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Baikal-1 Skyshine Experiment

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Baikal-1 Skyshine Experiment

Auspices

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Baikal-1 Skyshine Experiment

Introduction

This benchmark is published in the ICSBEP Handbook as ALARM-REAC-AIR-SKY-001. Neutron and photon radiation scattering experiments were conducted between 1996-1998 at the RA reactor at the "Baikal-1" research reactor complex near Semipalatinsk by the Khurchatov Institute of Atomic Energy in the Kazakhstan National Nuclear Center.

Dimensions

Dimensions are taken from figures published in ALARM-REAC-AIR-SKY-001 with additional annotations by the authors. Note that Figure 1 shows the lower Be reflector (red) under the fuel (green) rather than the Be plugs. This is corrected in the COG model.

Figure. 1. Axial view of the reactor core and its immediate environs

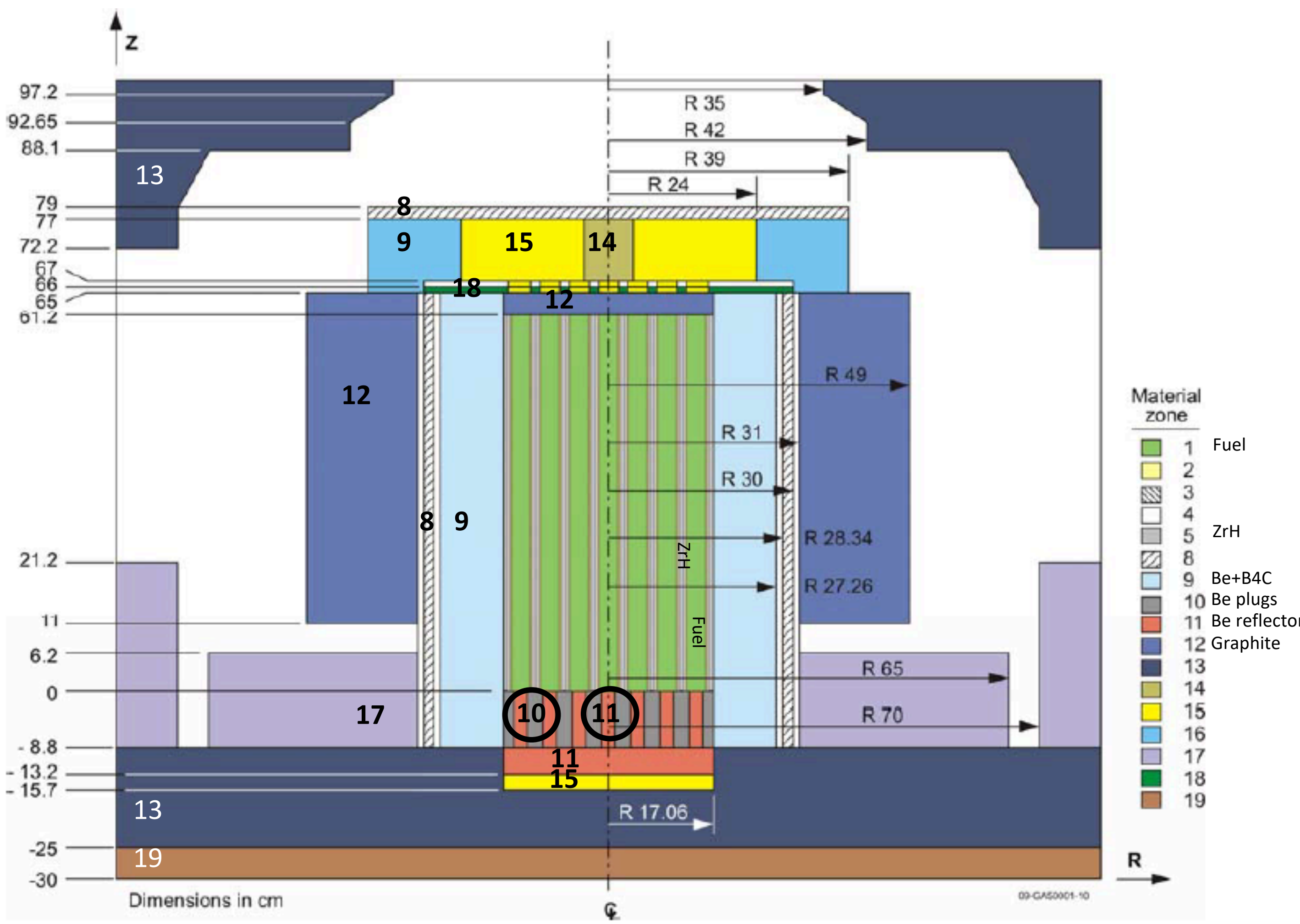

Figure 3.6. Model of the RA Reactor Core and its Environment.
(Numbered material zones are described in Table 3.8)

Figure 4. Plane view of RA reactor and fuel cylinder (4.75 cm pitch)

