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KSU Cs-137 Air-Over-Concrete/Ground Shielding Benchmarks

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Auspices

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Disclaimer

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Introduction:

In addition to the famous KSU silo skyshine measurements using Co-60, Roseberry and Nason report the results of calibration experiments using Cs-137 sources in air-over-concrete/ground geometry, which is the subject of this report.

Roseberry and Nason provide no information on material compositions other than some reported densities. In lieu of measured data, compositions are assumed based on data published in the PNNL compendium and by ORNL.

Note that experimental results are given in units of exposure (R = Roentgens). Contemporary fluence-to-exposure data published by Rogers are used for COG simulations.

The details of the COG simulation model are provided in the sections: **Dimensions** and **Materials**. Due to cylindrical (R-Z) symmetry, the detector is a reaction detector in a torus of 2-inch radius at various lateral distances and 36 inches above the concrete.

References:

1. Murray Lee Roseberry, "Benchmark Skyshine Exposure Rates," Master's Thesis, Kansas State University, 1980.

2. Randall Robert Nason, "Analysis of Skyshine Spectral Measurements," Master's Thesis, Kansas State University, 1979.

3. PNNL-15870, Rev. 2, "Compendium of Material Composition Data for Radiation Transport Modeling," April 2021.

4. ORNL-4289, Vol. II, "Time-Dependent Neutron and Secondary Gamma-Ray Transport in an Air-Over-Ground Geometry, Volume II. Tabulated Data," E. A. Straker, September 30, 1968.

5. D. W. O. Rogers, "Fluence to Dose Equivalent Conversion Factors Calculated with EGS3 for Electrons from 100 keV to 20 GeV and Photons from 11 keV to 20 GeV," Health Physics: **46** (4) 891-914, 1984.

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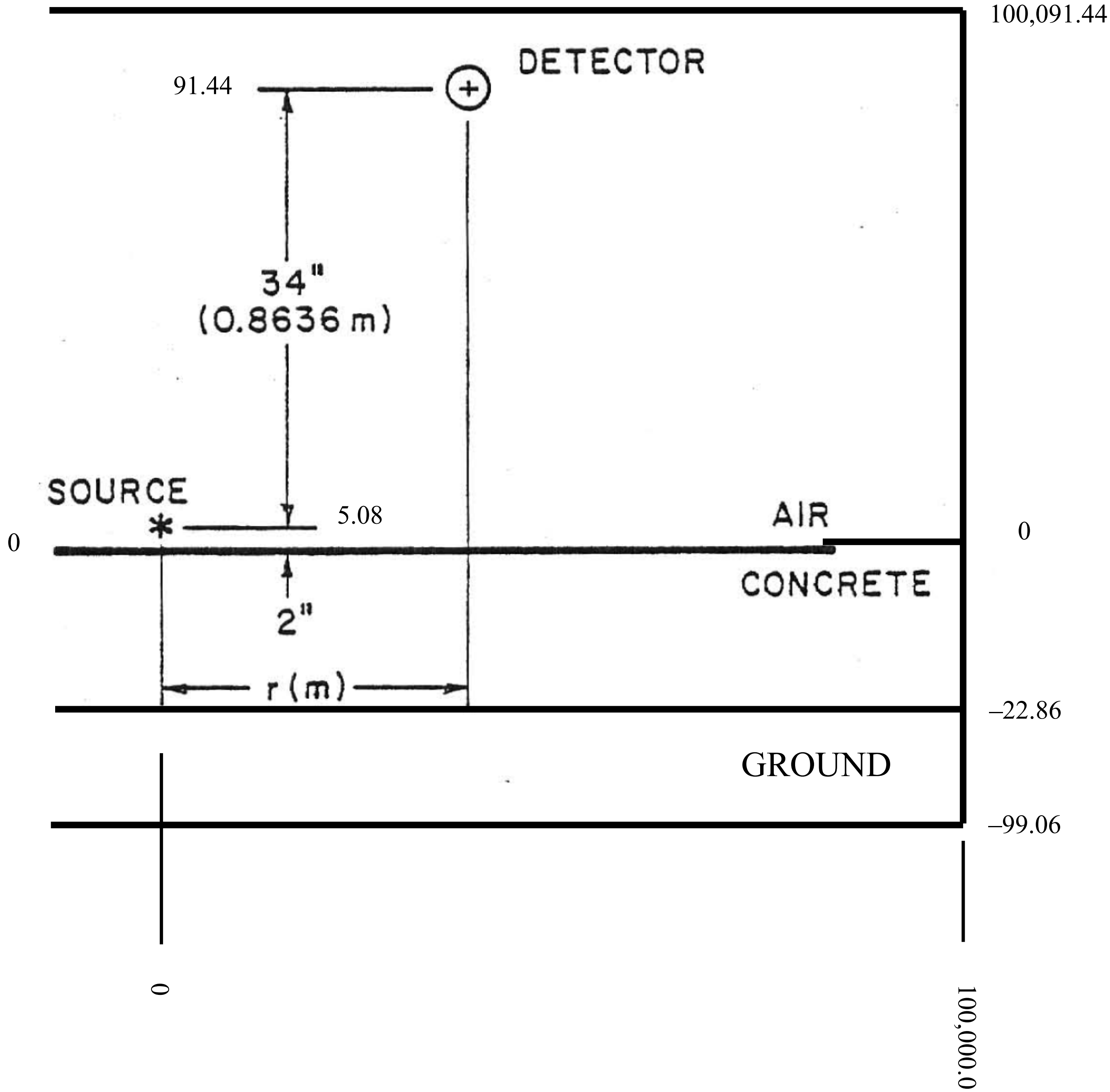
Dimensions: R-Z model details



