Shielding calculations for an X-ray machine in 1140 Etcheverry Hall

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Abstract -

In order to determine the safety of putting an X-ray source in the southeast corner of 1140 Etcheverry Hall, a series of worst-case scenarios are modeled in MCNP. This report outlines the assumptions, models, and calculations which were made in support of demonstrating the safety of this proposed X-ray source. This report does not discuss in detail the validity of the assumed worst-case scenarios. It is demonstrated that the three worst-case scenarios deliver a dose that is within the limitations outlined by the campus safety guidelines for people standing outside of the shielded area surrounding the X-ray source. For one scenario, a dose higher than the designated threshold is seen outside of the shielded area, however at an elevated position high above where any person would likely be located. A discussion of the Monte Carlo statistical error is given and it is judged that the MCNP results are accurate. Based on these calculations, it is extended that the proposed X-ray generator should be safe to people outside of the shielding for all operating directions and positions within the proposed shielded region.

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Preface -

The MCNP models, processing scripts, outputs, and all supporting documentation used to obtain the results in this report are available at the public Github repository https://github.com/keckler/shielding. It is hoped that making this repository available will enable for the results of this report to be repeatable and transparent. It should also be noted that .fig versions of all of the 3D contour plots are also available in this repository. These files may be opened in MATLAB and manipulated so that the details of the results may be more easily examined and analyzed.

Anybody may download and use the contents of this repository, however no guarantees are made as to the accuracy of any results obtained through the use of the contents.

Introduction and Background -

Professor Simo Markiharju of the Mechanical Engineering department intends to put an X-ray generator in the southeast corner of 1140 Etcheverry Hall for performing fluids experiments. In order to ensure that the X-ray generator is adequately shielded to comply with campus safety requirements, a series of worst-case scenarios are being modeled to determine the dose to people in the vicinity of the machine. The X-ray machine is to be placed near the existing shielding for the High Flux Neutron Generator (HFNG), with additional shielding blocks added to close off the southeast corner, while leaving the top open, allowing a clear path between the generator and the ceiling. The shielding blocks are to be made of barite, while the HFNG shielding is made of ordinary concrete.

A schematic diagram of the room, giving the location of the X-ray machine, is shown in Figures 1 and 2. Figure 3 gives a zoomed in top-down view with relevant dimensions. The height of the HFNG shielding, shielding blocks, 1140 ceiling, and upstairs room from the floor of 1140 are 246.125, 144.00, 402.00, and 628.00 inches, respectively. The height of the second floor is assumed to be 18 feet, although there is no basis for this. It is seen from the results, however, that this dimension has no impact on the outcome. All walls and ceilings are taken to be 10 inches thick, as per email correspondence with the facilities manager for Etcheverry Hall [1]. Dimensions and materials for the HFNG shielding are taken from the HFNG Safety Manual [2].

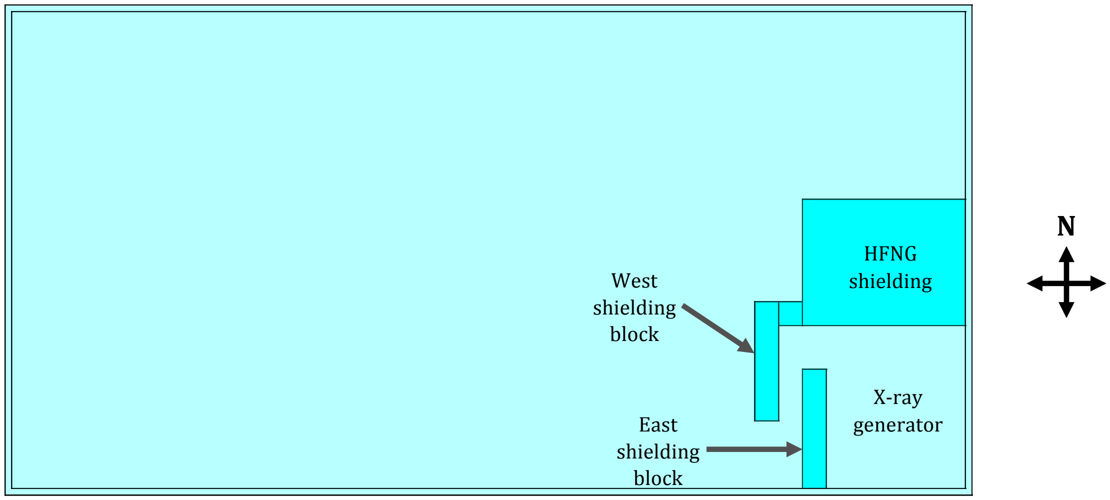


Figure 1: Top-down view of 1140 Etcheverry Hall showing the HFNG shielding and the proposed shielding blocks for the X-ray generator.

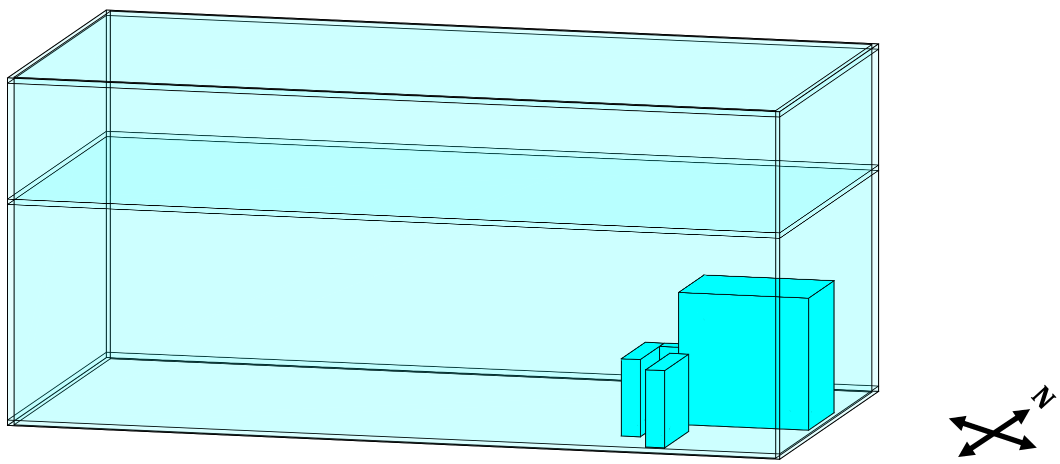


Figure 2: Side-view of 1140 Etcheverry Hall and the above classroom space showing the HFNG shielding and the proposed shielding blocks for the X-ray generator.

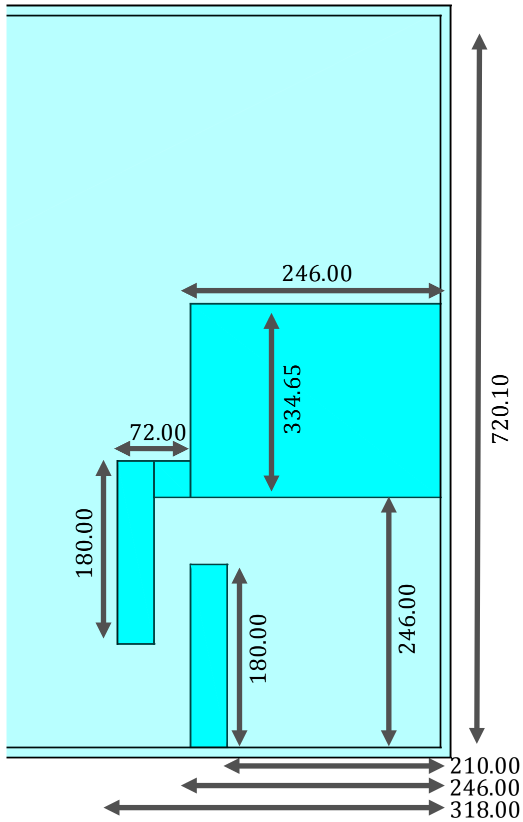


Figure 3: Positions and dimensions of the shielding blocks. Building walls are 10 inches thick. Dimensions are depicted in inches.