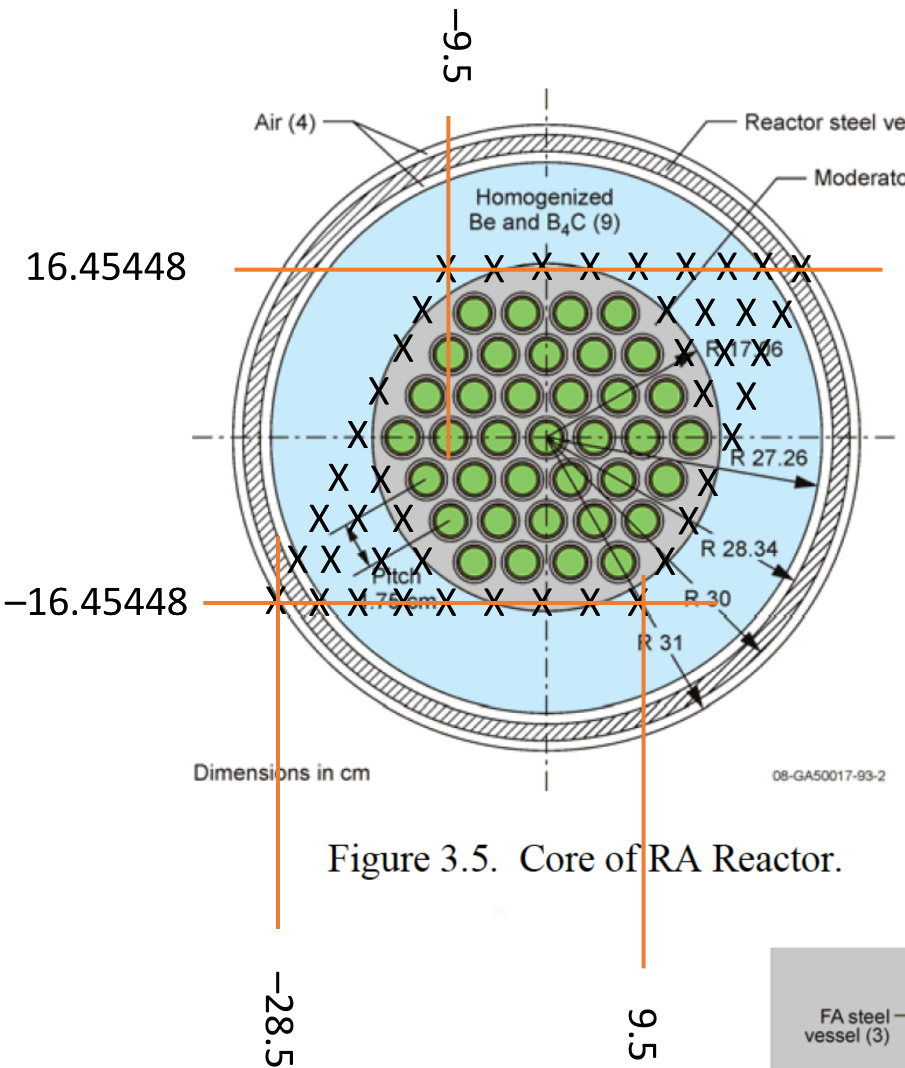

Figure 3.5. Core of RA Reactor.

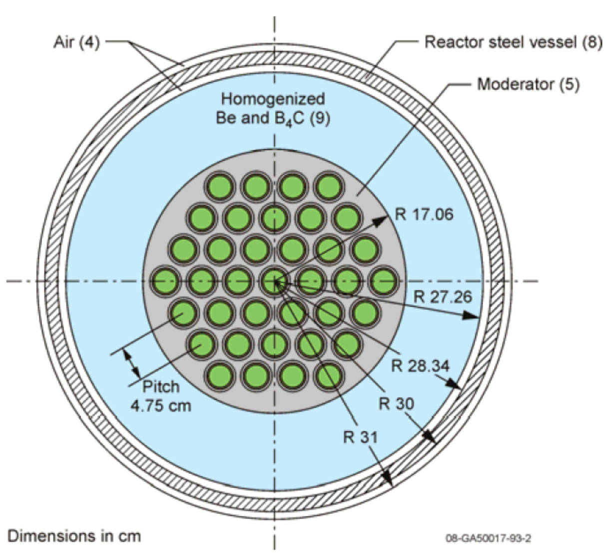

Figure 3.5. Core of RA Reactor.