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Materials: Concrete, Air, and Ground

The concrete composition was not specified. Ordinary (NIST) concrete assumed per PNNL-15870, Rev. 2, Entry 102, as shown in Table 1. A density of 2.17 g/cc was assumed based on the average concrete construction of the Silo as reported by Rosebury, Table 2-2.

The composition of the air was not specified. Dry air near sea level assumed per PNNL-15870, Rev. 2, Entry No. 4, as shown in Table 2. Note that this composition corresponds to 0.03% CO_2, 78.09% N_2, 20.95% O_2, and 0.93% Ar. The composition for humid air adjusts these parameters assuming 4% H_2O as provided in Table 3.

Table 1. Concrete

Element	wt.-%
H	30.5322
C	0.2880
O	50.0410
Na	0.9212
Mg	0.0725
Al	1.0298
Si	15.1046
K	0.3578
Ca	1.4924
Fe	0.1605

Table 2. Dry Air

Element	at.-%
C	0.0150
N	78.4429
O	21.0750
Ar	0.4671

Table 3. Humid Air

Element	at.-%
C	0.014
N	73.621
O	21.999
Ar	0.438
H	3.928

The composition of the ground was not specified. Ground assumed per ORNL-4289, Volume II, Table 1 as repeated in Table 3. Note that this composition is consistent with that specified in the Baikal (ICSBEP/SINBAD) benchmark.

Table 4. Ground

Element	at.-%
H	16
O	57
Si	19
Al	8

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Calculations:

All calculations were performed using COG11.3 with ENDF/B-VIII.0 cross sections and fluence-to-exposure conversion factors by Rogers (Table 3). A summary of the basic model details is provided in Table 5. The input file (ksu0) is provided in Attachment A.

Table 5. COG calculational model details

File	Source Elevation	Neutrons	Model	Range	Air (mg/cc)	Humidity
ksu0	5.08 cm	1E+8	^{137}Cs in air-above-concrete/ground.	2 – 18 m	1.142	Dry Air
ksuh	5.08 cm	1E+8	^{137}Cs in air-above-concrete/ground.	2 – 18 m	1.142	Humid Air

Results:

The calculational results normalized to a source strength of 1 mCi are provided in Tables 6 and 7 for dry air and humid air, respectively, which are identical. A graph of the results is provided in Appendix B demonstrating the applicability of the inverse square law in the near field.

The results are considered very good and likely within experimental errors if the error in detector positioning were known – see Roseberry, Table 2-10, which reports an error of ±0.5 m at 30 m corresponding to $\Delta\dot{X}$ = ±3.3%.

