

Harmonex X-Ray Tutorial

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Introduction

Harmonex *X-Ray* can be applied to x-ray calculations from the most common lab situations to sophisticated research topics. In this article, we show you how to use *X-Ray* by examples. In each example, we introduce the problem, discuss the physics of the equations and formulas, and then use *X-Ray* to solve the problem. We have included spreadsheets of the calculations in the examples. These were created with Harmonex *X-Ray*. For each example, you can open the spreadsheet and follow along with the calculations. Then, the spreadsheets can be re-used and combined for your own calculations. The diskette provided is for Windows so the files can be opened directly by Microsoft Excel. To use on a Macintosh, convert the files with the Apple File Exchange utility. Then open the files from within Excel (using $\text{⌘} \text{O}$).

Because *X-Ray* provides both physical data and a software environment for doing calculations, its potential applications are unlimited. A solution to a particular problem with *X-Ray* is implemented in a spreadsheet. The spreadsheet contains both x-ray data, calculations, and parameters. In this tutorial, you will see how to set up a spreadsheet to do useful calculations that previously required a specially written program. This approach gives you a way to implement the calculations that are done repeatedly and also to rapidly modify and extend them for new situations.

The examples that we will discuss are:

1. calculate image values in a computed tomography image,
2. design shielding for a Co^{60} Source,
3. calculate exposure (Roentgens) with an industrial x-ray tube source, and
4. compute (photons/cm²)/milliRoentgen for molybdenum anode tubes.

If you wish to discuss your particular application, please give us a call.

Before we begin our discussion of the examples, we will introduce the use of the spreadsheet user "front-end" with *X-Ray*.

Spreadsheets for X-Ray Calculations

The tools typically used for x-ray calculations are hand calculators or writing and compiling programs in languages such as Fortran or C. Hand calculations give quick results but are error prone and tedious for calculations of any complexity. Compiled programs can process large amounts of data but are difficult to write, test and debug. Spreadsheets provide an alternative intermediate between these two methods. Calculations can be started and done as quickly as by hand. Data can be entered directly

into spreadsheet cells and calculations done by simply by entering formulas into other cells. Modern spreadsheets provide a variety of built in mathematical functions to implement the calculations. The spreadsheet interface provides the capabilities shown in Table 1.

Table 1
Calculation Capabilities of the Interface

<p>Mathematical Functions</p> <ul style="list-style-type: none"> exponential logarithm trigonometric 	<p>Statistical</p> <ul style="list-style-type: none"> average median variance standard deviation
<p>Matrix</p> <ul style="list-style-type: none"> multiply inverse determinant 	<p>Database</p> <ul style="list-style-type: none"> lookup match index

The spreadsheet can also process large amounts of data like a compiled program. Different cases can be handled by entering the data in a column and then copying the formulas that implement the calculations. The spreadsheet will automatically do the computation with the corresponding data. Examples of the use of the spreadsheet to process data sets are given later. For sophisticated users, the spreadsheet also provides a powerful macro language with capabilities similar to compiled computer languages.

Although the capabilities listed in Table 1 are powerful, they, of course, do not provide the physical data required for x-ray calculations. These data are provided by the *X-Ray* program tools. The examples show how to combine the data with these tools to provide complete calculations.

Example 1. Computed Tomography Image Value

X-ray computed tomography (CT) provides images with two unique characteristics. The most widely known feature of CT is that it gives an image of a cross section slice through an object. But perhaps equally important is that the image is a highly accurate "map" of the the linear attenuation coefficient of the material of the object. The x-ray attenuation coefficient varies strongly with energy so the CT value of an object depends on the energy spectrum used to measure it. The first example shows how the x-ray software tools can be used with the spreadsheet functions to calculate the average attenuation coefficient, and therefore the CT value. To carry out this calculation, we will need two quantities: the attenuation coefficient $\mu(E)$ and the spectrum $S(E)$. With these quantities, one way to define the average attenuation coefficient $\bar{\mu}$ is

$$\bar{\mu} = -\frac{1}{L} \ln \left(\frac{\int_0^{eV} S(E) \exp(-L\mu(E)) dE}{\int_0^{eV} S(E) dE} \right) \quad (1)$$

where L is the thickness of the object, e is the charge of an electron and V is the tube voltage so eV is the maximum energy in the tube's spectrum. Notice that the quantity in brackets is the transmission τ (the flux with the object in the x-ray beam divided by the flux with no object). Equation 1 simply solves the equation, $\tau = \exp(-\bar{\mu} L)$, for the average attenuation coefficient $\bar{\mu} = -\frac{1}{L} \ln(\tau)$.