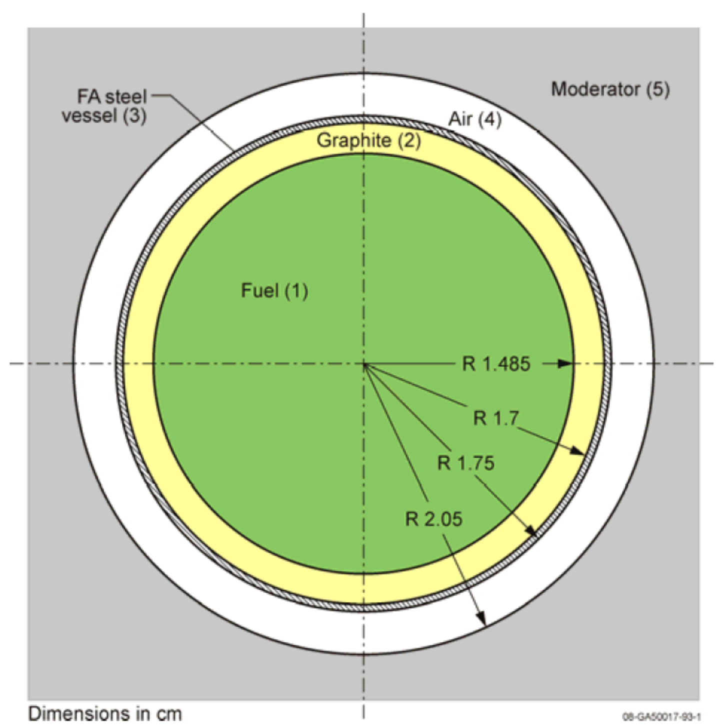

Figure 3.4. RA Reactor Fuel Cylinder.

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Figure 2. Axial view of the RA reactor environment

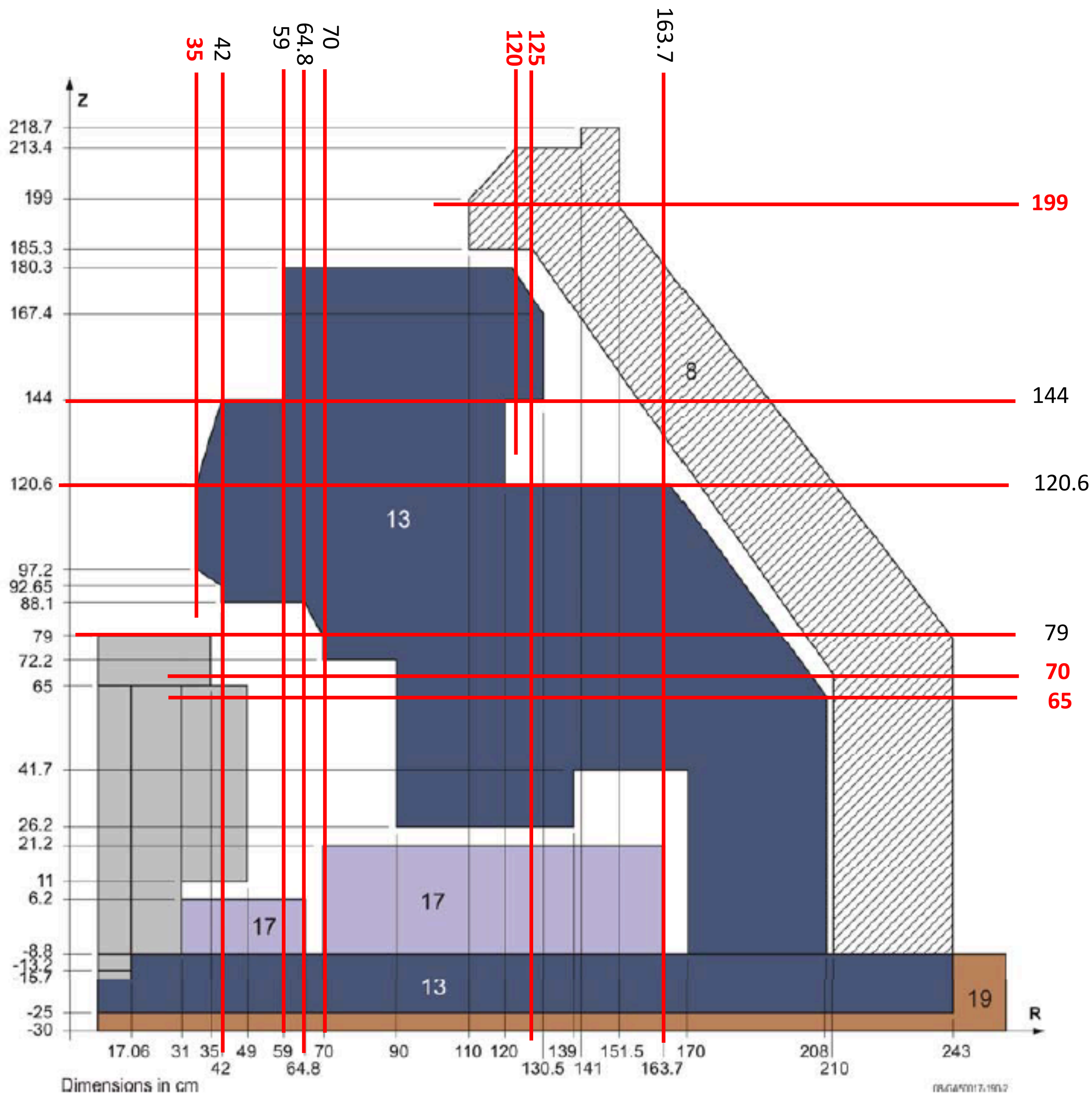

Figure 3.7. Model of the RA Reactor Environment.
(Numbered material zones are given in Table 3.8)

Note that missing radii and elevations as estimated by the authors are shown in **RED**.