Table 6. Results for Photon Transport in Dry Air (file: ksu0)

Experiment						COG		
r (m)	ρ* (mg/cc)	ρr (g/cm^2)	Source** (mCi)	Exposure Rate (μR/hr)	Exposure Rate (μR/hr•mCi)	Exposure Rate (R/s•mCi)	Exposure Rate (μR/hr•mCi)	C/E
2	1.142	2.28	3.094	246.8 ± 0.8	79.77 ± 0.26	2.543E-8 ± 0.1%	91.54 ± 0.1%	1.15 ± 3.5%
4	1.142	4.57	14.22	320.3 ± 0.7	22.53 ± 0.05	7.117E-9 ± 0.1%	25.62 ± 0.1%	1.14 ± 3.5%
5	1.142	5.71	14.22	208.8 ± 0.8	14.68 ± 0.06	4.580E-9 ± 0.1%	16.49 ± 0.1%	1.12 ± 3.5%
7	1.142	7.99	14.22	105.8 ± 0.8	7.44 ± 0.06	2.317E-9 ± 0.1%	8.34 ± 0.1%	1.12 ± 3.6%
8	1.142	9.14	14.22	79.8 ± 0.6	5.62 ± 0.04	1.762E-9 ± 0.1%	6.34 ± 0.1%	1.13 ± 3.6%
10	1.142	11.42	14.22	53.8 ± 0.8	3.78 ± 0.06	1.114E-9 ± 0.1%	4.01 ± 0.1%	1.06 ± 3.8%
12	1.142	13.70	14.22	35.3 ± 0.6	2.48 ± 0.04	7.636E-10 ± 0.2%	2.75 ± 0.1%	1.11 ± 3.9%
14	1.142	15.99	14.22	25.7 ± 0.6	1.81 ± 0.04	5.531E-10 ± 0.2%	1.99 ± 0.2%	1.10 ± 4.1%
18	1.142	20.56	14.22	14.1 ± 0.6	0.99 ± 0.04	3.273E-10 ± 0.2%	1.18 ± 0.2%	1.19 ± 5.3%

* 2% error in air density (negligible).
** 3.5% error in source strength.

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Table 6. Results for Photon Transport in Humid Air (file: ksuh)

Experiment						COG		
r (m)	ρ* (mg/cc)	ρr (g/cm^2)	Source** (mCi)	Exposure Rate (μR/hr)	Exposure Rate (μR/hr•mCi)	Exposure Rate (R/s•mCi)	Exposure Rate (μR/hr•mCi)	C/E
2	1.142	2.28	3.094	246.8 ± 0.8	79.77 ± 0.26	2.545E-8 ± 0.1%	91.60 ± 0.1%	1.15 ± 3.5%
4	1.142	4.57	14.22	320.3 ± 0.7	22.53 ± 0.05	7.124E-9 ± 0.1%	25.65 ± 0.1%	1.14 ± 3.5%
5	1.142	5.71	14.22	208.8 ± 0.8	14.68 ± 0.06	4.577E-9 ± 0.1%	16.48 ± 0.1%	1.12 ± 3.5%
7	1.142	7.99	14.22	105.8 ± 0.8	7.44 ± 0.06	2.311E-9 ± 0.1%	8.32 ± 0.1%	1.12 ± 3.6%
8	1.142	9.14	14.22	79.8 ± 0.6	5.62 ± 0.04	1.761E-9 ± 0.1%	6.34 ± 0.1%	1.13 ± 3.6%
10	1.142	11.42	14.22	53.8 ± 0.8	3.78 ± 0.06	1.112E-9 ± 0.1%	4.00 ± 0.1%	1.06 ± 3.8%
12	1.142	13.70	14.22	35.3 ± 0.6	2.48 ± 0.04	7.627E-10 ± 0.2%	2.75 ± 0.1%	1.11 ± 3.9%
14	1.142	15.99	14.22	25.7 ± 0.6	1.81 ± 0.04	5.527E-10 ± 0.2%	1.99 ± 0.2%	1.10 ± 4.1%
18	1.142	20.56	14.22	14.1 ± 0.6	0.99 ± 0.04	3.275E-10 ± 0.2%	1.18 ± 0.2%	1.19 ± 5.3%

* 2% error in air density (negligible).
** 3.5% error in source strength.