We will show how to implement Equation 1 using the *X-Ray* software tools. We will assume the object consists of water. The menubar in Figure 1 shows the categories of tools available—the **Attenuation** menu is pulled down displaying its tools.

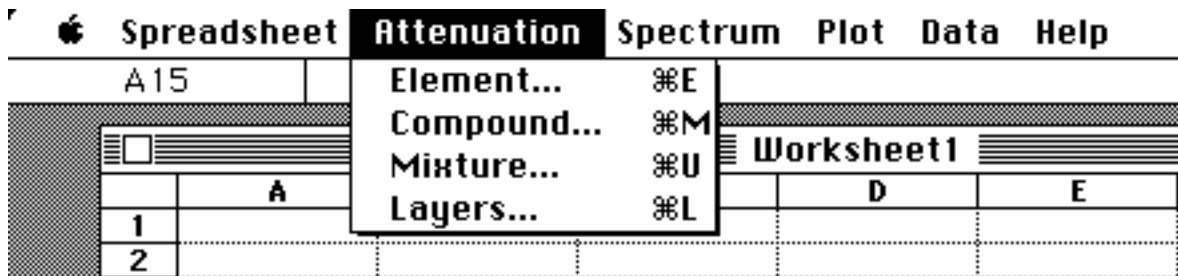


Figure 1 **Software menu bar. This shows the categories of tools available for building software models. The Attenuation menu is pulled down showing its tools.**

Suppose we want to calculate the average linear attenuation coefficient of water. We select **Compound** in the **Attenuation** menu which brings up the dialog box in Figure 2. We specify the material by using its chemical symbol, for example H₂O for water. In the Output Units box we can specify the linear attenuation coefficient. This requires the density (which is, of course, 1.0 for water). Clicking on **OK** causes the server to calculate the attenuation coefficient and place the results in the spreadsheet. The results are shown in columns C and D of Figure 3. The value in D1 is the density used in the calculation.

Attenuation Coefficients of Compound

formula:

Start Energy (keV):
 or Energy List (keV;keV;...)

End Energy (keV):

step (keV):

Formula Type:

- Atoms/Molecule
- Weight Fraction

Output Units:

- mass att. (cm²/gm)
- linear (1/cm)
- cross sections
- mass abs (cm²/gm)
- linear abs. (1/cm)

Density (gm/cm³):

Figure 2 Dialog box to calculate the attenuation coefficient of water.

Next, we can use the X-ray Tube tool in the Spectrum menu to calculate the spectrum. This brings up a dialog box similar to Figure 2 to specify the spectrum parameters. We enter the same energy range as for the attenuation coefficient and the server calculates the spectrum in columns A and B of Figure 3. Before invoking the tool, we selected cell A1 to tell the program where to put the results. Now we can use the spreadsheet tools to calculate the average attenuation coefficient. In column E we calculate the products of the spectrum and the transmission at every energy. To do this we select cell E3 and enter the formula $=B3*\exp(-\$C\$20*D3)$. This calculates the product at 10 keV. To calculate at other energies we "click and drag" over cells E3 to E17 then select Fill Down under the Spreadsheet menu. This copies the formulas down (the appropriate row number is used for every row, the \$ signs in $\$C\20 causes the same cell to be used in every row for the thickness, L). We approximate the integrals in Equation 1 as sums using the spreadsheet's SUM() function. The formula for the average attenuation coefficient is entered in cell D20. The formula is shown at the top of Figure 3. It's a straight forward implementation of Equation 1. The CT value displayed is proportional to the average attenuation coefficient. The exact relationship depends on the CT system.

