one calculated with build-up and the other without build-up. To get rid of the distance effect with a screen of variable thickness, the calculations were performed with a distance b of100 m.

thickness (mm)	DRANK	Fp (BU included)	F * p (excluding BU)
0	1	1	1
10	1.86	2.22	4.1
20	2.57	3.87	9.9
30	3.28	6.47	21
40	3.8	11.3	42
50	4.47	18.6	83
70	5.98	48.6	290
100	8.35	199	1661
120	10.19	491	5003
150	12.88	1.90E + 03	2.4 E + 04
200	18.46	1.68E + 04	3.1E + 05
300	32.6	1.24E + 06	4.0E + 07



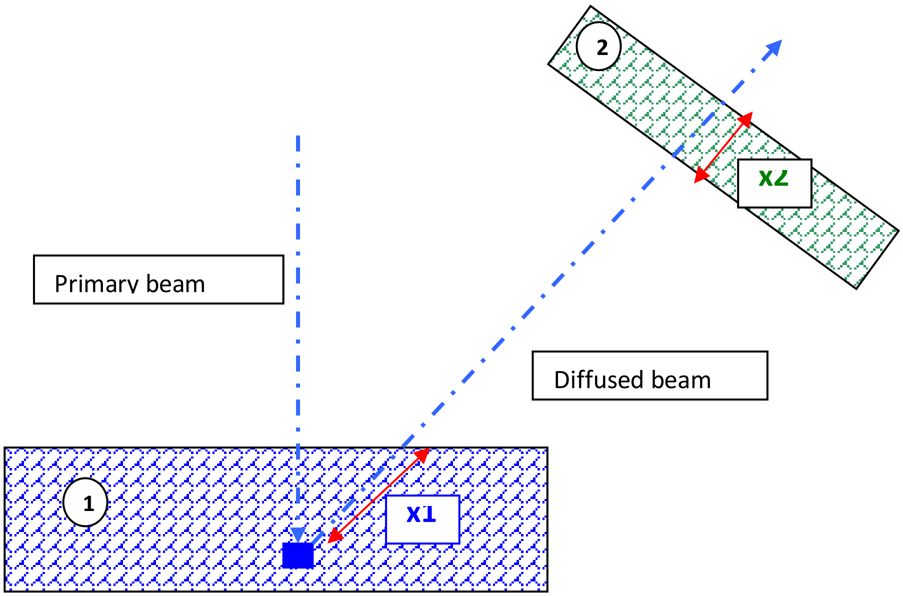
We see that the attenuation curve excluding build-up is very optimistic, and thus minimizes the calculation of the dose rate behind the screen in proportions that increases with the screen thickness.

I.6.2 BUILD-UP ON THE BROADCAST

The build-up on the scattered beam is calculated according to the same principles as for a volume source and a screen.

Here the diffusing screen placed on the path of the primary (screen 1) acts as a source of scattered radiation. Each volume element on this screen behaves like an elementary X-ray emitting volume (obtained in the diffusion calculation, see below). Outside this scattered radiation undergoes a phenomenon of self-absorption but also of diffusion on its pathx1in the screen before emerging. This scattering effect (that is to say effectively scattering on the scattered radiation, we are indeed in the presence of a multi-scattering phenomenon here) is taken into account by the build-up factor calculated in a conventional manner depending on the nature of the screen, the energy of the photons and the value ofx1.

This build-up factor is then combined in the usual way with the build-up factor of the radiation emerging through the screen 2.



The build-up thus obtained, and displayed in the summary sheet, is not the intrinsic build-up of the screen on the path of the broadcast, but takes account of the build-up in the diffuser screen. This effect has 2 consequences:

- **Consequence 1**: If there is no screen 2 on the broadcast path, a build-up value different from 1 is displayed on the summary sheet. In this case, this is the build –up in re-emission calculated in screen 1. It is notedBU (1).

- **Consequence 2** : In the presence of a screen on the broadcast, the value of the build-up displayed in the summary sheet, noted then BU (1 + 2) may vary considerably depending on the nature of the diffuser screen (1)

Example: calculation with HT = 100 kV of the valueBU (1 + 2) for a screen (2) of 100 mm of water placed on the path of the diffuser for two different diffusers screen: a screen (1) of 400 mm thick (very diffusing) then a lead screen of 1 mm thick (not very diffusing).

