RADIATION SHIELDING: TECHNIQUES AND LESSONS LEARNED

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INTRODUCTION

- Some organizations still perform shielding calculations by hand.
- My goal is to show you some tools that will speed up this process with no loss of accuracy and with good documentation.

SHIELDING TECHNIQUES – MANUAL

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- NCRP Methods:
  - Report 38: Protection Against Neutron Radiation
  - Report 49: Structural Shielding Design and Evaluation for Medical Use of X Rays and Gamma Rays of Energies up to 10 MeV
  - Report 51: Radiation Protection Design Guidelines for 0.1 – 100 MeV Particle Accelerator Facilities
  - Report 144: Radiation Protection for Particle Accelerator Facilities
  - Report 147: Structural Shielding Design for Medical X-Ray Imaging Facilities
  - Report 151: Structural Shielding Design and Evaluation for Megavoltage X-and Gamma-Ray Radiotherapy Facilities
- Use Microsoft Excel or similar spreadsheet software to automate.
- Here is an example.

SPREADSHEET EXAMPLE

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This is a small portion. The actual spreadsheet has over 100 lines and 8 tabs.

P: Dose goal in Uncontrolled Areas	Sv/wk	2.00E-05	100 mrem per year/50 weeks per year x 0.001 rem/mrem x 0.01 Sv/rem	NCRP 151
d_{pri}	meters	6.7056	Distance from x-ray source to 1 foot out side the primary shield wall	See drawing
W (workload) 4 MeV	Gy m^2 wk^{-1}	7973.28	4 Gy/min x 7 hrs/shift x 3 shifts/day x 7 days/wk x 60 mins/hr x 0.01 m^2 x 22.6 Areas	Field size defined by Varian as 10 cm by 10 cm which equals 0.01 m^2
W (workload) 6 MeV	Gy m^2 wk^{-1}	15946.56	8 Gy/min x 8 hrs/shift x 3 shifts/day x 7 days/wk x 60 mins/hr x 0.01 m^2 x 22.6 Areas	Area of a 30 degree cone at 1 meter is 0.226 m^2. Need to Increase work load by 22.6
W (workload) 9 MeV	Gy m2 wk^{-1}	59799.6	30 Gy/min x 8 hrs/shift x 3 shifts/day x 7 days/wk x 60 mins/hr x 0.01 m^2 x 22.6 Areas	Based on Varex product sheet
U: Use Factor	unitless	1	X-Ray machine points one direction only	Defined by user
T: Occupancy Factor Primary	unitless	0.025	Area is outside and is a restricted area with limited to no access	NCRP 151 Table B.1 Outdoor area
T: Occupancy Factor Adjacent Vault	unitless	0.5	Assumes area could be occupied during x-ray	NCRP 151 Table B.1 Adjacent Shielded Vault
T: Occupancy Factor - Offices and training	unitless	1	User Input	NCRP 151 Table B.1 Full Occupancy Areas
T: Occupancy Factor Corridor	unitless	0.2		NCRP 151 Table B.1 Corridor
T: Occupancy Factor Control Room	unitless	1	Assumes 24/7 operation	NCRP 151 Table B.1 Full Occupancy Areas
T: Occupancy Factor Staging Area	unitless	0.2		NCRP 151 Table B.1 Adjacent Areas

SPREADSHEET EXAMPLE – CONTINUED

Here is the primary beam transmission factor equation used by the NCRP.

$$B_{pri} = \frac{P\left(d_{pri}\right)^2}{WUT}$$

Where:

B_{pri} = transmission factor
P = Dose goal in area of interest
d_{pri} = distance to dose point
W = workload
U = Use factor for that barrier
T = Occupancy Factor in area of interest

In Excel, the formula might look like this: =C4*C5^2/(C8*C9*C10)

These are all cell references. Using them automates the calculations.

SHIELDING PROGRAMS

- MicroShield – Available from Grove
  - Point Kernel shielding program
  - Easy to use
  - Flexible
  - Does not address neutrons
- MCNP – Only available from RSICC
  - DOS-based
  - Very detailed
  - Requires training and experience
  - Addresses photons, neutrons, electrons and other particles

MICROSHIELD EXAMPLE

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MicroShield 10.06
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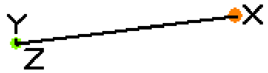
Date	**By**	**Checked**

File Name	**Run Date**	**Run Time**	**Duration**
9MV with spectrum 1 meter.msd	July 11, 2025	6:47:46 AM	-01:59:6

Project Info	
Case Title	9MV 1m
Description	:load with spectrum
Geometry	1 - Point

Dose Points			
A	**X**	**Y**	**Z**
#1	100.0 cm (3 ft 3.4 in)	0.0 cm (0 in)	0.0 cm (0 in)