D20		=-LN(SUM(E3:E17)/SUM(B3:B17))/C20				
CT value						
	A	B	C	D	E	F
1	150 kV	1 mAs, Al, 2.7	H2O lin. att	1		
2	E (keV)	Spectrum	E (keV)	1/cm	S(E)*exp(-L*mu(E))	
3	10	0	10	5.06611	0	
4	20	0.0403655	20	0.761401	4.8511E-12	
5	30	0.127353	30	0.361208	2.5055E-06	
6	40	0.156622	40	0.262847	5.892E-05	
7	50	0.158113	50	0.224476	0.00018806	
8	60	0.276576	60	0.204645	0.00059639	
9	70	0.136013	70	0.191865	0.00043033	
10	80	0.120783	80	0.183302	0.00049408	
11	90	0.104558	90	0.176178	0.00052962	
12	100	0.0877266	100	0.170612	0.00052512	
13	110	0.0705579	110	0.165297	0.00049536	
14	120	0.0531359	120	0.160809	0.00042681	
15	130	0.0355393	130	0.156937	0.00032063	
16	140	0.0178169	140	0.153538	0.000178	
17	150	0	150	0.150515	0	
18			L (cm)	average mu		
19						
20			30	0.19292126		
21						

Figure 3 Spreadsheet to calculate the average attenuation coefficient.

We have now created a general purpose tool. To see its use, follow along in the spreadsheet. Load the file CTvalue.xls into Excel. Select cell C20. This contains the size of the object in cm. If we change the size to 10 cm, we immediately see the average mu increase to 0.206. This change is due to beam hardening. The thinner object causes less beam hardening so the average energy is lower and the attenuation coefficient is larger. You can also change the composition of the object. In columns G and H, we have placed the attenuation coefficient of carbon. Select cells G1:H17 and copy them onto the clipboard. Then select cell C1 and paste. The spreadsheet then computes the average linear attenuation coefficient of carbon as 0.385. To calculate the average attenuation coefficient of any other material, we select cell C1 then either **Element** or **Compound** from the **Attenuation** menu. *X-Ray* places the data into the spreadsheet which then automatically calculates the average coefficient for the new material. We can save the spreadsheet as a disk file and load it again whenever we need it. It can be distributed to other users—so long as they have their own software. The other users do not need to do their own programming. They can simply enter the parameters for their immediate application and use the results.

Example 2: Design Shielding for a Co⁶⁰ Source

The second example is the design of shielding for a Co⁶⁰ radioactive isotope source. We will assume that we have a specification of 0.1 milliRoentgen per hour at a distance of 1 meter from the lead shielded 1 milliCurie source. The approach is to calculate the exposure rate (in Roentgens per hour) at a specified distance attenuated by a shield material. We can then interactively vary the thickness of the shield to give the desired exposure rate. The same model can be used for many different applications. For example, in radiography the model can be used to calculate the time to produce a well

exposed film image of an object (We will need to know the exposure at the film to give the required film density.).The model's geometry is shown in Figure 4. A radio-isotope source with activity C (curies) is located at a distance R (cm) from a measurement or image plane. The radiation from the source passes through a thickness t (cm) of material with linear attenuation coefficient μ (cm^{-1}). The exposure rate D can be calculated from the energy flux rate ϕ (energy per unit area per unit time) multiplied by the mass energy absorption coefficient of air $(\mu/\rho)_e$. The activity C gives the the number of radioactive nuclei disintegrating per second (one Curie is 3.7×10^{10} disintegrations per second). If E_γ is the energy of the radiation produced per disintegration, then $\phi = CE_\gamma / 4\pi R^2$. Multiplying by the shield transmission gives

$$D = \frac{C}{4\pi R^2} E_\gamma (\mu/\rho)_e \exp(-\mu t) \quad (2)$$

If, as is the case with Co^{60} , two photons are produced for every disintegration of the radio-isotope, the model generalizes to

$$D = (\mu_1/\rho)_e E_{\gamma 1} \exp(-\mu(E_{\gamma 1}t)) + (\mu_2/\rho)_e E_{\gamma 2} \exp(-\mu(E_{\gamma 2}t)) \quad (3)$$

where $E_{\gamma 1}$ and $E_{\gamma 2}$ are the energies of the two gamma rays produced by the radio-isotope. For Co^{60} , these energies are 1170 and 1330 keV. To convert the units, we will also need the conversion factor: 1 Roentgen corresponds to 5.5×10^{10} keV absorbed per gram of air.