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Appendix A: COG input listing file (ksu0)

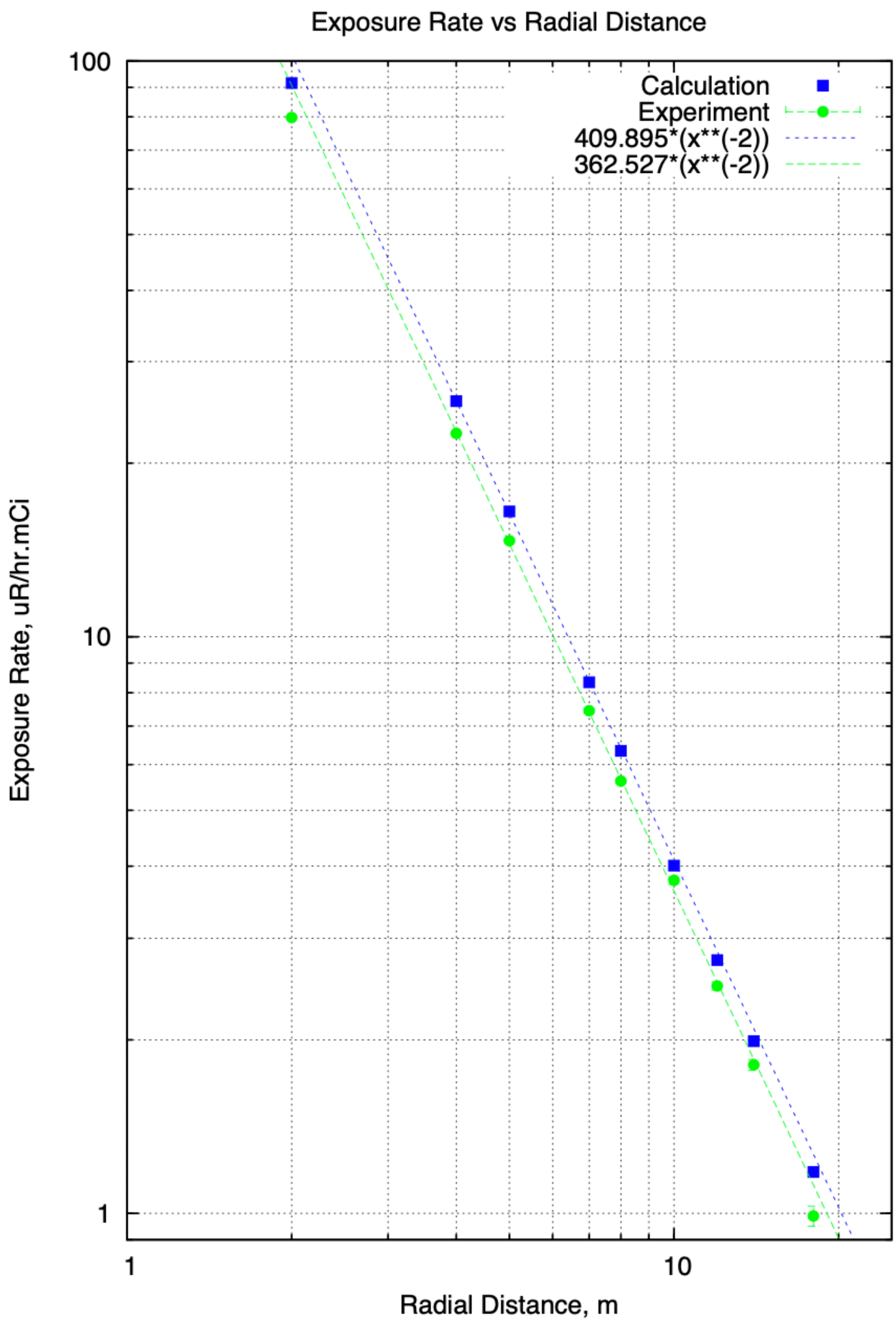
```
KSU Cs-137 Air-Over-Concrete/Ground Calibration Experiments (dry air)
$
$  References:
$    1. Murray Lee Roseberry, "Benchmark Skyshine Exposure Rates," Master's Thesis, Kansas
$       State University, 1980.
$    2. Health Physics, Vol. 46, No. 4, pp. 891-914, 1984, "Fluence to Dose Equivalent
$       Conversion Factors Calculated with EGS3 for Electrons from 100 keV to 20 GeV and
$       Photons from 11 keV to 20 GeV," D. W. O. Rogers, National Research Council of
$       Canada, Ottowa.
$
basic
  photon MEV
source
  npart=1E+8                                       $
  define position = 1 point 0 0 5.08               $ Point source
  define energy   = 1 photon line 0.6617 1.0       $ Cs-137
  define time     = 1 steady                       $
  define angle    = 1 isotropic                    $
  increment 3.7E+7 position=1 energy=1 time=1 angle=1 $ (3.7E+7 dps/mCi)(1 photon/dis)
mix nlib=ENDFB8R0, ptlib=PT.ENDFB8R0.ACE sablib=T.ENDFB8R0
   mat=1 a-f 1.7 (h.h2o) 16 o16 57 si 19 al 8                             $ Ground
   mat=2 a-f 2.17 (h.h2o) 30.4245   c  0.2870 o16 49.8628 na 0.9179 mg 0.0717 $ Ordinary concrete
                       al  1.0261  si 15.0505   k  0.7114 ca 1.4882 fe 0.1599 $  - pad
   mat=3 a-f 0.001142      c 0.0150 n 78.4429 o16 21.0750 ar 0.4671           $ Dry air
$  mat=3 a-f 0.001142      c 0.014  n 73.621  o16 21.999  ar 0.438  h 3.928   $ Humid air, 4% H2O
assign-m
   301 3 302 3 303 3 304 3 305 3 306 3 307 3 308 3 309 3
assign-mc
   1 brown 2 gray 3 white 301 orange 302 red 303 pink 304 purple 305 blue 306 sky 307 green
                          308 lime 309 black
geometry
  sector   1 ground   -1 -2
  sector   2 concrete -1  2 -3
  sector 301 det02m -301
  sector 302 det04m -302
  sector 303 det05m -303
  sector 304 det07m -304
  sector 305 det08m -305
  sector 306 det10m -306
  sector 307 det12m -307
  sector 308 det14m -308
  sector 309 det18m -309
  fill     3 $ air
  boundary vacuum      1
picture cs sector color
  -450 0  150 -450  0 -100 450  0 -100 title="x/z detail"
picture cs material color