Shields			
Shield N	**Dimension**	**Material**	**Density (g/cm³)**
Air Gap		Air	0.00122



Source Input: Grouping Method - User Defined Energies

Group No.	**Energy (MeV)**	**Activity (Photons/sec)**	**Point Source Photons/sec**	**%Energy Activity**
1	1.0	3.8100e+015	3.8100e+015	20.697%
2	2.0	2.2900e+015	2.2900e+015	24.880%
3	3.0	1.0200e+015	1.0200e+015	16.623%
4	4.0	5.4900e+014	5.4900e+014	11.929%
5	5.0	3.6200e+014	3.6200e+014	9.832%
6	6.0	2.2200e+014	2.2200e+014	7.236%
7	7.0	1.3100e+014	1.3100e+014	4.981%
8	8.0	6.7900e+013	6.7900e+013	2.951%
9	9.0	1.7800e+013	1.7800e+013	0.870%

Buildup: The material reference is Air Gap.
Integration Parameters

Results

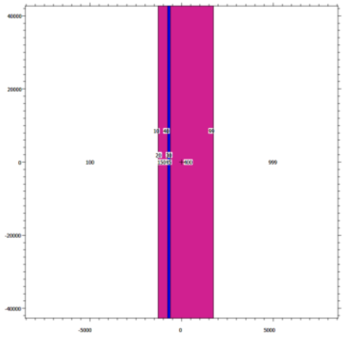
Energy (MeV)	**Activity (Photons/sec)**	**Fluence Rate MeV/cm²/sec No Buildup**	**Fluence Rate MeV/cm²/sec With Buildup**	**Exposure Rate mR/hr No Buildup**	**Exposure Rate mR/hr With Buildup**	**Absorbed Dose Rate mrad/hr No Buildup**	**Absorbed Dose Rate mrad/hr With Buildup**	**Absorbed Dose Rate mGy/hr No Buildup**	**Absorbed Dose Rate mGy/hr With Buildup**
1.0	3.810e+15	3.009e+10	3.027e+10	5.546e+07	5.579e+07	4.841e+07	4.870e+07	4.841e+05	4.870e+05
2.0	2.290e+15	3.625e+10	3.638e+10	5.606e+07	5.625e+07	4.894e+07	4.911e+07	4.894e+05	4.911e+05
3.0	1.020e+15	2.424e+10	2.431e+10	3.289e+07	3.298e+07	2.872e+07	2.879e+07	2.872e+05	2.879e+05
4.0	5.490e+14	1.741e+10	1.745e+10	2.154e+07	2.158e+07	1.880e+07	1.884e+07	1.880e+05	1.884e+05
5.0	3.620e+14	1.436e+10	1.438e+10	1.646e+07	1.648e+07	1.437e+07	1.439e+07	1.437e+05	1.439e+05
6.0	2.220e+14	1.057e+10	1.058e+10	1.148e+07	1.149e+07	1.002e+07	1.003e+07	1.002e+05	1.003e+05
7.0	1.310e+14	7.276e+09	7.286e+09	7.573e+06	7.582e+06	6.611e+06	6.619e+06	6.611e+04	6.619e+04
8.0	6.790e+13	4.311e+09	4.316e+09	4.333e+06	4.338e+06	3.783e+06	3.787e+06	3.783e+04	3.787e+04
9.0	1.780e+13	1.272e+09	1.273e+09	1.242e+06	1.243e+06	1.084e+06	1.085e+06	1.084e+04	1.085e+04
Total	**8.470e+15**	**1.458e+11**	**1.462e+11**	**2.070e+08**	**2.077e+08**	**1.807e+08**	**1.814e+08**	**1.807e+06**	**1.814e+06**