In order to determine the safety of the X-ray machine during operation, two zones are established as characterized by the dose to human tissue at that point in space. The first threshold establishes a zone in which nobody should be present during machine operation, and is 2.0 mrem/hr. The second threshold defines a zone where all people present should be wearing dosimiters, and is defined at 0.2 mrem/hr. Outside of this dose level, no restrictions are required, and therefore it is desired that the added shielding blocks will bring the dose down to below this level. The purpose of this study is to establish the boundaries of these zones through the use of Monte Carlo photon transport calculations.

Source Term Definition -

The source term for the X-ray generator was determined by Simo Makiharju through the use of the software SpekCalc [3]. A picture of the results generated from SpekCalc for the X-ray generator is given in Attachment C. The X-ray beam is collimated into a cone of 30 degrees [4], and the machine is operated at 225 kV and 320 W.

Using the operating parameters of the generator in conjunction with the output of the SpekCalc calculation, the beam intensity can be determined as follows,

$$I = JAi$$

where I is the beam intensity, J is the normalized X-ray flux at 1 meter, A is the beam area at 1 meter, and i is the electrical current in the machine.

The normalized flux per unit energy is given as an output from a SpekCalc calculation in units of $\frac{1}{keV*cm^2*mA*s}$ at 1 meter (provided in Appendix C). In order to determine the normalized flux at 1 meter, the normalized flux per unit energy can be summed over all energies. Doing this gives a value of $J = 2.1048E9\frac{1}{cm^2*mA*s}$.

The beam area at 1 meter is calculated simply by determining the radius of a circle at 1 meter from the beam collimator, knowing the angle of the beam is 30 degrees.

$$A = r^2\pi = \left(\tan(15°)\,(1)\right)^2\pi = 2255.56\ cm^2$$

The electrical current of the generator is determined very simply by knowing the operating power and voltage.

$$i = \frac{P}{V} = \frac{320\ W}{225E3\ V} = 1.42\ mA$$

Combining all of these factors gives a beam intensity of $6.7415E12\frac{Xrays}{s}$ at nominal operating conditions. The intensity of the beam is considered as uniform throughout the cone of the beam.

Worst-Case Scenarios -

In order to avoid performing shielding calculations for each particular position and direction of the X-ray generator as required, a series of worst-case scenarios are being posited to show that the dose is below accepted limits for all imaginable beam positions. A summary of these worst-case scenarios is given in Table 1. The listed positions are with reference to an origin located at the inner southeast corner of the room, at the intersection of the east wall, south wall, and floor of 1140 Etcheverry Hall. The x-y plane is taken as the floor of the room, with the positive x-axis pointed north and the z-axis points straight upwards towards the ceiling. All scenarios assume the beam operating at nominal power and voltage of 320 W and 225 kV.

Table 1: Position and direction of the beam for the three worst-case scenarios.

Scenario	Beam Position (x,y,z) (inches)	Beam Direction (x,y,z)
1	(-174, 90, 108)	(0, 0, 1)
2	(-174, 90, 108)	(-0.707, 0, 0.707)
3	(-209.8, 222, 72)	(-1, 0, 0)

Scenario 1 represents the beam being pointed straight upwards with no shielding between the beam and the room upstairs. Scenario 2 represents the beam being pointed at a 45 degree angle upwards over the top of the shielding blocks, pointed towards the rest of 1140 Etcheverry Hall. Scenario 3 represents the beam pointed horizontally straight at the shielding blocks, where is it positioned such that only a single shielding block is between the X-ray machine and the rest of the room. These three scenarios represent some of the worst imaginable positions, as pointing the beam any other direction would either be straight at the basement walls or floor (which are 10 inches thick and surrounded by soil) or straight at the HFNG shielding (which is thicker than the proposed shielding blocks).

Model Description -

The dose calculations are performed with MCNP5, version 1.60 [5]. A number of simplifications are included in the model to make the problem tractable. These simplifications are outlined below:

1. All shielding blocks, floors, and walls are assumed to be made of ordinary concrete [6]. This is a conservative assumption, as some of the shielding blocks are in fact made of barite, which is a much better photon shielding material than ordinary concrete due to the higher density (3.35 $\frac{g}{cm^3}$ for barite versus 2.30 $\frac{g}{cm^3}$ for NIST ordinary concrete)
2. The outside surfaces of the walls and floor are assumed to be reflecting (i.e. photons penetrating to the dirt are reflected back). This is a conservative assumption, as typically any photons that penetrate into the dirt would not return. This is assumed, however, to avoid modeling the dirt surrounding 1140
3. No structures in either 1140 Etcheverry or the room above besides the shielding blocks, the room walls, and the HFNG shield are considered in the model. In fact, structures such as the beams on the ceiling are also ignored. This is to reduce the complexity of the model, and is seen to be justified by the final results
4. The physical shape of the HFNG shielding block is simplified to a solid rectangle, ignoring details of the structure such as the beveled corners and the details of the cavity containing the HFNG. Approximating as a solid rectangle is justified by the final results
5. All walls and floors of the room are assumed to be 10 inches thick, which is the lower bound of the range provided by the facilities manager [1]. This is a conservative assumption, when paired with assumption (2)
6. The room above 1140 Etcheverry is assumed to be 18 ft. This value is arbitrary, but is seen to be irrelevant to the desired results
7. The open space in both rooms is assumed to be filled with air [7]

Each model is run with 10^{10} particles. Due to the fact that pair production is not taking place at these low photon energies and the scattering cross sections are comparable to the photoelectric effect, the simulations finish running in a relatively short amount of time (~2 hours, on 2 nodes of 20 cores/node). Because of the reasonable run times and the good statistics obtained with the large number of particles, the simulations are performed without the use of a variance reduction technique.

In order to determine the dose from the results of the MCNP calculation, an F4 mesh tally is used along with an appropriate multiplier to convert from normalized flux to the dose to human tissue. This is done through the use of the FMESH4 card combined with the FM4 card. The tally mesh is over the entire domain, and divides the geometry up into volumes of 1 cubic foot. The multiplier to convert from the track length estimate of cell flux into dose to human tissue is constructed as follows.