  -450 0  150 -450  0 -100 450  0 -100 title="x/z detail"
surfaces
  1 c z 100000.0 -99.06 100091.44 $ BCD
  2 p z  -22.86                   $ Ground/concrete
  3 p z    0.0                    $ Concrete/air

301 torus  200 5.08 tr 0 0 91.44 0 0 999 0 999 91.44 $ Detector at  2 m =   200 cm
302 torus  400 5.08 tr 0 0 91.44 0 0 999 0 999 91.44 $ Detector at  4 m =   400 cm
303 torus  500 5.08 tr 0 0 91.44 0 0 999 0 999 91.44 $ Detector at  5 m =   500 cm
304 torus  700 5.08 tr 0 0 91.44 0 0 999 0 999 91.44 $ Detector at  7 m =   700 cm
305 torus  800 5.08 tr 0 0 91.44 0 0 999 0 999 91.44 $ Detector at  8 m =   800 cm
306 torus 1000 5.08 tr 0 0 91.44 0 0 999 0 999 91.44 $ Detector at 10 m = 1,000 cm
307 torus 1200 5.08 tr 0 0 91.44 0 0 999 0 999 91.44 $ Detector at 12 m = 1,200 cm
308 torus 1400 5.08 tr 0 0 91.44 0 0 999 0 999 91.44 $ Detector at 14 m = 1,400 cm
309 torus 1800 5.08 tr 0 0 91.44 0 0 999 0 999 91.44 $ Detector at 18 m = 1,800 cm


detector
  number=#0000001 title="Photon exposure at 2m, R/s.mCi"
    reaction 301 1.01880E+5   $ Reaction detector in air, V=(2*PI*200)(PI*(5.08**2))
```

```
    drf-e photon              $ Exposure in R/cm2.s per Rogers
       0.01 8.54-10 0.015 3.59-10 0.02 1.94-10 0.03 8.29-11 0.04 4.93-11 0.05 3.71-11
       0.06 3.32-11 0.08  3.52-11.0.10 4.26-11 0.15 6.88-11 0.2  9.82-11 0.3  1.58-10
       0.4  2.17-10 0.5   2.73-10 0.6  3.25-10 0.8  4.24-10 1.0  5.12-10 1.25 6.11-10
       1.5  7.02-10 2.0   8.61-10 3.0  1.18-9  4.0  1.37-9  5.0  1.60-9  6.0  1.82-9
       8.0  2.24-9 10.0   2.66-9 20.0  4.80-9
  number=#0000002 title="Photon exposure at 4m, R/s.mCi"
    reaction 302 2.03759E+5   $ Reaction detector in air, V=(2*PI*400)(PI*(5.08**2))
    drf-e photon              $ Exposure in R/cm2.s per Rogers
       0.01 8.54-10 0.015 3.59-10 0.02 1.94-10 0.03 8.29-11 0.04 4.93-11 0.05 3.71-11
       0.06 3.32-11 0.08  3.52-11.0.10 4.26-11 0.15 6.88-11 0.2  9.82-11 0.3  1.58-10
       0.4  2.17-10 0.5   2.73-10 0.6  3.25-10 0.8  4.24-10 1.0  5.12-10 1.25 6.11-10
       1.5  7.02-10 2.0   8.61-10 3.0  1.18-9  4.0  1.37-9  5.0  1.60-9  6.0  1.82-9
       8.0  2.24-9 10.0   2.66-9 20.0  4.80-9
  number=#0000003 title="Photon exposure at 5m, R/s.mCi"