		Primaire	Configuration avec écran de Eau de 400mm		
		Diffusé	Configuration avec écran Eau de 100mm		
		Avec Build-up	Sans Build-up	Build-up moyen	
Prim.	Kerma	4.42E+03 µGy/h	6.78E+01 µGy/h	65,12	
	H*(10)	7.58E+03 µSv/h	1.16E+02 µSv/h	Fp (BU + eff. dist.)	
	H'(0,07)	7.03E+03 µSv/h	1.08E+02 µSv/h	2,36E+02	
	Hp(10)	8.26E+03 µSv/h	1.27E+02 µSv/h		
	Hp(3)	7.33E+03 µSv/h	1.13E+02 µSv/h		
	E (AP)	5.92E+03 µSv/h	9.09E+01 µSv/h	BU diff. (1+2)	
Diff.	*Kerma*	5.12E+02 µGy/h	*7.60E+01 µGy/h*	6,73	Rend. diff.
	H(10)*	8.18E+02 µSv/h	*1.21E+02 µSv/h*	Fs	4,58E-04
	H'(0,07)	7.69E+02 µSv/h	*1.14E+02 µSv/h*	4,99E+00	k (m^2)
	Hp(10)	8.59E+02 µSv/h	*1.28E+02 µSv/h*		4,58E-04
	Hp(3)	7.98E+02 nSv/h	*1.19E+02 µSv/h*		alpha
	E (AP).	5.34E+02 nSv/h	*7.94E+01 µSv/h*		1,15E-06

		Primaire	Configuration avec écran de Plomb de 0,1mm		
		Diffusé	Configuration avec écran Eau de 100mm		
		Avec Build-up	Sans Build-up	Build-up moyen	
Prim.	Kerma	1.93E+02 mGy/h	1.87E+02 mGy/h	1,04	
	H*(10)	3.18E+02 mSv/h	3.05E+02 mSv/h	Fp (BU + eff. dist.)	
	H'(0,07)	2.98E+02 mSv/h	2.86E+02 mSv/h	5,62E+00	
	Hp(10)	3.40E+02 mSv/h	3.27E+02 mSv/h		
	Hp(3)	3.09E+02 mSv/h	2.97E+02 mSv/h		
	E (AP)	2.26E+02 mSv/h	2.18E+02 mSv/h	BU diff. (1+2)	
Diff.	*Kerma*	9.98E+00 µGy/h	*2.62E+00 µGy/h*	3,80	Rend. diff.
	H(10)*	1.64E+01 µSv/h	*4.31E+00 µSv/h*	Fs	9,17E-06
	H'(0,07)	1.52E+01 µSv/h	*4.01E+00 µSv/h*	1,31E+01	k (m^2)
	Hp(10)	1.74E+01 µSv/h	*4.58E+00 µSv/h*		9,17E-06
	Hp(3)	1.59E+01 nSv/h	*4.18E+00 µSv/h*		alpha
	E (AP).	1.13E+01 nSv/h	*2.99E+00 µSv/h*		2,29E-08

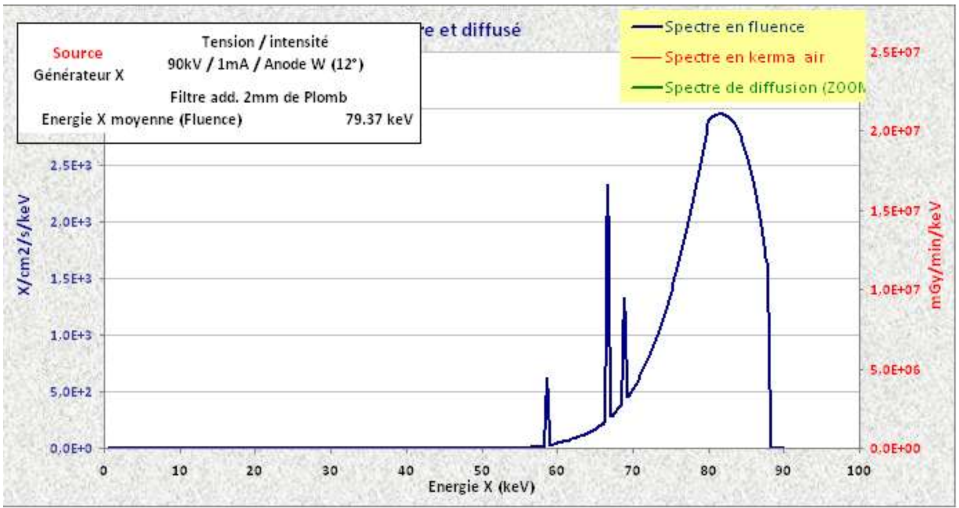
This observation makes it possible to identify a method for estimating the intrinsic average build-up of screen 2 if necessary: it is necessary to set up a very thin screen 1 in terms of average free path in front of screen 2.