Figure 3. Axial view of the detector placements

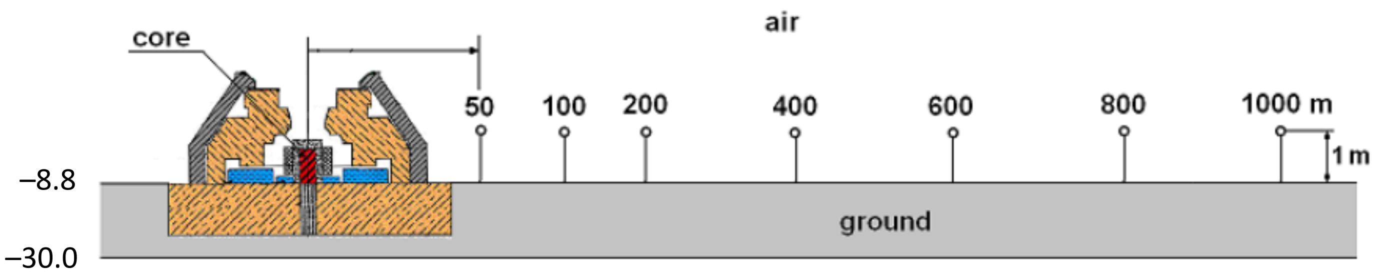

Figure 1.1. Schematic Configuration of the Experiment Showing On-site Measurement Positions. (not to scale)

Boundary Conditions

The height of the air is 1200 m = 120,000 cm. The radial boundary condition is at R = 1200 m = 120,000 cm.

Detectors

Rather than a 1-m high cylindrical surface crossing detector, the COG model uses a toroidal reaction detector centered at 1-m elevation at the radial distances shown in Figure 1.1 above.

Normalization

COG is run in CRITICALITY mode and COG detector results in Rem/sec correspond to the default source strength of 1 fission/sec with the following calculated energy deposition rates in the core:

Table 1. Energy deposition rate per 1 fission/sec

Region	Material	Energy Deposition Rate
1	Fuel	189.415 MeV/s
2	Graphite	0.565 MeV/s
3	FA steel	0.454 MeV/s
5	ZrH	7.658 MeV/s
9	Be+B4C	0.729 MeV/s
10	Be plugs	0.100 MeV/s
11	Be reflector	0.119 MeV/s
Sum	Reactor	199.0 MeV/s

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The benchmark-model results are normalized to 300 kW ± 12% reactor power. 1 Watt-sec = 6.2415E+12 MeV, so 300 kW = (1.87245E+18 MeV/sec)([1 fission/sec]/[199.0 MeV/sec]) = 9.409E+15 fissions/sec from the COG energy deposition calculation. Since COG calculates 2.599 neutrons per fission in this case, the neutron emission rate is 2.445E+16 n/sec, which is 7% higher than the 2.288E+16 value given in the sample MCNP input file of ALARM-REAC-AIR-SKY-001.

Since the details of the reactor thermal power determination are not provided, the value from the evaluation sample input is used, which corresponds to (2.288E+16 n/sec)/(2.599 n/fission) = 8.803E+15 fissions/sec. Since (1 REM/sec)(1 Sv/100 Rem)(1E+6 μSv/Sv)(60 sec/min)(60 min/hr) = 3.6E+7 μSv/hr, the normalization factor for COG results in (REM/sec)/(fission/sec) is: (8.803E+15)(3.6E+7) = 3.169E+23 μSv/hr per 300 kW.

Materials

Materials taken from the ICSBEP evaluation are reproduced here as Table 3. The discrepancies observed in the numbering convention used in the sample MCNP deck versus the evaluation (Table 3) are summarized below to aid readers in understanding the MCNP sample input.

Table 2. Discrepancies in material assignment numbers

Material	Table 2	MCNP Input	Comment
4	Air	Graphite	MCNP same as Table 2, #12
6	Not used	Be + B4C	MCNP same as Table 2, #8
7	Not used	Lower Be reflector	MCNP same as Table 2, #11
8	Steel reactor vessel	Fe-55 at 4.325E-2 a/b.cm	MCNP doesn't match anything
9	Be + B4C	Air + steel mixture 2	MCNP same as Table 2, #15
10	Be plugs	Air + steel mixture 4	MCNP same as Table 2, #18
11	Lower Be reflector	Steel reactor vessel	MCNP same as Table 2, #8
12	Lateral graphite reflector	Air (errors)	MCNP same as Table 2, #4
14	Air + Steel mixture 1	Water in tanks	MCNP same as Table 2, #17
15	Air + Steel mixture 2	Ground	MCNP same as Table 2, #19
17	Water in tanks	Be plugs	MCNP same as Table 2, #10
18	Air + steel mixture 4	Air +steel mixture 1	MCNP same as Table 2, #14
19	Ground	Air + steel mixture 3	MCNP same as Table 2, #16
20	Not used	Unknown	MCNP doesn't match anything

The noted errors in material specifications 8 and 20 and possible errors in material assignments may be the cause of differences in the calculated k-eff values.