1. The tally material is taken to be human tissue [6]
2. A -5 multiplier is used to multiply by the total photon cross section
3. A -6 multiplier is used to multiply by the photon heating number
4. A multiplicative constant is used to convert units as follows

$$C = \frac{N}{\rho}\nu I$$

$$= \frac{8.879 * 10^{-2}\,\frac{1}{b * cm}}{1.000\,\frac{g}{cm^3}}\Bigg(1.6022 * 10^{-13}\,\frac{J}{MeV}\Bigg)\left(\frac{1\,rad}{0.01\,\frac{J}{kg}}\right)\left(1000\,\frac{g}{kg}\right)\left(6.7415 * 10^{12}\,\frac{photons}{s}\right)$$

$$= 9593.09\,\frac{rad * cm^3 * src.part.}{b * cm * MeV * s}$$

where N is the number density of human tissue, ρ is the mass density of human tissue, ν is a unit conversion factor, and I is the beam intensity

When points 1-4 above are put together, a tally of the following form is produced, where φ is the MCNP normalized flux, σ_t is the total microscopic cross section, and H is the photon heating number:

$$C\int \varphi(E)\sigma_t(E)H(E)dE \doteq \frac{rad}{s}$$

In the specification of the source, the directional distribution of emitted particles is input through the use of an MCNP distribution table. The fractional solid angle of the cone of emitted X-rays used in this distribution is calculated according to the following:

$$\frac{\int_{0^\circ}^{15^\circ}\int_0^{2\pi} dA}{\int_{0^\circ}^{360^\circ}\int_0^{2\pi} dA} = \frac{\int_{0^\circ}^{15^\circ}\int_0^{2\pi} r^2\sin(\phi)\,d\theta d\phi}{\int_{0^\circ}^{360^\circ}\int_0^{2\pi} r^2\sin(\phi)\,d\theta d\phi} = 0.017$$

The energy distribution is also input to MCNP through the use of a distribution table. For this, the values in Appendix C are normalized to a sum of 1 and then input into the S1 distribution.

Post-processing -

The results of each MCNP run are provided in a separate file for the case of mesh tallies. MATLAB is used to extract the results of each run, reorganize them into a useable format, and plot them on a 3-D map of the geometry. Additionally, this script is used to convert the results from $\frac{rad}{s}$ into $\frac{rad}{hr}$. No additional calculations are performed in this post-processing script.

Results Preliminaries -

Before presenting the final results of the dose computations, a few preliminary statements are made. First, the figure titles state that the units of the plots are $\frac{mrad}{hr}$. These units are interchangeable with $\frac{mrem}{hr}$, because the quality factor for photons at these low energies is 1. Therefore, the results should be interpreted as directly corresponding to the target thresholds of 2.0 and 0.2 $\frac{mrem}{hr}$.

Additionally, when using Monte Carlo methods, special attention should be paid towards the statistical accuracy of the results. In the results obtained for all three scenarios, the standard statistical checks that MCNP calculates are all passed. Additionally, the precision of the tallies has been analyzed and deemed to be sufficiently precise. This was determined based upon looking through the tally statistics and ensuring that the uncertainty is below a threshold of 0.05 for all regions of importance (0.05 is a value given in the MCNP manual as being reliable even for point detectors, which require tighter statistical tolerances than volume-averaged detectors).

When looking through the mesh tally file, it is clear that many of the tallies do not meet this target threshold of <0.05, however these tallies correspond to regions which are considered to be unimportant based upon other results of the calculation. For instance, a tally to the north of the HFNG shielding may have very poor statistics, but if it can be shown that the dose rate drops far below the dose rate thresholds before reaching this point of poor statistics, it can be judged that the dose rate at this point will also be far below our dose rate thresholds (provided the geometry is such that nothing would cause the photon flux to increase when moving away from the source). For the scenarios considered, the statistics are extremely good in the regions where the dose rate thresholds occur ($R < 0.001$), and the results are even reliable down to dose rates more than an order of magnitude lower than the dose rate thresholds. Therefore regions where the statistics are poor have all been deemed to be below the targeted dose rate thresholds.

Finally, on the contour maps of the results, contours have been drawn at the two dose rate thresholds of 2.0 and 0.2 $\frac{mrem}{hr}$, but also at an order of magnitude lower so that it can be demonstrated that the dose rates throughout the geometry are below the acceptable limits.

Results -

A 3D contour map of the dose from Scenario 1 is given in Figure 4. Due to the fact that multiple shielding blocks are between the X-ray generator and the rest of the room, the exclusion zones do not extend beyond the shielding blocks. It is also important to note that the dose falls below the threshold of 0.2 $\frac{mrem}{hr}$ before reaching into the classroom above, due nearly only to geometric attenuation, as the X-ray attenuation in air is low. Another important feature to note is that the dose falls substantially below the lower threshold of 0.2 $\frac{mrem}{hr}$ in the very first thin layer of the HFNG shielding, which validates assumption 4 in the MCNP model.

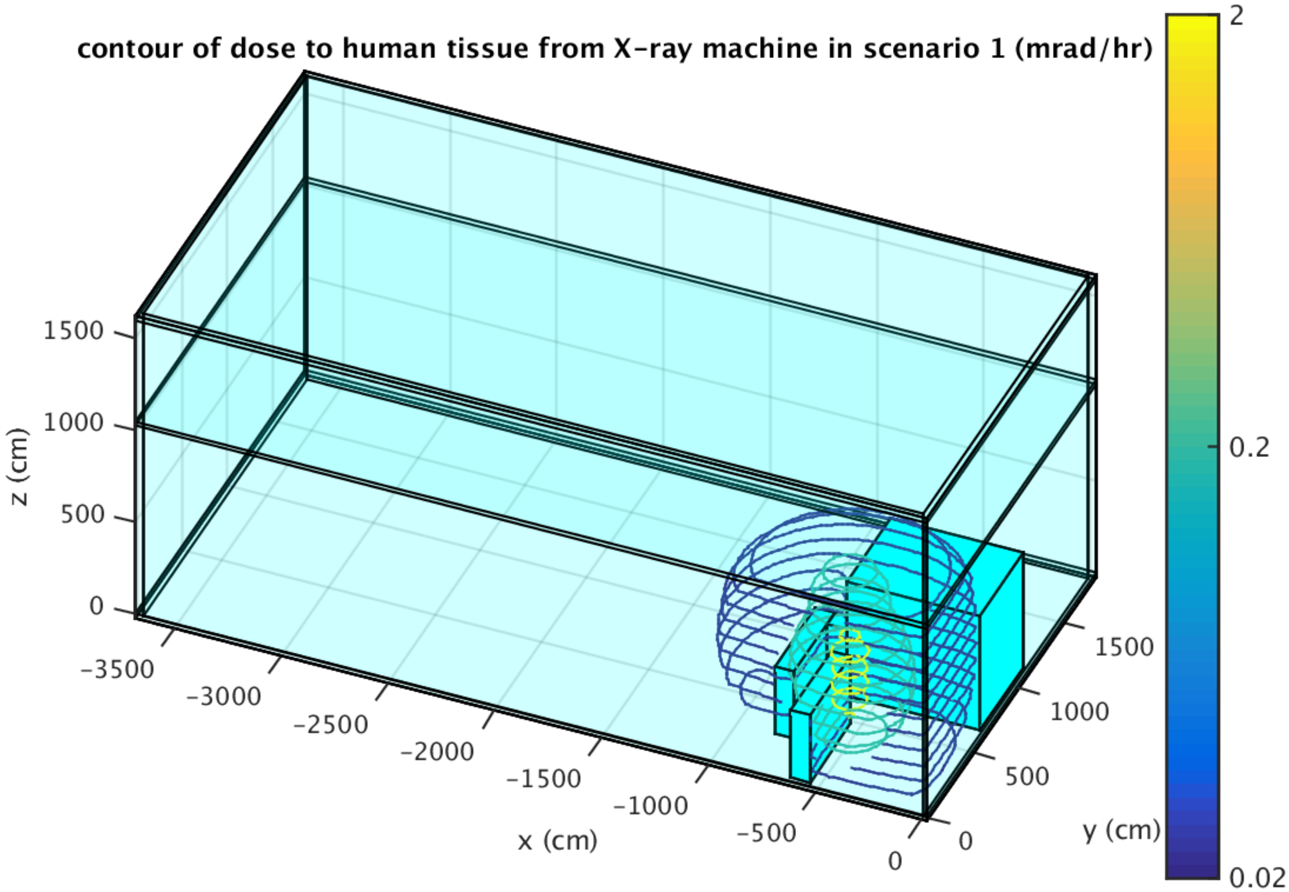


Figure 4: Contour lines of the regions above the safety thresholds of 2.0 and 0.2 mrem/hr for Scenario 1.