It should not be forgotten that it is above all the value µx (number of relaxation length or thickness of the screen in average free path unit) which is taken into account for the combination of build-ups

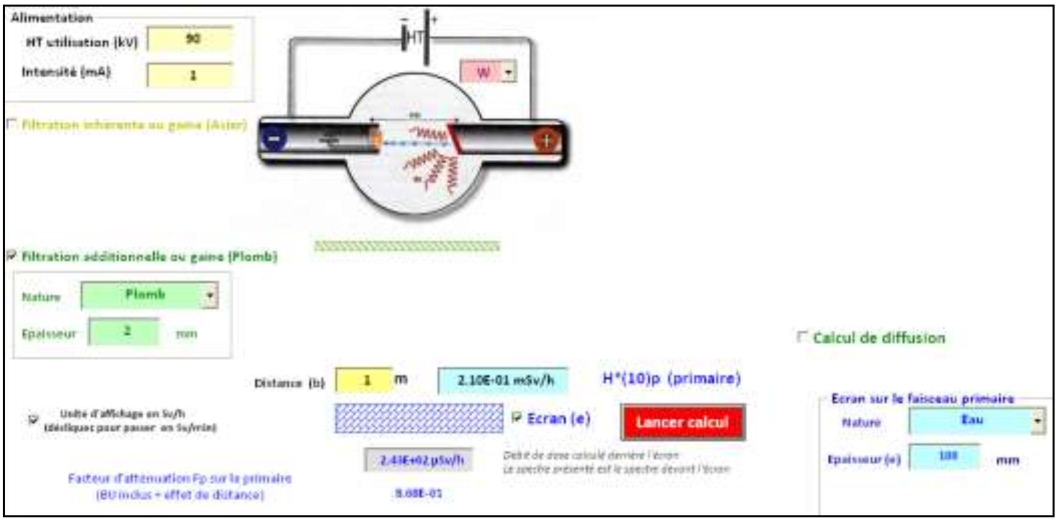
I.6.3 VALIDATION OF BUILD-UP CALCULATION

I.6.3.1 On the primary spectrum

The previous remark allowed us a minimum validation of the build-up values thus obtained. First, having no reference to build-ups averaged over continuous spectra, we hardened the primary spectrum using an input window of2 mmlead for a HT of 90 keV. This gives a very sharp spectrum centered on an average energy of 80 keV:



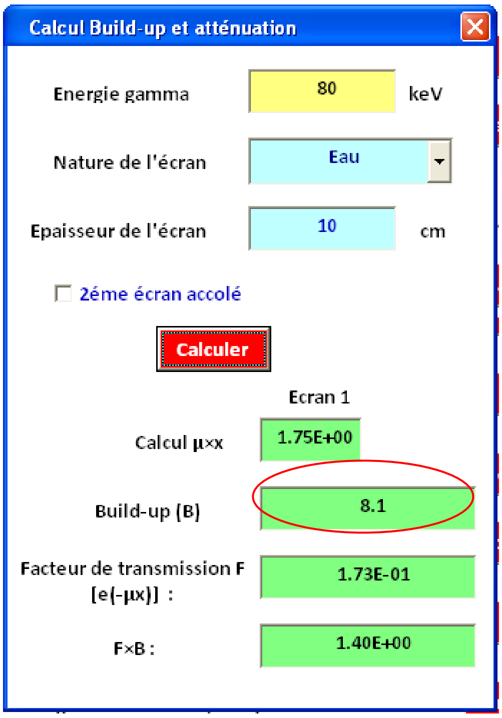
Using this primary spectrum to calculate the build-up for a screen of 100 mm of water:



We get a build-up of 8.11:

	Primaire	Configuration avec écran de Eau de 100mm	
	Avec Build-up	Sans Build-up	Build-up moyen
Kerma	1.41E+02 µGy/h	1.74E+01 µGy/h	8,11
H*(10)	2.43E+02 µSv/h	2.99E+01 µSv/h	Fp (BU + eff. dist.)
H'(0,07)	2.23E+02 µSv/h	2.75E+01 µSv/h	8,68E-01
Hp(10)	2.69E+02 µSv/h	3.32E+01 µSv/h	
Hp(3)	2.36E+02 µSv/h	2.91E+01 µSv/h	
E (AP)	1.99E+02 µSv/h	2.45E+01 µSv/h	

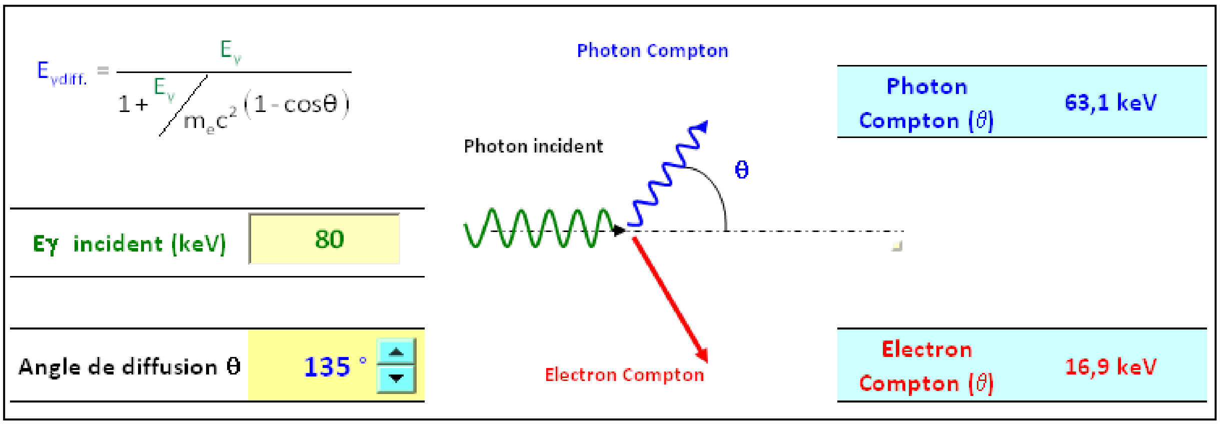
This result should be compared to the calculation on a monoenergetic value with the “buid-up” option of Dosimex-GX:



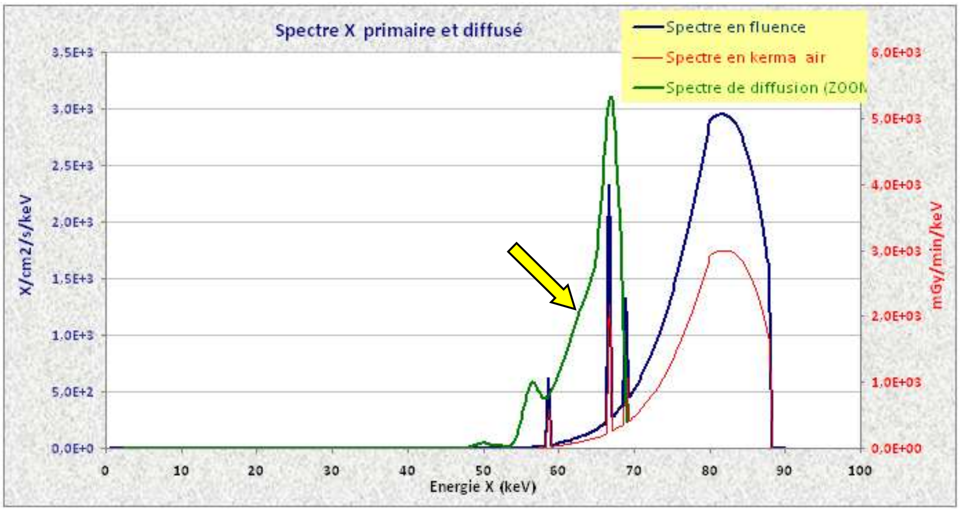
Recall here that these build-up values are obtained by logarithmic interpolation of the reference values tabulated in the ANS / ANSI document (see gamma validation file)