Materials

Table 3. Materials by Zone

Number of the Material Zone	Title	Approximate Density, g/cm^3	Element or Nuclide	Atom Density, 10^{24}/cm^3
Core				
1	Fuel (FAs)	3.85	^{235}U	1.3236E-03
			^{238}U	1.4707E-04
			Nb	3.6607E-03
			Hf	1.8751E-06
			W	6.0833E-06
			Ta	9.382E-07
			Zr	1.4821E-02
			C	2.3198E-02
2	Graphite FA holder, graphite type 30 PG	1.72	C	8.6315E-02
3	FA vessel, steel 12X18H10T	7.84	C	4.70E-04
			Cr	1.65E-02
			Ni	8.10E-03
			Ti	9.83E-04
			Fe	5.98E-02
4 [(a)]	Air (ρ_0) on date 13.11.96	1.364E-3	N	4.4253E-05
			O	1.1931E-05
			H	8.3828E-08
			Ar	2.6467E-07
			C	9.4079E-09
	Air (ρ_0) on date 30.09.97	1.212E-3	N	3.9176E-05
			O	1.0640E-05
			H	2.2885E-07
			Ar	2.3430E-07
			C	8.3284E-09
	Air (ρ_0) on date 07.10.97	1.135E-3	N	3.6527E-05
			O	1.0155E-05
			H	6.8140E-07
			Ar	2.1846E-07
			C	7.7654E-09
5	Moderator (homogeneous zirconium hydride)	5.630	Nb	3.640E-04
			H	6.4312E-02
			Zr	3.6056E-02

Table 3. Materials by Zone (continued)

Number of the Material Zone	Title	Approximate Density, g/cm^3	Element or Nuclide	Atom Density, 10^{24}/cm^3
Reflectors				
8	Reactor vessel, steel X16H6	7.85	Cr	1.4545E-02
			Ni	4.89E-03
			Fe	6.602E-02
9	Homogeneous lateral beryllium reflector with boron carbide	1.83	Be	0.1221
			C	1.269E-05
			^{10}B	1.0755E-05
			^{11}B	4.4089E-05
10	Beryllium plugs in cells	1.84	Be	0.123
11	Lower beryllium reflector, volume fraction 0.73	1.35	Be	9.016E-02
12	Lateral graphite reflector, graphite plugs in cell, upper graphite reflector, graphite type 30 PG	2.25	C	1.128E-01
Surroundings				
4 [(a)]	Air (see "Core", above, for ρ_0 values)			
13	Concrete foundation, heavy concrete	3.5	H	5.3219E-03
			O	4.3892E-02
			Al	7.88E-04
			Si	8.363E-03
			Ca	2.3943E-03
			Fe	1.8771E-02
14	Air-steel mixture 1, steel 12X18H10T, steel volume fraction 0.85	6.67	C	3.995E-04
			Cr	1.4025E-02
			Ni	6.885E-03
			Ti	8.3555E-04
			Fe	5.083E-02
15	Air-steel mixture 2, steel 12X18H10T, steel volume fraction 0.55	4.316	C	2.585E-04
			Cr	9.075E-03
			Ni	4.455E-03
			Ti	5.406E-04
			Fe	3.289E-02
16	Air-steel mixture 3 (upper reactor cover), steel 12X18H10T, steel volume fraction 0.20	1.569	C	9.40E-05
			Cr	3.30E-03
			Ni	1.62E-03
			Ti	1.966E-04
			Fe	1.196E-02
17	Water in tanks	1.00	H	6.69E-02
			O	3.35E-02

Table 3. Materials by Zone (continued)

Number of the Material Zone	Title	Approximate Density, g/cm^3	Element or Nuclide	Atom Density, 10^{24}/cm^3
18	Air-steel mixture 4 (upper reactor cover), steel 12X18H10T, steel volume fraction 0.02	0.1569	C	9.40E-06
			Cr	3.30E-04
			Ni	1.62E-04
			Ti	1.966E-05
			Fe	1.196E-03
19	Ground	1.76	H	9.60E-03
			O	3.69E-02
			Si	1.17E-02
			Al	4.93E-03

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Benchmark-Model and Sample Results