Figure 5 gives a contour map of the dose for Scenario 2. The results for this scenario are similar to those from Scenario 1, except that the region with dose above 0.2 $\frac{mrem}{hr}$ extends outside of the area enclosed by the shielding blocks. To the west of the shielded area, a zone extending from the top of the shielding blocks to the ceiling of 1140 exists where the dose level would require people to be wearing dosimeters. It should be noted that this zone of elevated dose level does not offer much opportunity to have an impact on human health, as it is much higher than human height (at the lowest, 12 feet), and no existing platform is in place within this zone which would allow for a human to be subjected to this radiation field (the Compact Integral Effects Test (CIET) facility is located well away from this zone). Again, the dose level falls off below the threshold levels before penetrating into the classroom above due mainly to geometric attenuation.

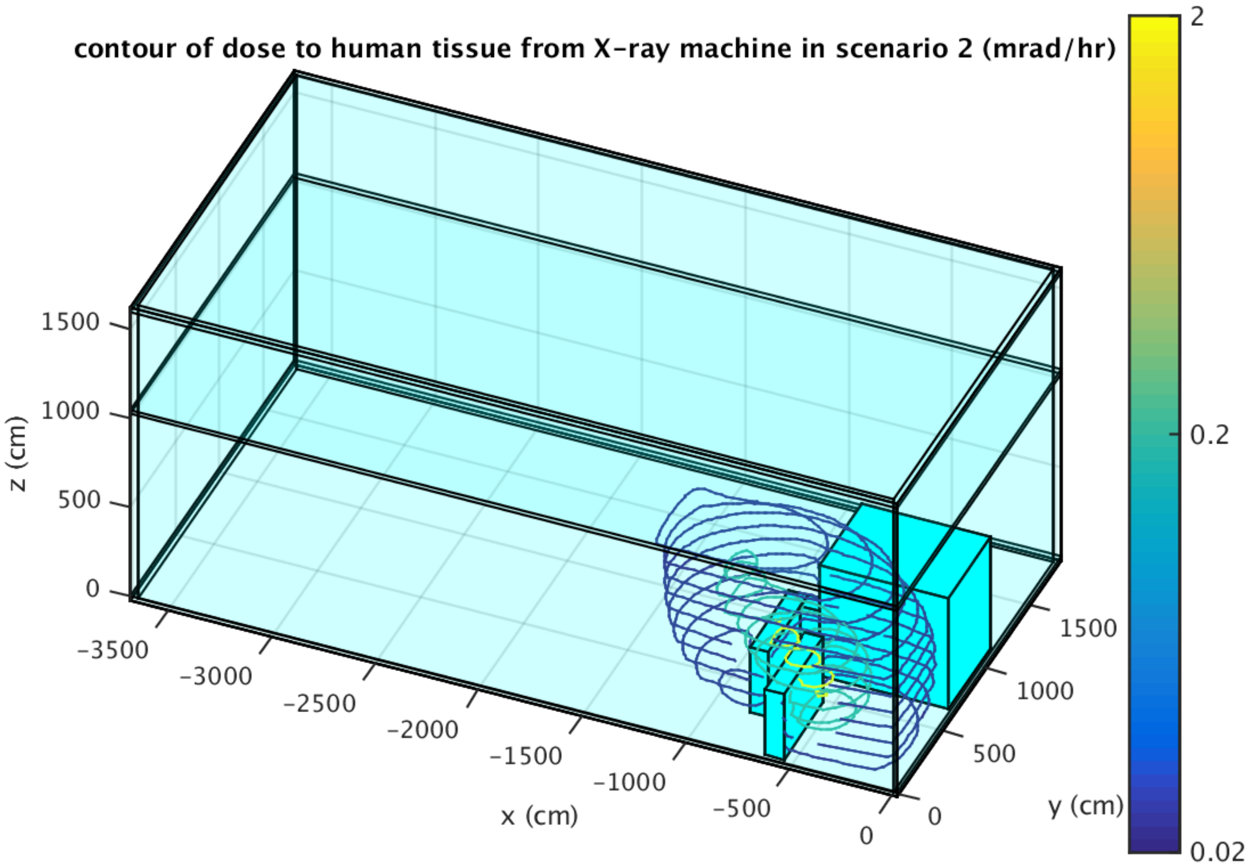


Figure 5: Contour lines of the regions above the safety thresholds of 2.0 and 0.2 mrem/hr for Scenario 2.

Figure 6 provides the final dose contour map for Scenario 3. As with Scenario 1, the exclusion zones for both of the dose rate thresholds are contained entirely within the shielded region surrounding the X-ray generator. However, contrary to the other scenarios, the dose rate drops off below the target thresholds well before reaching the ceiling, due to the fact that the beam is pointed horizontally. The results from this calculation line up well with a simple 1-D hand calculation of uncollided flux, where it is found that essentially none of the photons make it through the concrete shielding uncollided. Due to the fact that scattering and absorption cross sections at these low photon energies are roughly equal, it is expected that the dose rate would fall well below the desired thresholds before penetrating through the shielding block, and therefore confidence in the simulation results is gained.

It is interesting to note that the single shielding block is enough to fully attenuate the beam below $0.02\,\frac{mrem}{hr}$ when the beam is pointed straight at the block, while for Scenario 2, dose levels above

$0.02\,\frac{mrem}{hr}$ are seen outside of the shielding blocks at the level of the floor. This shows that a significant amount of photons are being scattered off of the ceiling and back towards the portion of the room outside of the shielding blocks in Scenario 2. Because of this, Scenario 2 ends up being the most limiting case, as the shielding blocks and room walls/ceiling are more than capable of attenuating the X-ray beam when the photons are directed towards them, but the reflection of photons off of the ceiling offers the possibility for dose rates to be higher than expected outside of the shielded area.