I.6.3.2 Build-up on the broadcast

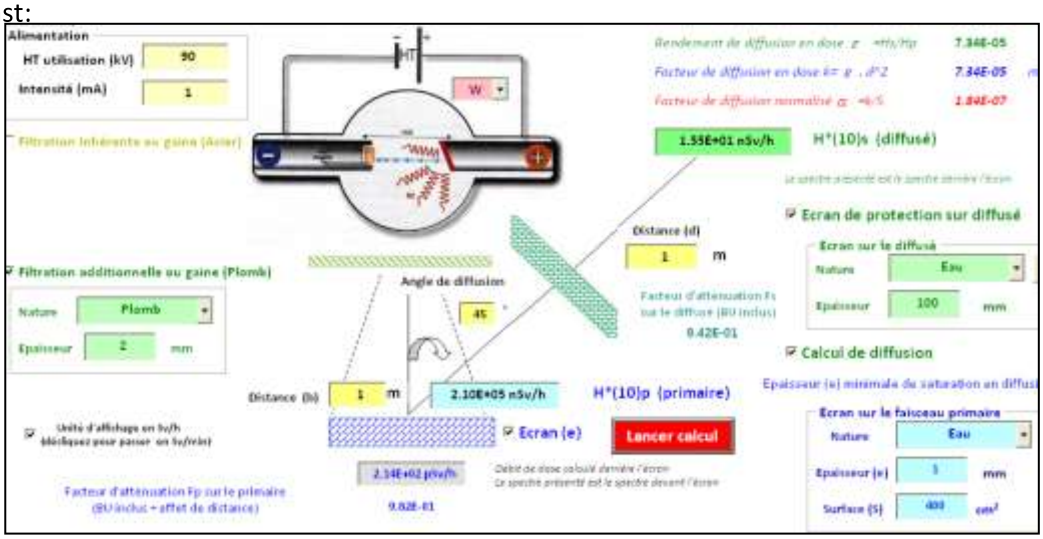
Using this same primary spectrum very hardened at 80 keV, we can expect for a 45 ° backscatter (or 135 ° counted in the opposite direction) to a quasi-monoenergetic spectrum at 63 keV (see MRI Photon Compton tab):



Which is consistent with the scattered spectrum obtained with Dosimex-GX



By taking a very thin diffuser screen (1) (1 mm water) in front of the screen (2) placed on the path of the broadcast:

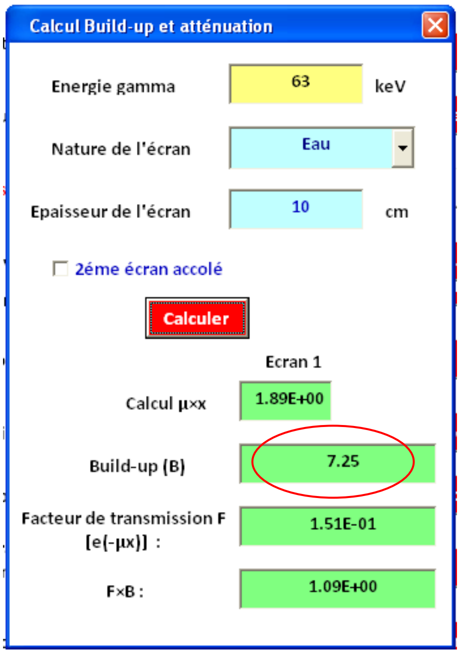


We then obtain a good estimate of the intrinsic build-up of the screen of 100 mm on the broadcast:

Primaire — Configuration avec écran de Eau de 1mm
Diffusé — Configuration avec écran Eau de 100mm

		Avec Build-up	Sans Build-up	Build-up moyen	
Prim.	Kerma	1.25E+02 µGy/h	1.20E+02 µGy/h	1,04	
	H*(10)	2.14E+02 µSv/h	2.06E+02 µSv/h	Fp (BU + eff. dist.)	
	H'(0,07)	1.97E+02 µSv/h	1.90E+02 µSv/h	9,82E-01	
	Hp(10)	2.38E+02 µSv/h	2.29E+02 µSv/h		
	Hp(3)	2.09E+02 µSv/h	2.01E+02 µSv/h		
	E (AP)	1.76E+02 µSv/h	1.69E+02 µSv/h	BU diff. (1+2)	
Diff.	Kerma	8.86E+00 nGy/h	1.22E+00 nGy/h	7,25	Rend. diff.
	H*(10)	1.55E+01 nSv/h	2.13E+00 nSv/h	Fs	7,34E-05
	H'(0,07)	1.44E+01 nSv/h	1.98E+00 nSv/h	9,42E-01	k (m²)
	Hp(10)	1.66E+01 nSv/h	2.29E+00 nSv/h		7,34E-05
	Hp(3)	1.49E+01 nSv/h	2.06E+00 nSv/h		alpha
	E (AP).	1.20E+01 nSv/h	1.66E+00 nSv/h		1,84E-07

Value confirmed by calculation in monoenergetics:



We can then note that for the same screen, depending on whether it is placed on the primary or broadcast path, the build-up is different because the incident spectra are different. It is the same for the intrinsic attenuation factors which will be generally, for the same screen, higher on the broadcast than on the primary, always due to the shift of the broadcast spectrum towards lower energies.

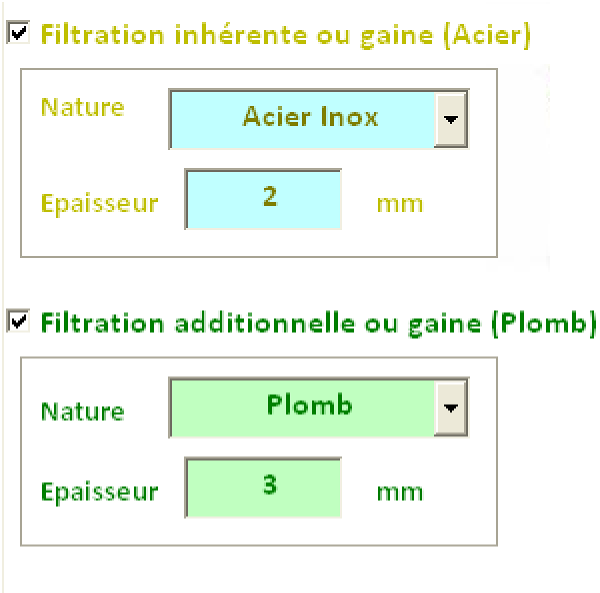
I- 7 : Sheath leakage calculation

One of the 3 components taken into consideration in standard NF 15-160 is that of the sheath leak. The model used in the standard is based on rarely known and somewhat esoteric parameters. The values taken by default in the standard quite often lead to pessimistic results (ie DED higher than reality)

However, on the physical level, the sheath radiation is simply conditioned by the nature and thickness of said sheath which surrounds and protects the tube X (excluding collimator), generally steel often lined with lead. It will be noted that under these conditions the cladding leakage spectrum is a very hardened quasi-monoenergetic spectrum with a value close to the maximum value of the spectrum (HT).

This aspect conditions the attenuation factors on the sheath leakage component, factors which are weaker than on the primary spectrum.

To find out the dose equivalent flow rate due to the sheath leak, simply replace the filters placed on the collimator (a hole in the sheath) with the corresponding thicknesses of steel and / or lead:



The results obtained under these conditions are more realistic than the values obtained (implicitly) in the standard.

Note: it is not always easy to have sectional plans of the tube and its sheath, so do not hesitate to insist with the distributor or the manufacturer to know the thickness and the nature of the sheath.