Table 4. Neutron Dose Rates

Distance meter	ρR g/cm²	COG (REM/s)/(fission/s)	COG** μSv/hr	Experiment* μSv/hr	C/E
13 November 1996 with ρ(air) = 1.364E-3 g/cc. File: Baikal-1					
50	6.82	1.043E-18 ± 0.1%	3.31E+5	3.22E+5	1.03 ± 19%
100	13.64	3.167E-19 ± 0.2%	1.00E+5	9.90E+4	1.01 ± 19%
200	27.28	6.423E-20 ± 0.3%	2.04E+4	1.80E+4	1.13 ± 19%
300	40.92	1.792E-20 ± 0.5%	5.68E+3	4.53E+3	1.25 ± 19%
400	54.56	6.114E-21 ± 0.7%	1.94E+3	1.64E+3	1.18 ± 19%
500	68.20	2.271E-21 ± 1.0%	7.20E+2	5.13E+2	1.40 ± 19%
600	81.84	8.637E-22 ± 1.6%	2.74E+2	1.73E+2	1.58 ± 19%
800	109.12	1.382E-22 ± 3.7%	4.38E+1	2.60E+1	1.68 ± 19%
1000	136.40	2.198E-23 ± 8.0%	6.97E+0	4.64E+0	1.50 ± 21%
30 September 1997 with ρ(air) = 1.210E-3 g/cc. File: Baikal-1b					
200	24.20	6.839E-20 ± 0.2%	2.17E+4	1.84E+4	1.18 ± 19%
300	36.30	2.076E-20 ± 0.3%	6.58E+3	6.38E+3	1.03 ± 19%
400	48.40	7.769E-21 ± 0.5%	2.46E+3	1.95E+3	1.26 ± 19%
500	60.50	3.101E-21 ± 0.7%	9.83E+2	7.60E+2	1.29 ± 19%
600	72.60	1.238E-21 ± 1.0%	3.92E+2	2.82E+2	1.39 ± 19%
800	96.80	2.245E-22 ± 2.1%	7.11E+1	4.61E+1	1.54 ± 19%
1000	121.10	4.136E-23 ± 4.2%	1.31E+1	8.90E+0	1.47 ± 20%
07 October 1997 with ρ(air) = 1.135E-3 g/cc. File: Baikal-1c					
100	11.35	2.997E-19 ± 0.1%	9.50E+4	1.11E+5	0.86 ± 19%
200	22.70	6.698E-20 ± 0.2%	2.12E+4	2.41E+4	0.88 ± 19%
300	34.05	2.069E-20 ± 0.3%	6.56E+3	6.78E+3	0.97 ± 19%
400	45.40	7.815E-21 ± 0.5%	2.48E+3	2.35E+3	1.05 ± 19%
500	56.75	3.130E-21 ± 0.7%	9.92E+2	8.52E+2	1.16 ± 19%
600	68.10	1.297E-21 ± 1.0%	4.11E+2	3.44E+2	1.19 ± 19%
800	90.80	2.451E-22 ± 2.1%	7.77E+1	6.17E+1	1.26 ± 19%
1000	113.50	5.110E-23 ± 4.2%	1.62E+1	1.22E+1	1.32 ± 19%
1250	141.88	7.092E-24 ± 8.9%	2.25E+0	2.01E+0	1.12 ± 21%
1500	170.25	1.423E-24 ± 17.6%	4.51E-1	3.80E-1	1.19 ± 26%

*Benchmark-model results are ±19%. **3.169E+23 μSv/hr at 300 kW per (REM/s)/(fission/s).