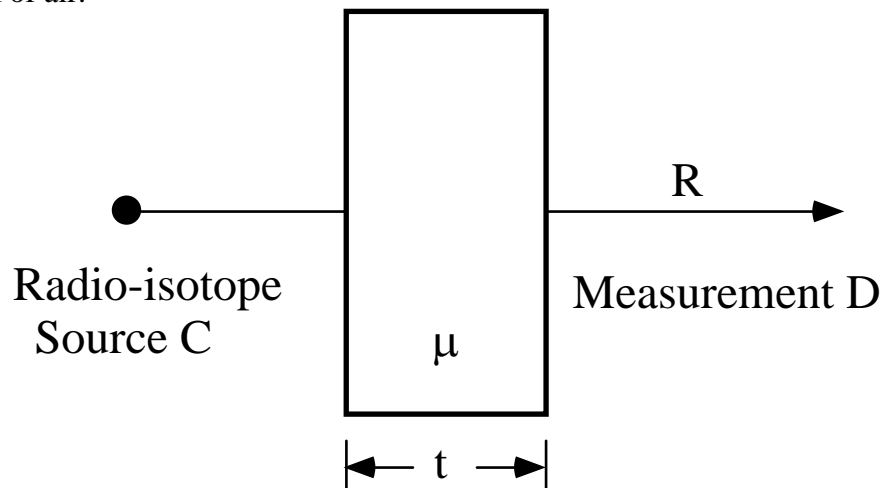


Figure 4 Geometry for dose rate calculations. The model gives the exposure rate D at a distance R cm from a C curie source with t cm absorber having a linear attenuation coefficient μ .

The spreadsheet (Cobalt60.xls) in Figure 5 implements Equation 3. The calculation requires two types of coefficients. One is the linear attenuation coefficient of lead. This can be calculated using the **Element** tool of the **Attenuation** menu. This brings up a dialog box similar to Figure 2. For elements, *X-Ray* provides the density (by checking the "builtin" option box) for the linear attenuation coefficient. We can use the energy list feature of *X-Ray* to enter the Co^{60} energies. In the "Start Energy or Energy List" box, we enter 1170;1330 (the gamma ray energies in keV) and *X-Ray* calculates the values at exactly these two energies. The results are placed in the spreadsheet in columns A and B rows 1 to 4.

We also need the energy absorption coefficient of air. This can be calculated using the **Compound** tool. We use the cell entry feature of *X-Ray*. The fraction by weight formula for air is entered in cell E1 (.755 N, .232 O, and 0.013 Ar). In the **Compound** dialog box (Figure 2) we enter the cell location for E1 in RC notation, r1c5. *X-Ray* then reads the formula from this cell. We also need to check the "Fraction by Weight" option in the "Formula Type" box on the lower left of the dialog. The results are placed in the spreadsheet in columns C and D rows 1 to 4.

We can now use the spreadsheet to compute the other results. These are shown in Figure 5 (rows 7 and 8). Cells A8,B8, and C8 contain values for the variables: source activity C, source to measurement plane distance R, and object thickness t. Cell D8 contains the formula to calculate the dose rate. The formula, shown in the top row of Figure 5, is a straight forward implementation of the equation. Conversion factors to go from disintegrations per second to Curies, seconds to hours, and keV/gm to Roentgen are entered in cells E4, E6, and E8 (the factor of 1000 converts from Roentgens to milliRoentgen). Now, the power of the spreadsheet can be applied immediately. We can change any of the parameters and the effect on the dose rate will be calculated immediately. By adjusting the lead thickness in cell C8, we see that it takes 3.8 cm (about 1.5 inches) of lead to reduce the exposure rate to the specification. What thickness gives 1 mR/hr? (answer: 0.37 cm).

We can extend the spreadsheet model to include buildup factors for scattered gamma rays. For imaging, we can compute the time to produce a well exposed image on our film or other detector with a particular object material and thickness.

=1000*E4*E6*E8*A8/(4*PI()*B8*B8)*(1170*D3*EXP(-B3*C8)+1330*D4*EXP(-B4*C8))						
Cobalt Source						
	A	B	C	D	E	F
1	Pb lin. att	11.3400002	r1c5 mass energy abs.		N.755O.232Ar.013	
2	E (keV)	1/cm	E (keV)	cm ² /gm		
3	1170	0.694053	1170	0.0268501	(dis/sec)/Curie	
4	1330	0.625373	1330	0.0260805	3.7E+10	
5					seconds/hour	
6					3600	
7	C (Curies)	R (cm)	t (cm)	Dose Rate mr/E (keV/gm)/r		
8	0.001	100	3.8	0.10540842	1.8182E-11	
9						

Figure 5 Design of shielding for a Co⁶⁰ source. The software places the results of the calculations in the spreadsheet in rows 1 to 4. The formulas entered in rows 7 and 8 implement Equation 3. The formula in cell D8 is displayed along the top. It implements Equation 3 using the values in the spreadsheet.