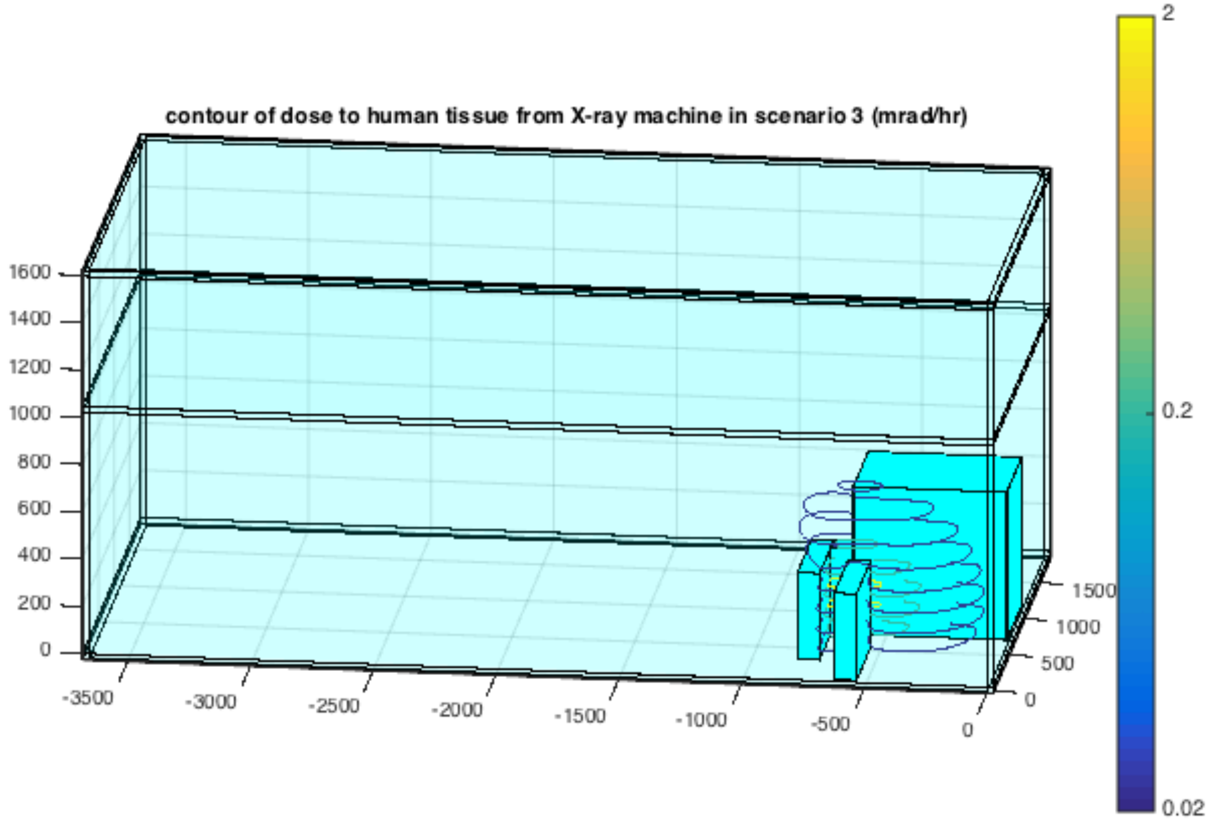


Figure 6: Contour lines of the regions above the safety thresholds of 2.0 and 0.2 mrem/hr for Scenario 3.

Conclusions -

A series of calculations of the dose rate from an X-ray generator in the southeast corner of 1140 Etcheverry Hall have been performed. The calculations were designed to demonstrate the safety of this machine towards people in 1140 and the rooms immediately above for a set of worst-case scenarios, so that it can be further extended that the machine is safe under all operating positions. The X-ray source is shielded by blocks of barite stacked adjacent to the existing HFNG shielding structure. In all three examined scenarios, the dose rate to human tissue is found to fall below the regulatory thresholds of 2.0 and $0.2\,\frac{mrem}{hr}$ within the area surrounded by the shielding blocks below the height of the blocks. Furthermore, it is found that the dose rate falls below the thresholds before reaching into the room above. The scenario that poses the greatest safety challenge is Scenario 2, where the X-ray beam is directed at an angle over the tops of the shielding blocks. In this scenario, the dose rate exceeds the $0.2\,\frac{mrem}{hr}$ threshold outside of the shielded region between an elevation bounded by the tops of the shielding blocks and the bottom of the ceiling. However, due to the fact that there is no current method for a human to be located in this region, this poses no current safety threat, but should be kept in mind for future plans in the room.

References -

[1] D. Essley (personal communication, September 14, 2016). (See attachment A)

[2] P. Broughton (personal communication, August 23, 2016). (See Attachment B)

[3] "Calculation of x-ray spectra emerging from an x-ray tube. Part I. Electron penetration characteristics in x-ray targets," Poludniowski, Gavin G. and Evans, Philip M., Medical Physics, 34, 2164-2174 (2007), DOI:http://dx.doi.org/10.1118/1.2734725.

[4] S. Makiharju (personal communication, August 18, 2016). (See Attachment D)

[5] "MCNP -- A General Monte Carlo N-Particle Transport Code, Version 5," Volumes I, II, and III, X-5 Monte Carlo Team, Los Alamos National Laboratory, April 24, 2003.

[6] McConn, R., C. Gesh, R. Pagh, R. Rucker, R. Williams III, "Compendium of Material Composition Data for Radiation Transport Modeling," PNNL-15870 Rev. 1, March 4, 2011.

[7] http://www.engineeringtoolbox.com/air-composition-d_212.html, accessed November 22, 2016.

Attachment A: Personal communication with Dan Essley regarding wall thicknesses

From: makiharju@berkeley.edu
Subject: Re: Questions on 1140 Dimensions
Date: September 14, 2016 10:25:01 AM PDT
To: Dan ESSLEY <dessley@nuc.berkeley.edu>, Chris Keckler <keckler@berkeley.edu>

Thanks Dan!

On Wed, Sep 14, 2016 at 10:19 AM -0700, "Dan ESSLEY" <dessley@nuc.berkeley.edu> wrote:

> Hi Chris
>
> The wall and floor thickness is roughly 10 - 12 inches thick and the ceiling height is 33.50 ft. Thanks Dan
>
> On Tue, Aug 30, 2016 at 8:53 AM, Chris Keckler <keckler@berkeley.edu> wrote:
>
> > Hi Dan,
> >
> > I am performing some shielding calculations for Professor Simo Markiharju in the ME department (copied), and have some questions on the geometry that you may be able to answer. Professor Makiharju is planning to put an X-ray source in the southeast corner of 1140 for his experiments, and for this, he needs some calculations to determine the dose throughout the room.
> >
> > Professor Makiharju was able to give me many of the dimensions that I require for these calculations, however I am still missing some key pieces of info. Below I have listed these questions, which I am hoping you can help me answer.
> >
> > 1. What is the thickness of the outer walls of 1140?
> > 2. What is the thickness of the floor and ceiling?
> > 3. How tall is 1140 from floor to ceiling?
> >
> > Any help you can give me will be much appreciated. If any of my questions are unclear, please let me know so that I can clarify.
> >
> > Thanks,
> >
> > Chris Keckler

Attachment B: HFNG schematics copied from the HFNG Safety Manual via personal communication with Phillip Broughton