    reaction 303 2.54699E+5   $ Reaction detector in air, V=(2*PI*500)(PI*(5.08**2))
    drf-e photon              $ Exposure in R/cm2.s per Rogers
       0.01 8.54-10 0.015 3.59-10 0.02 1.94-10 0.03 8.29-11 0.04 4.93-11 0.05 3.71-11 0.06 3.32-
11 0. 0.01 8.54-10 0.015 3.59-10 0.02 1.94-10 0.03 8.29-11 0.04 4.93-11 0.05 3.71-11
       0.06 3.32-11 0.08  3.52-11.0.10 4.26-11 0.15 6.88-11 0.2  9.82-11 0.3  1.58-10
       0.4  2.17-10 0.5   2.73-10 0.6  3.25-10 0.8  4.24-10 1.0  5.12-10 1.25 6.11-10
       1.5  7.02-10 2.0   8.61-10 3.0  1.18-9  4.0  1.37-9  5.0  1.60-9  6.0  1.82-9
       8.0  2.24-9 10.0   2.66-9 20.0  4.80-9
  number=#0000004 title="Photon exposure at 7m, R/s.mCi"
    reaction 304 3.56579E+5   $ Reaction detector in air, V=(2*PI*700)(PI*(5.08**2))
    drf-e photon              $ Exposure in R/cm2.s per Rogers
       0.01 8.54-10 0.015 3.59-10 0.02 1.94-10 0.03 8.29-11 0.04 4.93-11 0.05 3.71-11
       0.06 3.32-11 0.08  3.52-11.0.10 4.26-11 0.15 6.88-11 0.2  9.82-11 0.3  1.58-10
       0.4  2.17-10 0.5   2.73-10 0.6  3.25-10 0.8  4.24-10 1.0  5.12-10 1.25 6.11-10
       1.5  7.02-10 2.0   8.61-10 3.0  1.18-9  4.0  1.37-9  5.0  1.60-9  6.0  1.82-9
       8.0  2.24-9 10.0   2.66-9 20.0  4.80-9
  number=#0000005 title="Photon exposure at 8m, R/s.mCi"
    reaction 305 4.07518E+5   $ Reaction detector in air, V=(2*PI*800)(PI*(5.08**2))
    drf-e photon              $ Exposure in R/cm2.s per Rogers
       0.01 8.54-10 0.015 3.59-10 0.02 1.94-10 0.03 8.29-11 0.04 4.93-11 0.05 3.71-11
       0.06 3.32-11 0.08  3.52-11.0.10 4.26-11 0.15 6.88-11 0.2  9.82-11 0.3  1.58-10
       0.4  2.17-10 0.5   2.73-10 0.6  3.25-10 0.8  4.24-10 1.0  5.12-10 1.25 6.11-10
       1.5  7.02-10 2.0   8.61-10 3.0  1.18-9  4.0  1.37-9  5.0  1.60-9  6.0  1.82-9
       8.0  2.24-9 10.0   2.66-9 20.0  4.80-9
  number=#0000006 title="Photon exposure at 10m, R/s.mCi"
    reaction 306 5.09398E+5   $ Reaction detector in air, V=(2*PI*1000)(PI*(5.08**2))
    drf-e photon              $ Exposure in R/cm2.s per Rogers
       0.01 8.54-10 0.015 3.59-10 0.02 1.94-10 0.03 8.29-11 0.04 4.93-11 0.05 3.71-11
       0.06 3.32-11 0.08  3.52-11.0.10 4.26-11 0.15 6.88-11 0.2  9.82-11 0.3  1.58-10