Example 3: X-ray Tube Output

The third example is calculating the exposure rate with an x-ray tube source. This model can be used, for example, to make quantitative calculations of x-ray tube output. For this example, we will compare the exposure rate calculated by *X-Ray* to the manufacturer's specification. The data sheet for the Philips MCN 421 industrial x-ray tube states that, with the voltage at 300 kV and the current at 10 mA, the tube produces

an exposure rate of 9800 Roentgen/min at a distance of 20 cm. Let's compare this to the predicted exposure rate by *X-Ray*.

The exposure (in Roentgens) with a broad spectrum source—like an x-ray tube—is

$$X = \int_0^{eV_T} \frac{S(E)}{4\pi R^2} \left(\frac{\mu_{\text{abs}}(E)}{\rho} \right)_{\text{air}} dE . \quad (4)$$

This equation is analogous to Equation 3. *X-Ray* produces an energy spectrum so $S(E) dE$ is the x-ray energy of photons with energy from E to $E+dE$. Dividing this by $4\pi R^2$ gives the flux density and multiplying by the mass energy absorption coefficient of air gives the exposure. The *X-Ray Spectrum* tool produces units of joules so we will have to use the conversion factor that one Roentgen is equivalent to 8.8×10^{-6} joule/gram of air. The integral can be calculated by breaking up the energy range into a large number of intervals, calculating the integrands at each interval, and summing them.

Generating spectra

The software can automatically generate an x-ray tube spectrum. Selecting **X-ray Tube** from the **Spectrum** menu calculates a spectrum and places the results in the spreadsheet. It can be plotted using the tools in the **Plot** menu. The results are shown in Figure 6. The sharp peak near 60 keV is the tube's fluorescence radiation.

Calculating X-Ray Tube Output

The data can be used to calculate the tube output using the spreadsheet spectrum.xls shown in Figure 7. This implements the calculation of the tube output. The x-ray tube spectrum generated by *X-Ray* is in columns A and B. In columns C and D, we placed the mass energy absorption coefficient of air. Column E contains the product of the spectrum and absorption coefficient. The formula to implement Equation 4 is in cell E20 and is displayed at the top of Figure 7.

With the *X-Ray* spreadsheet model, we can now compare the calculated and experimental results. A tube current of 10 mA for one minute is 600 mAs which is entered in C20. The tube specification specifies that the output is measured at 20 cm from the tube so this is entered in cell D20. The calculated result is 9700 r which should be compared to the 9800 r in the tube specification. This close agreement is probably better than might be expected in general. It is very sensitive to the low energy spectrum where other factors such as the attenuation of air and of the case of the measurement instruments needs to be entered into the computation.

What is the exposure at 1 meter from the tube? This can be computed by changing cell C20 to 100 cm. (answer: 389 R/min).

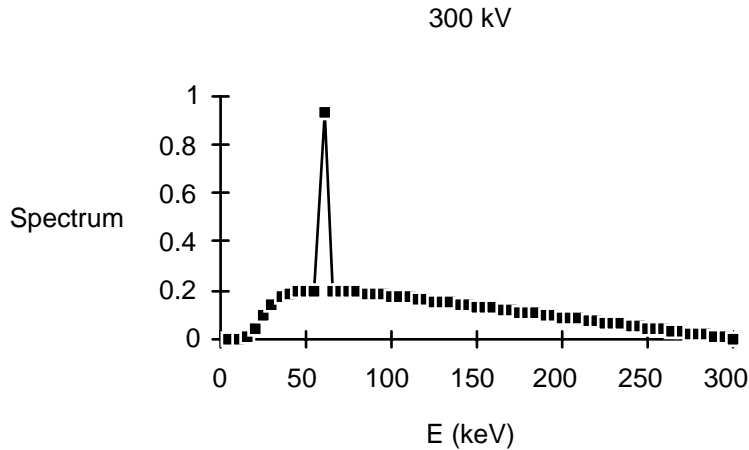


Figure 6 Plot of the spectrum data generated by the x-ray tube spectrum generation tool.