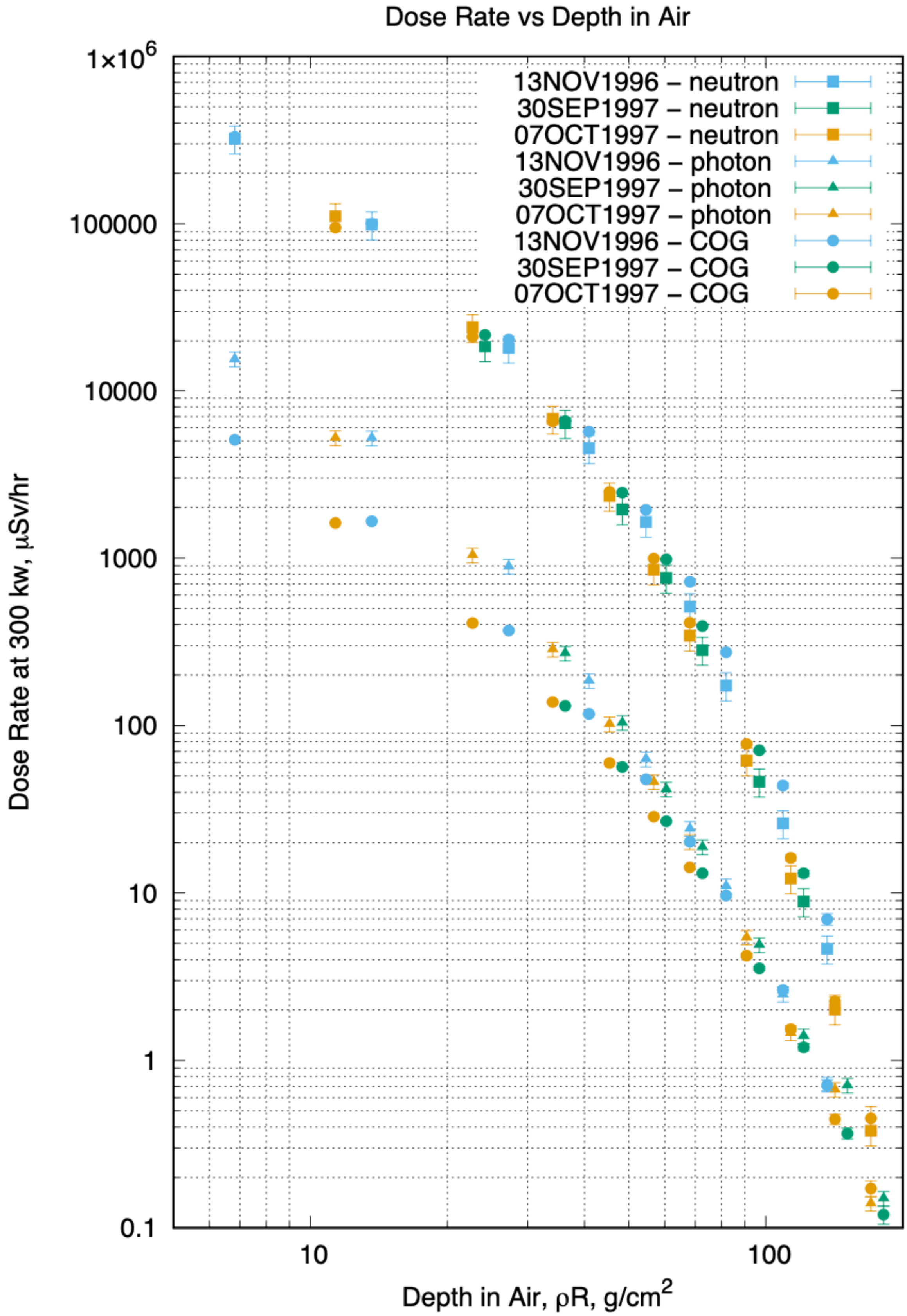
Benchmark-Model and Sample Results (continued)

Table 5. Photon Dose Rates

Distance meter	ρR g/cm^2	COG REM/(fission/sec)	COG μSv/hr	Experiment* μSv/hr	C/E
13 November 1996 with ρ(air) = 1.364E-3 g/cc. File: Baikal-1					
50	6.82	1.602E-20 ± 0.4%	5.08E+3	1.54E+4	0.33 ± 10%
100	13.64	5.240E-21 ± 0.4%	1.66E+3	5.20E+3	0.32 ± 10%
200	27.28	1.164E-21 ± 0.7%	3.69E+2	8.91E+2	0.41 ± 10%
300	40.92	3.685E-22 ± 1.0%	1.17E+2	1.85E+2	0.63 ± 10%
400	54.56	1.506E-22 ± 1.4%	4.77E+1	6.30E+1	0.76 ± 10%
500	68.20	6.385E-23 ± 1.9%	2.02E+1	2.42E+1	0.84 ± 10%
600	81.84	3.041E-23 ± 2.6%	9.64E+0	1.10E+1	0.88 ± 10%
800	109.12	8.339E-24 ± 4.4%	2.64E+0	2.48E+0	1.07 ± 11%
1000	136.40	2.248E-24 ± 7.6%	7.12E-1	7.20E-1	0.99 ± 13%
30 September 1997 with ρ(air) = 1.210E-3 g/cc. File: Baikal-1b					
300	36.30	4.149E-22 ± 0.7%	1.31E+2	2.70E+2	0.49 ± 10%
400	48.40	1.782E-22 ± 1.1%	5.65E+1	1.04E+2	0.54 ± 10%
500	60.50	8.456E-23 ± 1.3%	2.68E+1	4.16E+1	0.64 ± 10%
600	72.60	4.131E-23 ± 1.8%	1.31E+1	1.88E+1	0.70 ± 10%
800	96.80	1.121E-23 ± 2.9%	3.55E+0	4.90E+0	0.72 ± 10%
1000	121.10	3.771E-24 ± 4.6%	1.20E+0	1.40E+0	0.85 ± 11%
1250	151.25	1.154E-24 ± 7.4%	3.66E-1	7.10E-1	0.52 ± 12%
1500	181.50	3.802E-25 ± 12.5%	1.20E-1	1.50E-1	0.80 ± 16%
07 October 1997 with ρ(air) = 1.135E-3 g/cc. File: Baikal-1c					
100	11.35	5.116E-21 ± 0.4%	1.62E+3	5.22E+3	0.31 ± 10%
200	22.70	1.292E-21 ± 0.5%	4.09E+2	1.04E+3	0.39 ± 10%
300	34.05	4.361E-22 ± 0.7%	1.38E+2	2.85E+2	0.48 ± 10%
400	45.40	1.883E-22 ± 1.0%	5.97E+1	1.02E+2	0.58 ± 10%
500	56.75	9.034E-23 ± 1.3%	2.86E+1	4.60E+1	0.62 ± 10%
600	68.10	4.495E-23 ± 1.7%	1.42E+1	2.02E+1	0.71 ± 10%
800	90.80	1.336E-23 ± 2.8%	4.23E+0	5.43E+0	0.78 ± 10%
1000	113.50	4.863E-24 ± 4.2%	1.54E+0	1.46E+0	1.06 ± 11%
1250	141.88	1.409E-24 ± 6.9%	4.46E-1	6.70E-1	0.67 ± 12%
1500	170.25	5.416E-25 ± 10.8%	1.72E-1	1.40E-1	1.23 ± 15%