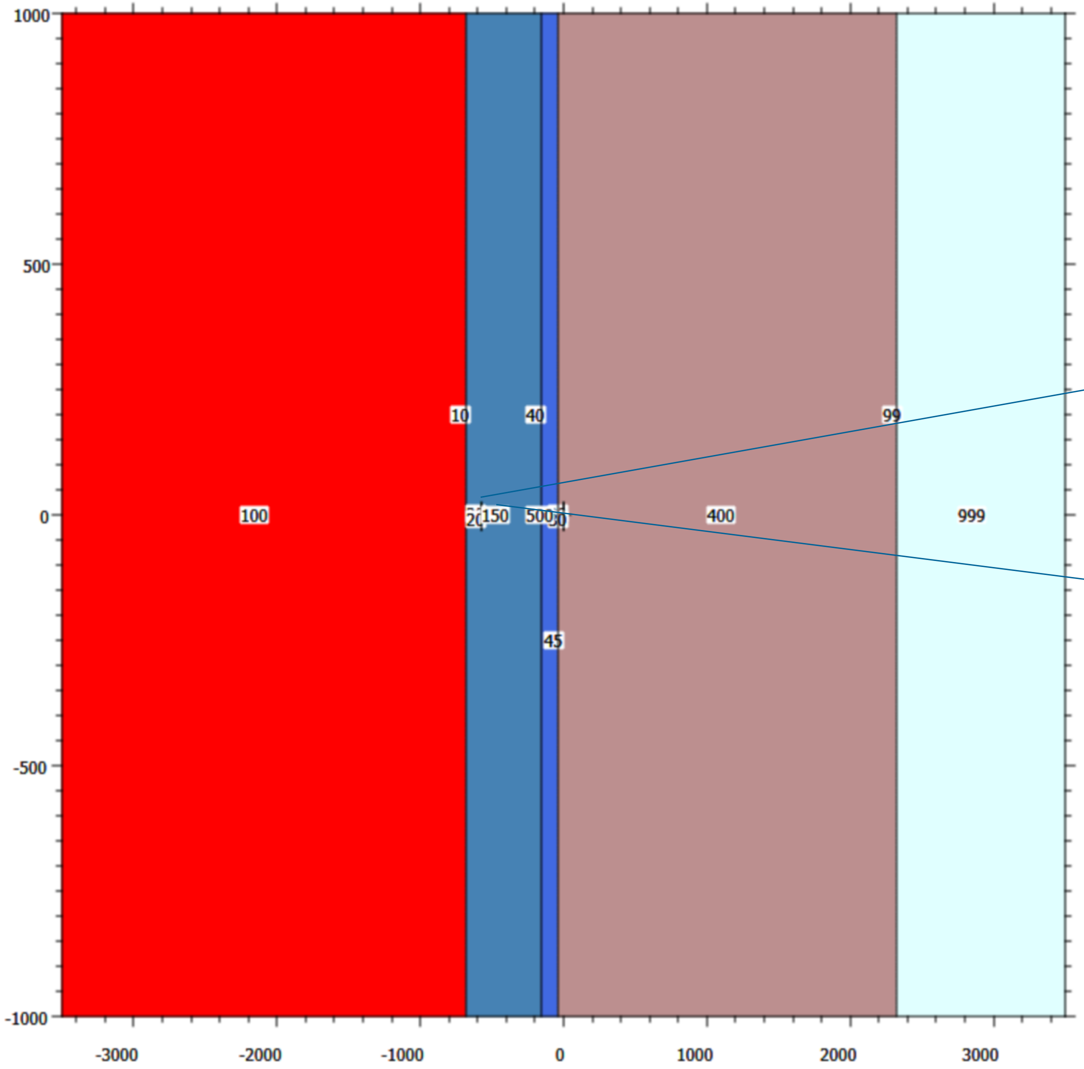
MCNP INPUT FILE EXAMPLE

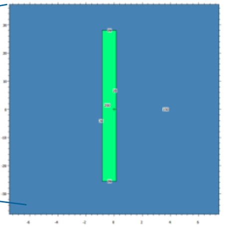
```
Dose Rate Example
c Geometry - cells
100 0 -10                    $Void to the left of the problem
150 1000   -0.001293 10 +20 -40              $source cell
200 1000   -0.001293 -20                 $detector at 1 meter
300 1000   -0.001293 -30
400 1000   -0.001293 30 45 -99
500 2000   -2.3  40 -45
999 0 99                                 $Void to right of the problem

c Geometry - Surfaces
10  pz -10
20  rcc 0 0 100   0 0 1   26.795
30  rcc 0 0 669.064   0 0 1   26.795
40  pz  518.16
45  pz  639.064
99  pz 3000

c sources and materials
nps 1e7
mode p e
imp:p,e 0 1 1 1 1 1 0
m1000  1001 -1.1e-3   1002 -5e-7      7014 -0.7447    7015 -2.95-3    &    $Air
      8016 -0.2383   8017 -9.7e-5   18036 -3.9e-5   18038 -7.7e-6    &
      18040 -1.2383e-2
m2000 1001 -0.022094 1002 -0.000005 6000 -0.002484 8016 -0.573373 8017 -0.000232 &
     8018 -0.001326 11023 -0.015208 12000 -0.001266 13027 -0.019953 14000 -0.304627 &
     19000 -0.010045 20000 -0.42951 26000 -0.006435
sdef pos 0 0 0 par=2 erg=d1 vec 0 0 1 dir=d2 wgt=58.8235
si1 h 0 1 2 3 4 5 6 7 8 9
sp1 d 0 0.449 0.27 0.12 0.0647 0.0427 0.0262 0.0154 0.008 0.0021
SI2 -1 0.966 1.0
SP2  0 0.983 0.017
SB2  0 0 1
f11:p 20.3
f21:p 30.3
df0 iu=1 fac=-3 log ic=99
print
```







THINGS TO CONSIDER

- The NCRP method automatically assumes an x-ray spectrum.
- You must develop a spectrum for MicroShield and MCNP.
- This applies to photons for MicroShield and to all particles for MCNP.