=A20*C20*SUM(E3:E17)/(4*PI()*D20*D20)						
spectrum calculations						
	A	B	C	D	E	F
1	300 kV	1 mAs, Be, 1.8	1.5 mass energy abs.		N.7550.232Ar.013	
2	E (keV)	Spectrum	E (keV)	cm ² /gm		
3	20	0.98671	20	0.500236	0.49358786	
4	40	0.936337	40	0.0614979	0.05758276	
5	60	1.66585	60	0.0283011	0.04714539	
6	80	0.799739	80	0.0231171	0.01848765	
7	100	0.729167	100	0.0226622	0.01652453	
8	120	0.657973	120	0.0235047	0.01546546	
9	140	0.586077	140	0.0243103	0.01424771	
10	160	0.513767	160	0.0250975	0.01289427	
11	180	0.441119	180	0.0258518	0.01140372	
12	200	0.368135	200	0.0265508	0.00977428	
13	220	0.294935	220	0.0270323	0.00797277	
14	240	0.221483	240	0.0274799	0.00608633	
15	260	0.147824	260	0.0278986	0.00412408	
16	280	0.0739876	280	0.0282923	0.00209328	
17	300	0	300	0.0286641	0	
18						
19	r/(joule/gm)		mAs	R(cm)		Roentgen
20	113636.364		600	20		9730.92422

Figure 7 Spreadsheet to calculate x-ray tube output. The output in Roentgen is in cell E20. The mAs (tube current multiplied by exposure time) is in cell F20 and the distance from the tube is in cell D20. The formula to implement Equation 4 is in the top row of the figure.

Example 4: Compute (Photons/cm²)/milliRoentgen for a Mo Tube

The fourth example shows two features of *X-Ray* : (1) implementing a new calculation by extending a template spreadsheet and (2) the accuracy of the spectrum calculation for a molybdenum (Mo) anode tube. After implementing our tube spectrum model, we needed to validate it using experimental data. We did this by comparing *X-Ray*'s computed spectrum to experimental data from the Bureau of Radiological Health (BRH)². The BRH report described measurements of the spectra of Mo anode x-ray tubes. From these measurements, the report computed the number of photons per square centimeter per milliRoentgen exposure. To check our spectrum data, we computed this quantity for *X-Ray*'s spectrum and compared it to the experimental results. We did these calculations by building on the spectrum.xls spreadsheet from Example 3.

The computation was done by implementing spreadsheet calculations for the numerator and denominator in the (photons/cm²)/milliRoentgen parameter. The spectrum.xls spreadsheet already computes a quantity close to the one required for the denominator. It computes the exposure for a tungsten anode tube; we need the exposure for a molybdenum anode tube. Modifying spectrum.xls to compute the Mo anode spectrum is straightforward. Simply click on cell A1 then choose Other Z Anode Tube in the **Spectrum** menu. In the dialog box, specify a Mo anode, a tube voltage of 20 kV and a window thickness of 0.06 cm of aluminum. This gives the result shown in Figure 8 (which is in file molyspec.xls). We also need to compute the air energy absorption at the new energies. This is done using the Compound command in the **Attenuation** menu as in Example 3.

E20		=A20*C20*SUM(E3:E17)/(4*PI()*D20*D20)				
MolySpec.xls						
	A	B	C	D	E	F
1	Mo 20 kV	1 mAs, Al, 2.7	1c5 mass energy abs.		N.7550.232Ar.013	
2	E (keV)	Spectrum	E (keV)	cm ² /gm		
3	6	0	6	21.9954	0	
4	7	7.40E-09	7	13.7503	1.0174E-07	
5	8	3.41E-07	8	9.15696	3.1238E-06	
6	9	3.55E-06	9	6.34055	2.2506E-05	
7	10	1.53E-05	10	4.56581	6.9825E-05	
8	11	3.98E-05	11	3.3671	0.00013415	
9	12	7.38E-05	12	2.5503	0.00018832	
10	13	0.00010912	13	1.97543	0.00021557	
11	14	0.00013729	14	1.55961	0.00021412	
12	15	0.00015251	15	1.25173	0.0001909	
13	16	0.00015257	16	1.01889	0.00015545	
14	17	0.00013605	17	0.8398	0.00011426	
15	18	0.00010392	18	0.699897	7.2736E-05	
16	19	5.79E-05	19	0.589088	3.4116E-05	
17	20	0	20	0.500236	0	
18						
19	r/(joule/gm)		mAs	R(cm)	Roentgen	
20	113636.364			1	20	0.03199304

Figure 8 Spreadsheet spectrum.xls is used to compute the exposure for a Mo anode x-ray tube. Note that the mAs cell was changed to 1.