       0.4  2.17-10 0.5   2.73-10 0.6  3.25-10 0.8  4.24-10 1.0  5.12-10 1.25 6.11-10
       1.5  7.02-10 2.0   8.61-10 3.0  1.18-9  4.0  1.37-9  5.0  1.60-9  6.0  1.82-9
       8.0  2.24-9 10.0   2.66-9 20.0  4.80-9
  number=#0000007 title="Photon exposure at 12m, R/s.mCi"
    reaction 307 6.11278E+5   $ Reaction detector in air, V=(2*PI*1200)(PI*(5.08**2))
    drf-e photon              $ Exposure in R/cm2.s per Rogers
       0.01 8.54-10 0.015 3.59-10 0.02 1.94-10 0.03 8.29-11 0.04 4.93-11 0.05 3.71-11
       0.06 3.32-11 0.08  3.52-11.0.10 4.26-11 0.15 6.88-11 0.2  9.82-11 0.3  1.58-10
       0.4  2.17-10 0.5   2.73-10 0.6  3.25-10 0.8  4.24-10 1.0  5.12-10 1.25 6.11-10
       1.5  7.02-10 2.0   8.61-10 3.0  1.18-9  4.0  1.37-9  5.0  1.60-9  6.0  1.82-9
       8.0  2.24-9 10.0   2.66-9 20.0  4.80-9
  number=#0000008 title="Photon exposure at 14m, R/s.mCi"
    reaction 308 7.13157E+5   $ Reaction detector in air, V=(2*PI*1400)(PI*(5.08**2))
    drf-e photon              $ Exposure in R/cm2.s per Rogers
       0.01 8.54-10 0.015 3.59-10 0.02 1.94-10 0.03 8.29-11 0.04 4.93-11 0.05 3.71-11
       0.06 3.32-11 0.08  3.52-11.0.10 4.26-11 0.15 6.88-11 0.2  9.82-11 0.3  1.58-10
       0.4  2.17-10 0.5   2.73-10 0.6  3.25-10 0.8  4.24-10 1.0  5.12-10 1.25 6.11-10
       1.5  7.02-10 2.0   8.61-10 3.0  1.18-9  4.0  1.37-9  5.0  1.60-9  6.0  1.82-9
       8.0  2.24-9 10.0   2.66-9 20.0  4.80-9
  number=#0000009 title="Photon exposure at 18m, R/s.mCi"
    reaction 309 9.16916E+5   $ Reaction detector in air, V=(2*PI*1800)(PI*(5.08**2))
    drf-e photon              $ Exposure in R/cm2.s per Rogers
       0.01 8.54-10 0.015 3.59-10 0.02 1.94-10 0.03 8.29-11 0.04 4.93-11 0.05 3.71-11
       0.06 3.32-11 0.08  3.52-11.0.10 4.26-11 0.15 6.88-11 0.2  9.82-11 0.3  1.58-10
       0.4  2.17-10 0.5   2.73-10 0.6  3.25-10 0.8  4.24-10 1.0  5.12-10 1.25 6.11-10
       1.5  7.02-10 2.0   8.61-10 3.0  1.18-9  4.0  1.37-9  5.0  1.60-9  6.0  1.82-9
       8.0  2.24-9 10.0   2.66-9 20.0  4.80-9
end
```

Appendix B:


Exposure Rate vs Radial Distance
Calculation
Experiment
409.895*(x**(-2))
362.527*(x**(-2))
100
10
1
1
10
Exposure Rate, uR/hr.mCi
Radial Distance, m