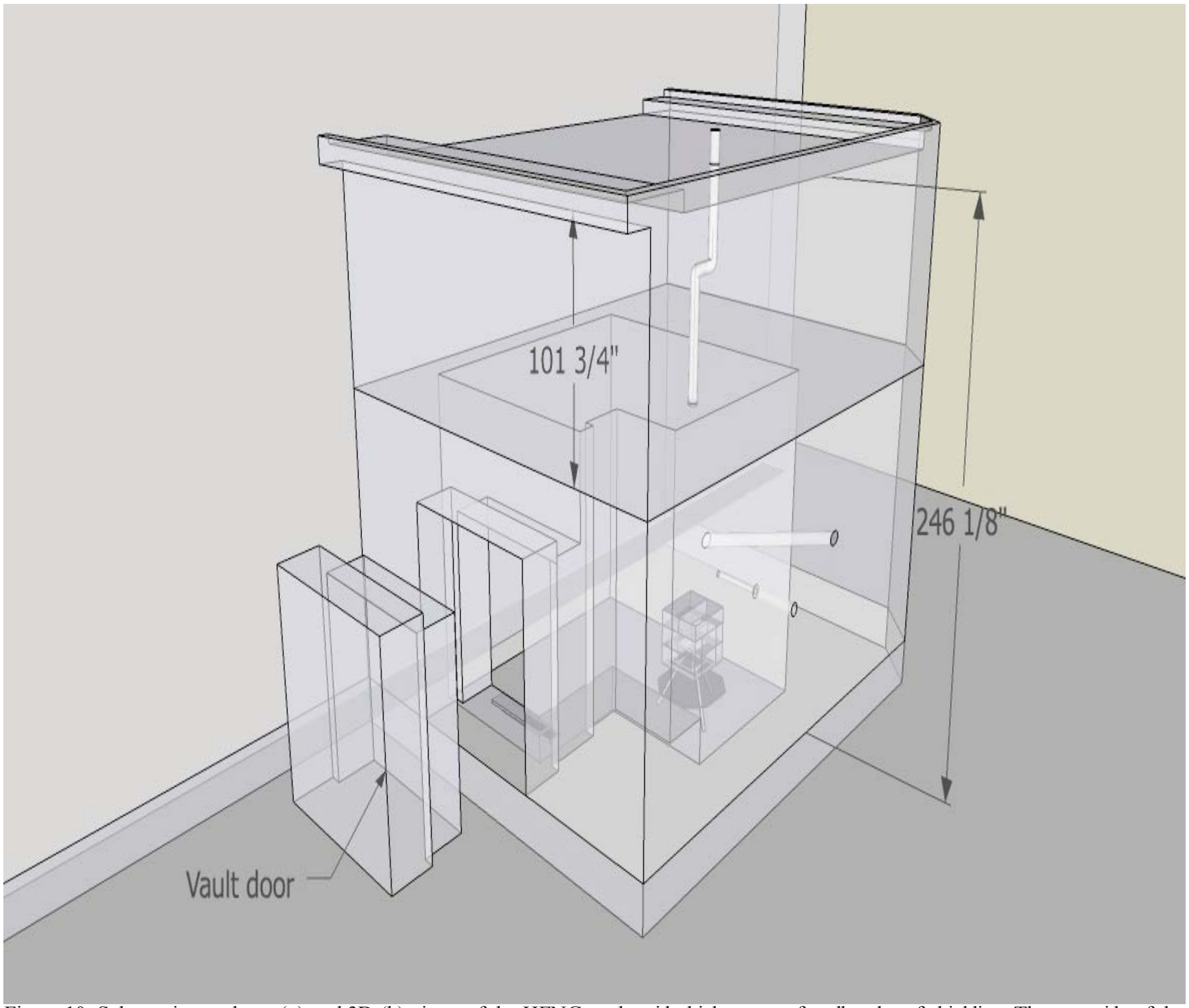


Figure 10. Schematic top-down (a) and 3D (b) views of the HFNG vault, with thicknesses of wall and roof shielding. The east side of the vault is the 53¼"-thick east wall of Room 1140 (which is underground).

HFNG photons (high-energy x-rays and gamma rays) are shielded by the thick concrete walls of the vault. The expected total radiation dose rate, including neutrons and gamma-rays, for an average adult standing 20 cm away from the outside wall of the vault is < 0.2 mrem/hour. The calculated neutron and gamma-dose rates in the plane of the HFNG target are shown in Figures 11a and 11b, respectively.