Next, we need to compute the number of photons per square centimeter. We did this by computing the photon number spectrum for each photon energy in column F then summing it. X-Ray produces an energy spectrum with physical units Joules per keV. To transform this to number of photons we just divide by the energy per photon (which is in column A). We need to transform Joules to keV so we multiply by the conversion factor in cell B20.

The parameter is computed in cell F20 of numspec.xls shown in Figure 9. We sum the number spectrum then divide by the area of a sphere with radius equal to the distance to the tube to give us the number of photons per unit of area. Dividing by the exposure in cell E20 (multiplied by 1000 to give milliRoentgen) gives the parameter. The BRH report gave an experimental value of 2.8350E+06 for this spectrum. Our value of 2.58E+06 is about 9% different.

F20		=SUM(F3:F17)/(4*PI()*D20^2)/(1000*E20)					
numspec.xls							
	A	B	C	D	E	F	
1	Mo 20 kV	1 mAs, Al, 2.7	1.5 mass energy abs.		N.7550.232Ar.013		
2	E (keV)	Spectrum	E (keV)	cm^2/gm		Number_Spect	
3	6	0	6	21.9954	0	0.000E+00	
4	7	7.40E-09	7	13.7503	1.0174E-07	6.598E+06	
5	8	3.41E-07	8	9.15696	3.1238E-06	2.662E+08	
6	9	3.55E-06	9	6.34055	2.2506E-05	2.462E+09	
7	10	1.53E-05	10	4.56581	6.9825E-05	9.546E+09	
8	11	3.98E-05	11	3.3671	0.00013415	2.261E+10	
9	12	7.38E-05	12	2.5503	0.00018832	3.841E+10	
10	13	0.00010912	13	1.97543	0.00021557	5.240E+10	
11	14	0.00013729	14	1.55961	0.00021412	6.121E+10	
12	15	0.00015251	15	1.25173	0.0001909	6.346E+10	
13	16	0.00015257	16	1.01889	0.00015545	5.952E+10	
14	17	0.00013605	17	0.8398	0.00011426	4.996E+10	
15	18	0.00010392	18	0.699897	7.2736E-05	3.604E+10	
16	19	5.79E-05	19	0.589088	3.4116E-05	1.903E+10	
17	20	0	20	0.500236	0	0.000E+00	
18							
19	r/(joule/gm)	keVperJoule	mAs	R(cm)	Roentgen	Pho./cm^2/mF	
20	113636.364	6.242E+15		1	20	0.03199304	
						2.58E+06	

Figure 9 Spreadsheet to compute (photons/cm²)/milliRoentgen parameter. This is saved in file numspec.xls.

The BRH report contained parameters for a set of tube voltages and added aluminum and Mo filtration thicknesses. A comparison of our results with the experimental results is plotted in Figure 10. The largest error is about 10% but most errors are substantially smaller. To compute these values we developed a more sophisticated spreadsheet that allows us to specify the Al and Mo added filter

thicknesses. The spreadsheet is in file numspec2.xls. This spreadsheet is a straightforward extension of numspec.xls. Study the formulas to convince yourself that it computes the parameter correctly.