USEFUL REFERENCE

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- PNNL Compendium of Materials
  - Gives densities and constituents

- **107. Concrete, Ordinary (NIST)**
- Formula = Molecular Weight (g/mole) =
- Density (g/cm3) = 2.3 Total Atom Weight (atoms/b-cm) = 9.946E-02
- The above density is estimated to be accurate to 2 significant digits. Uncertainties are not addressed.
- **Isotopic**

		Weight Fractions		Atom Fractions		Atom Densities
H1	1001	-0.022094	1001	0.305287	1001	0.030365
H2	1002	-0.000005	1002	0.000035	1002	0.000003
C	6000	-0.002484	6000	0.002880	6000	0.000286
O16	8016	-0.573373	8016	0.499194	8016	0.049652
O17	8017	-0.000232	8017	0.000190	8017	0.000019

– 200-DMAMC-128170 PNNL-15870, Rev. 2

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- ***Comments and References***
- Density and weight fractions from
- http://physics.nist.gov/PhysRefData/XrayMassCoef/tab2.html.

METHOD COMPARISON

- Beam is 9 MV
- Spectrum developed from (*Intan Dyah Ayu Permatasari et al 2019 J. Phys.: Conf. Ser. 1153 012109*)
- Shield wall is 4 feet of normal concrete, 3.37 TVL
- Dose rate is 30 Gy/m at 1 meter (manufacturer's specification)
- Dose point is at 6.7506 meters (1-foot past shield wall)
- Dose rate – unshielded

$$\mathrm{R} = 30\,{}^{Gy}/_{m} \times 60\,{}^{m}/_{h} \times \frac{1}{(6.7506)^2} m = 40\,{}^{Gy}/_{h} = 4{,}000\,{}^{Rad}/_{h}$$

- Shielded Dose Rate

$$D = D_0 \times \frac{1}{10^{TVL}} = 4000 \times \frac{1}{10^{3.37}} = 2.122\,{}^{Rad}/_{h} = 2{,}122\,{}^{mrad}/_{h}$$

METHOD COMPARISON – CONTINUED

- MicroShield
  - Point source using external source (9MV x-ray spectrum)
  - Scale the photons to get 1800 Gy/h at 1 meter
  - Dose point at 6.7506 meters
  - Source to wall distance = 5.1816 meters
  - 4-ft wall, normal concrete, 2.35 g/cm^3, normal density
  - Result = 2,110 mrad/h

- MCNP
  - Same dimensions
  - Same x-ray spectrum source term
  - Result is in mrem/h per source particle
  - Calculate a scaling factor based on the mrem/h per particle at 1 meter
  - Result = 1,570 mrem/h

ADVANTAGES AND DISADVANTAGES

ADVANTAGES

NCRP Method

- Fairly inexpensive and easily available
- Routinely used and easy to understand
- Can be both performed manually and verified manually
- Straightforward conversion to Excel

DISADVANTAGES

NCRP Method

- Manpower-intensive, especially for complex or multiple points and locations
- Some methods involve graphs that do not have all energies or that need interpolation

ADVANTAGES AND DISADVANTAGES – CONT'D

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ADVANTAGES

MicroShield

- Easy to use
- Can do multiple points in a single model
- Well-documented and accepted for photon shielding

DISADVANTAGES

MicroShield

- Cost, especially for a site license
- Does not address neutrons

ADVANTAGES AND DISADVANTAGES – CONT'D

ADVANTAGES

MCNP

- Handles complex geometries
- Handles all particles
- Is becoming an industry standard for calculations

DISADVANTAGES

MCNP

- Cost of program and training
- Difficult to use
- Results require interpretation
- Limited error checking
- Computer-intensive—Some runs can take hours to days to complete

SUMMARY

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- Tools are available that can automate and simplify shielding calculations.
- Need help? Resources are available.
- Tools have been used to support a wide range of efforts.
  - State agencies such as the Commonwealth of Massachusetts
  - Industrial users: Washington, West Virginia, Maryland, California
  - Medical users: Washington, California, Virginia
  - Isotope manufacturers and nuclear pharmacies: Indiana

QUESTIONS?

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Contact me for more information.

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