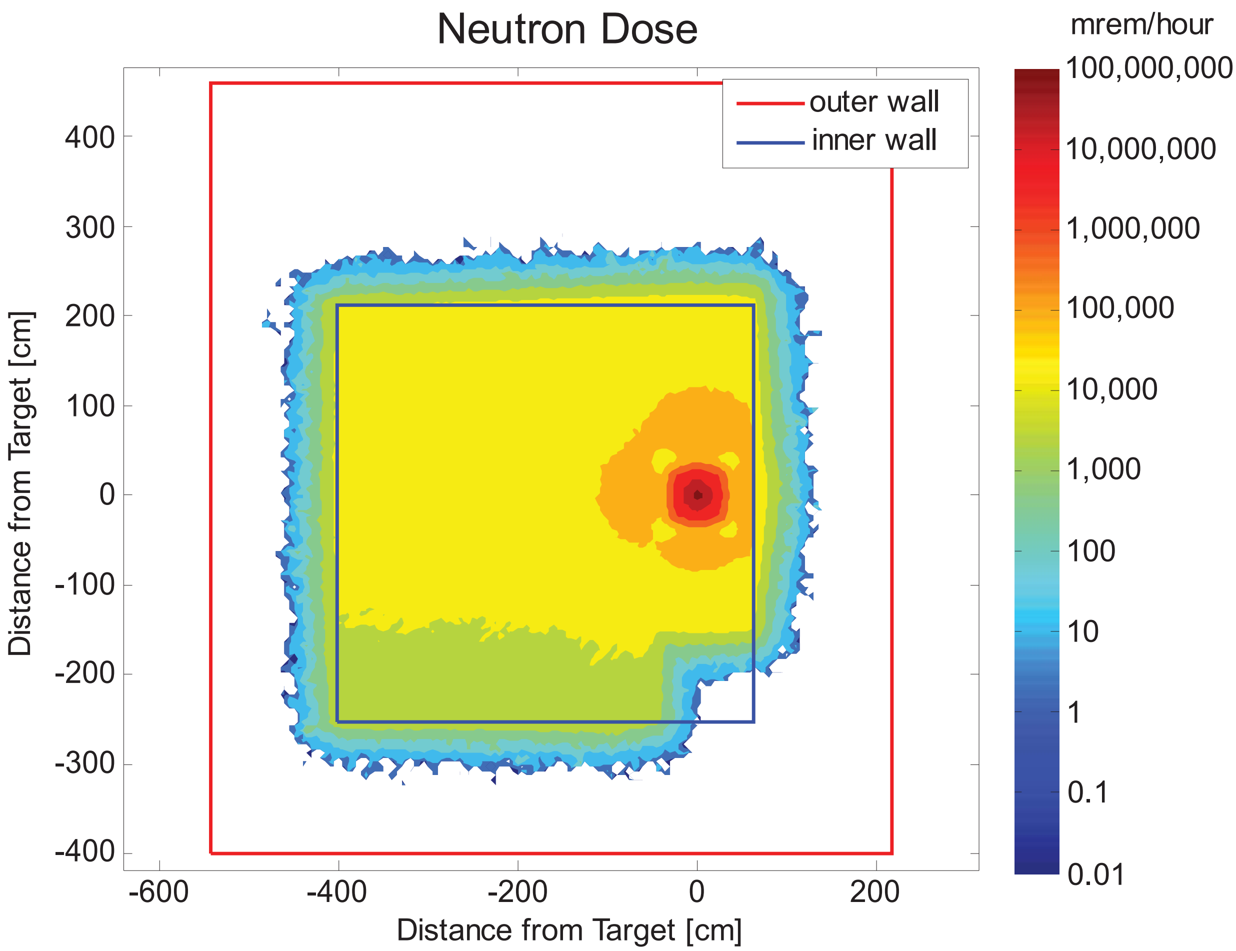
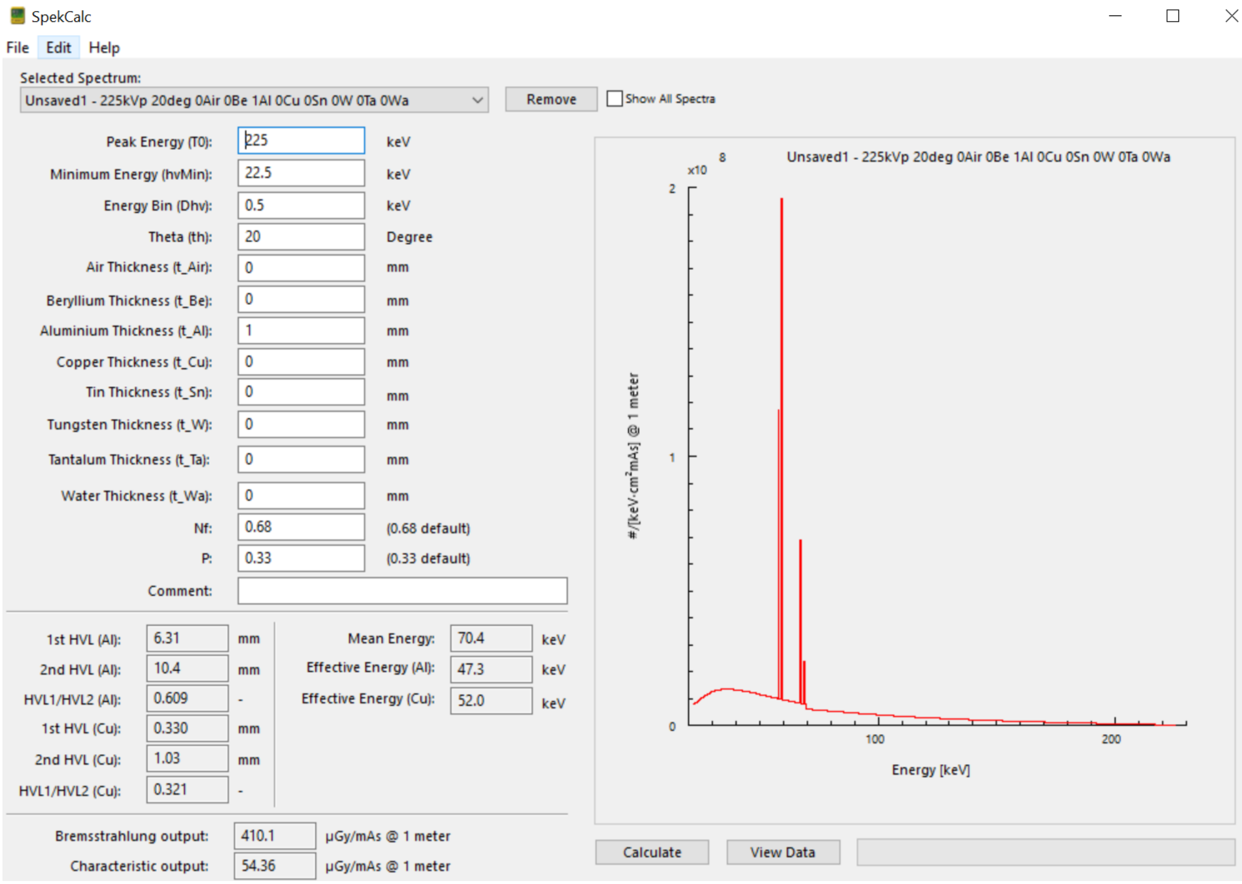


Figure 11a. Top-down view of the neutron dose rate in the target plane of the HFNG under full output. The inner and outer walls of the HFNG vault are shown by blue and red dashed lines, respectively.

Attachment C: Determination of the source term for the X-ray generator using SpekCalc



**** INPUTS ****
kVp [kV] hvMIN [keV] Dhv [keV]
225 22.5 0.5
Angle [deg.]
20
t_AIR t_BE t_AL t_CU t_SN t_W t_Ta t_Wa [mm]
0 0 1 0 0 0 0 0
Nf P
0.68 0.33
****CALCULATED OUTPUTS ****
Brem[uGy/mAs@1m] Char[uGy/mAs@1m]
410.0537 54.35847
HVL1[cm AL] HVL2[cm AL] HVL1[cmCu] HVL2[cmCu] MeanE[keV] EffEAl[keV] EffECu[keV]
0.6313424 1.035841 0.0329815 0.1026184 70.44508 47.2915 52.03697
**** CALCULATED SPECTRUM ****
Energy[keV] N[keV cm^2 mAs]^-1 @ 1 meter

22.5	7.71E+06
23	8.19E+06
23.5	8.59E+06
24	9.02E+06
24.5	9.37E+06
25	9.75E+06
25.5	1.01E+07
26	1.05E+07
26.5	1.07E+07
27	1.11E+07
27.5	1.13E+07
28	1.16E+07

28.5	1.18E+07
29	1.20E+07
29.5	1.22E+07
30	1.24E+07
30.5	1.26E+07
31	1.27E+07
31.5	1.28E+07
32	1.29E+07
32.5	1.30E+07
33	1.31E+07
33.5	1.32E+07
34	1.33E+07
34.5	1.33E+07
35	1.34E+07
35.5	1.34E+07
36	1.34E+07
36.5	1.34E+07
37	1.34E+07
37.5	1.33E+07
38	1.33E+07
38.5	1.33E+07
39	1.33E+07
39.5	1.32E+07
40	1.32E+07
40.5	1.31E+07
41	1.31E+07
41.5	1.30E+07
42	1.29E+07
42.5	1.28E+07
43	1.28E+07
43.5	1.27E+07
44	1.26E+07
44.5	1.25E+07
45	1.24E+07
45.5	1.23E+07
46	1.23E+07
46.5	1.22E+07
47	1.21E+07
47.5	1.20E+07
48	1.19E+07
48.5	1.18E+07
49	1.17E+07
49.5	1.16E+07
50	1.15E+07
50.5	1.14E+07
51	1.13E+07
51.5	1.12E+07
52	1.11E+07
52.5	1.10E+07
53	1.09E+07
53.5	1.08E+07
54	1.07E+07
54.5	1.06E+07
55	1.05E+07
55.5	1.03E+07
56	1.02E+07
56.5	1.01E+07
57	1.00E+07
57.5	9.95E+06
58	1.17E+08
58.5	9.76E+06
59	9.66E+06
59.5	1.96E+08
60	9.47E+06
60.5	9.37E+06
61	9.28E+06