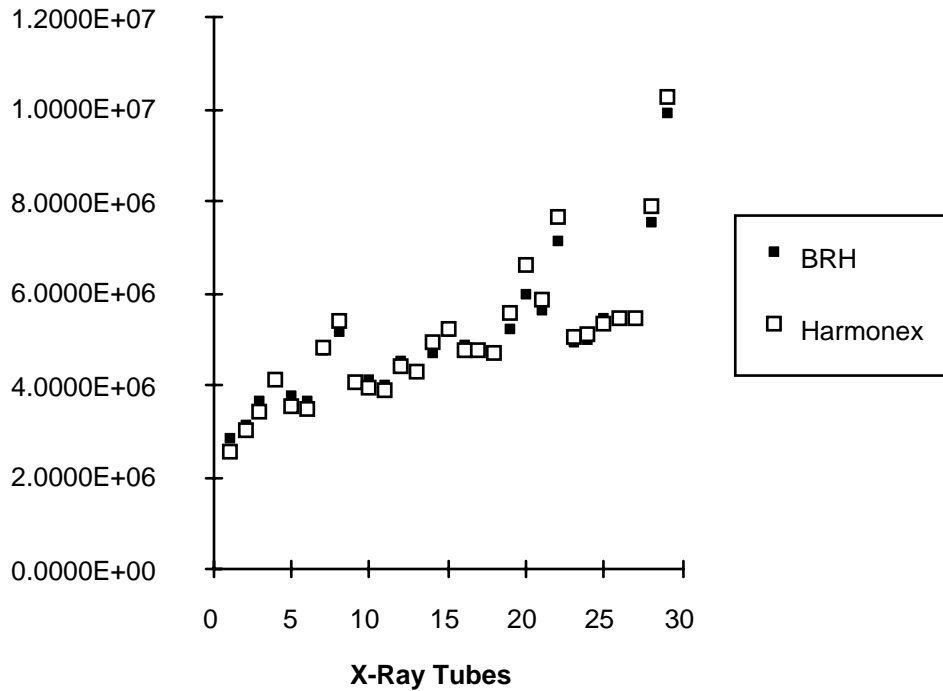


Figure 10 Comparison of (photons/cm²)/milliRoentgen parameter for experimental and X-Ray spectra. Values for corresponding X-Ray and experimental spectra are joined by a line. If only one box is shown, the values for both spectra are the same.

Implementation

The physical attenuation data are calculated from a table published by x-ray physics researchers³. The table combines and reconciles values from the best available references in the scientific literature^{4,5,6,7}. It is arranged as values for all the elements with atomic number from 1 to 94 versus energy. The energy values are chosen so that intermediate energies can be calculated by using log-log interpolation to an accuracy at least as good as the the original data. The software is based on the published table but rearranges it for efficient computer searches. The resulting method of computation is unique but still reproduces the values of the published table.

The bremsstrahlung x-ray spectrum data are calculated from Kramer's model⁸. The fluorescent radiation is then added if the tube voltage is sufficiently high. Two models are used for tungsten anode and other anode elements. The intensity of the tungsten anode fluorescent radiation is calculated using a model based on Tothill's

results⁹. The intensity for other anode materials is based on the model described in Green and Coslett¹⁰.

An important advantage of the software's implementation is that it can be ported to different platforms while still retaining the same user interface. Versions exist both for the Macintosh and Windows environments.

Conclusion

The software tools described provide an open architecture that the user can customize for individual needs. The tools provide efficient calculations of physical x-ray parameters with an interface that allows them to be combined for a specific application. The applications presented here show the power to implement calculations quickly and efficiently then to incorporate and extend them for other applications.

¹Glasstone, S. and A. Sesonske *Nuclear Reactor Engineering* (Van Nostrand, Princeton, 1967) p. 525.

²Bureau of Radiological Health, "Handbook of Mammographic X-Ray Spectra"

³Plechaty, E. "Tables and Graphs of Photon-Interaction Cross Sections from 0.1 keV to 100 MeV Derived from the LLL Evaluated-Nuclear-Data Library," *UCRL-50400* Vol. 6, Rev. 6, 1981.

⁴Hubbell, J.H., W.J. Veigele, E.A. Briggs, R.T. Brown, D.T. Cromer, and R.J. Howerton, "Atomic Form Factors, Incoherent Scattering Functions, and Photon Scattering Cross Sections," *J. Phys. & Chem. Ref. Data* **4**, pp. 471-538, 1975

⁵Hubbell, J.H., and M.J. Berger, *Photon Attenuation and Energy Absorption Coefficients, Tabulation, and Discussion*, National Bureau of Standards, Washington, D.C. Rept. 8681, 1966.

⁶Storm, E. and H.I. Israel, *Photon Cross Sections from 0.001 to 100 MeV for Elements 1 through 100* Los Alamos National Laboratory, Los Alamos, New Mexico, Rept. 3753, 1967.

⁷McMasters, W.H., N. Kerr, J.H. Mallett, and J.H. Hubbell, *Compilation of X-ray Cross Sections*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-50174, Sec. II, Rev. 1, 1969.

⁸Dyson, N.A. *X-rays in atomic and nuclear physics* (Longman, London, 1973) Ch. 2 and 3.

⁹Tothill, P. (1968) *Brit. J. Appl. phys. (J. Phys. D)* Ser. 2, Vol. 1, p. 1093.

¹⁰Green, M., and V.E. Cosslett, "Measurement of K,L and M shell x-ray production efficiencies," *Brit. J. Appl. Phys. (J. Phys. D)* Ser. 2, Vol. 1, 1968.