61.5	9.19E+06
62	9.10E+06
62.5	9.00E+06
63	8.91E+06
63.5	8.82E+06
64	8.74E+06
64.5	8.65E+06
65	8.56E+06
65.5	8.47E+06
66	8.39E+06
66.5	8.30E+06
67	6.87E+07
67.5	8.14E+06
68	8.06E+06
68.5	7.97E+06
69	2.36E+07
69.5	7.81E+06
70	5.97E+06
70.5	5.93E+06
71	5.90E+06
71.5	5.86E+06
72	5.82E+06
72.5	5.79E+06
73	5.76E+06
73.5	5.72E+06
74	5.69E+06
74.5	5.65E+06
75	5.62E+06
75.5	5.58E+06
76	5.54E+06
76.5	5.51E+06
77	5.47E+06
77.5	5.44E+06
78	5.40E+06
78.5	5.36E+06
79	5.33E+06
79.5	5.29E+06
80	5.26E+06
80.5	5.22E+06
81	5.18E+06
81.5	5.15E+06
82	5.11E+06
82.5	5.08E+06
83	5.04E+06
83.5	5.00E+06
84	4.97E+06
84.5	4.93E+06
85	4.89E+06
85.5	4.86E+06
86	4.82E+06
86.5	4.79E+06
87	4.75E+06
87.5	4.72E+06
88	4.68E+06
88.5	4.65E+06
89	4.61E+06
89.5	4.58E+06
90	4.55E+06
90.5	4.51E+06
91	4.48E+06
91.5	4.44E+06
92	4.41E+06
92.5	4.38E+06
93	4.34E+06
93.5	4.31E+06
94	4.28E+06

94.5	4.24E+06
95	4.21E+06
95.5	4.18E+06
96	4.15E+06
96.5	4.11E+06
97	4.08E+06
97.5	4.05E+06
98	4.02E+06
98.5	3.99E+06
99	3.96E+06
99.5	3.93E+06
100	3.90E+06
100.5	3.86E+06
101	3.83E+06
101.5	3.80E+06
102	3.77E+06
102.5	3.75E+06
103	3.72E+06
103.5	3.69E+06
104	3.66E+06
104.5	3.63E+06
105	3.60E+06
105.5	3.57E+06
106	3.54E+06
106.5	3.52E+06
107	3.49E+06
107.5	3.46E+06
108	3.43E+06
108.5	3.41E+06
109	3.38E+06
109.5	3.35E+06
110	3.32E+06
110.5	3.30E+06
111	3.27E+06
111.5	3.25E+06
112	3.22E+06
112.5	3.19E+06
113	3.17E+06
113.5	3.14E+06
114	3.12E+06
114.5	3.09E+06
115	3.07E+06
115.5	3.04E+06
116	3.02E+06
116.5	2.99E+06
117	2.97E+06
117.5	2.95E+06
118	2.92E+06
118.5	2.90E+06
119	2.87E+06
119.5	2.85E+06
120	2.83E+06
120.5	2.81E+06
121	2.78E+06
121.5	2.76E+06
122	2.74E+06
122.5	2.72E+06
123	2.69E+06
123.5	2.67E+06
124	2.65E+06
124.5	2.63E+06
125	2.61E+06
125.5	2.58E+06
126	2.56E+06
126.5	2.54E+06
127	2.52E+06

127.5	2.50E+06
128	2.48E+06
128.5	2.46E+06
129	2.44E+06
129.5	2.42E+06
130	2.40E+06
130.5	2.38E+06
131	2.36E+06
131.5	2.34E+06
132	2.32E+06
132.5	2.30E+06
133	2.28E+06
133.5	2.26E+06
134	2.24E+06
134.5	2.23E+06
135	2.21E+06
135.5	2.19E+06
136	2.17E+06
136.5	2.15E+06
137	2.13E+06
137.5	2.11E+06
138	2.10E+06
138.5	2.08E+06
139	2.06E+06
139.5	2.04E+06
140	2.03E+06
140.5	2.01E+06
141	1.99E+06
141.5	1.98E+06
142	1.96E+06
142.5	1.94E+06
143	1.92E+06
143.5	1.91E+06
144	1.89E+06
144.5	1.88E+06
145	1.86E+06
145.5	1.84E+06
146	1.83E+06
146.5	1.81E+06
147	1.80E+06
147.5	1.78E+06
148	1.76E+06
148.5	1.75E+06
149	1.73E+06
149.5	1.72E+06
150	1.70E+06
150.5	1.69E+06
151	1.67E+06
151.5	1.66E+06
152	1.64E+06
152.5	1.63E+06
153	1.61E+06
153.5	1.60E+06
154	1.58E+06
154.5	1.57E+06
155	1.56E+06
155.5	1.54E+06
156	1.53E+06
156.5	1.51E+06
157	1.50E+06
157.5	1.49E+06
158	1.47E+06
158.5	1.46E+06
159	1.44E+06
159.5	1.43E+06
160	1.42E+06

160.5	1.40E+06
161	1.39E+06
161.5	1.38E+06
162	1.37E+06
162.5	1.35E+06
163	1.34E+06
163.5	1.33E+06
164	1.31E+06
164.5	1.30E+06
165	1.29E+06
165.5	1.28E+06
166	1.26E+06
166.5	1.25E+06
167	1.24E+06
167.5	1.23E+06
168	1.21E+06
168.5	1.20E+06
169	1.19E+06
169.5	1.18E+06
170	1.17E+06
170.5	1.15E+06
171	1.14E+06
171.5	1.13E+06
172	1.12E+06
172.5	1.11E+06
173	1.10E+06
173.5	1.08E+06
174	1.07E+06
174.5	1.06E+06
175	1.05E+06
175.5	1.04E+06
176	1.03E+06
176.5	1.02E+06
177	1.01E+06
177.5	994788.4
178	983753.9
178.5	972924.4
179	962188.5
179.5	951441.7
180	940789.9
180.5	930212.5
181	919566.4
181.5	908869.6
182	898266.6
182.5	887756.4
183	877337.8
183.5	867118
184	856985.4
184.5	846833.4
185	836518
185.5	826135.6
186	815843.7
186.5	805641.5
187	795527.8
187.5	785599.9
188	775756.4
188.5	765900.3
189	756129
189.5	746161.4
190	736142.4
190.5	726210.3
191	716364.1
191.5	706698.3
192	697113.8
192.5	687517.2
193	678002.7

193.5	668563.5
194	658871.1
194.5	649133.8
195	639480.5
195.5	629995.2
196	620589.6
196.5	611180.3
197	601851.4
197.5	592602.2
198	583431.6
198.5	573942.4
199	564414.7
199.5	555048.3
200	545760.2
200.5	536472.6
201	527264.4
201.5	518134.7
202	509082.5
202.5	500103.4
203	490733.4
203.5	481399.9
204	472144.2
204.5	462903
205	453740.5
205.5	444652.7
206	435642.2
206.5	426708.2
207	417849.9
207.5	408571.8
208	399265.4
208.5	389983.8
209	380781.3
209.5	371657.1
210	362610.3
210.5	353640.3
211	344746.1
211.5	335925.2
212	325939.6
212.5	315977.6
213	306098.4
213.5	296259.6
214	286504.8
214.5	276833.1
215	267243.7
215.5	257735.7
216	248308.3
216.5	238787.4
217	229252.6
217.5	219767.1
218	210362.4
218.5	201037.7
219	191792.1
219.5	182624.3
220	173534.2
220.5	164521.5
221	145753.2
221.5	126993
222	108390.5
222.5	89931.93
223	71632.85
223.5	53491.67
224	35506.83
224.5	17676.78
225	0

Attachment D: Beam dimension per personal communication with Simo Makiharju