*Benchmark-model results are ±10%. **3.169E+23 μSv/hr at 300 kW per (REM/s)/(fission/s).

Figure 1


Dose Rate vs Depth in Air
13NOV1996 – neutron
30SEP1997 – neutron
07OCT1997 – neutron
13NOV1996 – photon
30SEP1997 – photon
07OCT1997 – photon
13NOV1996 – COG
30SEP1997 – COG
07OCT1997 – COG
Dose Rate at 300 kw, µSv/hr
1×10^6
100000
10000
1000
100
10
1
0.1
10
100
Depth in Air, ρR, g/cm^2

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Conclusions

Neutron doses are shown to be in good agreement with benchmark values. A trend in increasing neutron dose with increasing depth in air is noted but results are within statistics throughout the entire range.

The significant underprediction by a factor of three in photon doses in the near field is an indicator of significant errors in the reactor material and/or geometry model as noted by the evaluators. Discrepancies in calculated k-eff also indicate significant errors. In the far field, photon doses are predominantly due to neutron capture reactions and calculated photon doses are in fair agreement with benchmark values at depths greater than 60 g/cm^2.

COG results are consistent with those provided by the ICSBEP evaluators. This benchmark provides an excellent example of how to calculate prompt and delayed neutron and photon doses in one CRITICALITY run using DETECTORS. A sample input deck is attached in Attachment 1.

Attachment 1

```
ALARM-REAC-AIR-SKY-001: Baikal-1 Skyshine Experiment
basic
  neutron delayedn photons delayedphotons 0 1E+10 CENTIMETERS URRPT
criticality
  npart=5000 nbatch=5000000 sdt=0.00001 nfirst=21 norm=1.0 nsource=1 0 0 30.6
  dump 1000000 2000000 3000000 4000000 5000000
mix nlib=ENDFB8R0 ptlib=PT.ENDFB8R0.ACE sablib=T.ENDFB8R0 dglib=DFG.ENDFB7R1
  mat=1  bunches    u2ALARM-REAC-AIR-SKY-001: Baikal-1 Skyshine Experiment
basic
  neutron delayedn photons delayedphotons 0 1E+10 CENTIMETERS URRPT
criticality
  npart=5000 nbatch=5000000 sdt=0.00001 nfirst=21 norm=1.0 nsource=1 0 0 30.6
  dump 1000000 2000000 3000000 4000000 5000000
$ npart=5000 nbatch=1020 sdt=0.00001 nfirst=21 norm=1.0 nsource=1 0 0 30.6
mix nlib=ENDFB8R0 ptlib=PT.ENDFB8R0.ACE sablib=T.ENDFB8R0 dglib=DFG.ENDFB7R1
  mat=1  bunches    u235 1.3236-3 u238 1.4707-4   nb 3.6607-3   hf 1.8751-6   w 6.0833-6  $ Fuel
                      ta 9.3820-7   zr 1.4821-2  (c) 2.3198-2                               $
  mat=2  bunches  (c30p) 8.6315-2                                                            $ Graphite, 1.72 g/cc
  mat=3  bunches       c 4.70-4     cr 1.65-2     ni 8.10-3     ti 9.83-4    fe 5.98-2     $ FA vessel steel
  mat=4  bunches (h.h2o) 8.3828-8    n 4.4253-5  o16 1.1931-5   ar 2.6467-7   c 9.4079-9  $ Air on 13.11.96
  mat=5  bunches (h.zrh) 6.4312-2 (zr.zrh) 3.6056-2 nb 3.6404-4                            $ Moderator
  mat=8  bunches      cr 1.4545-2   ni 4.89-3     fe 6.602-2                                $ Rx vessel steel
  mat=9  bunches    (be) 0.1221      c 1.269-5   b10 1.0755-5  b11 4.4089-5                $ Be+B4C lateral reflector
  mat=10 bunches    (be) 0.123                                                               $ Be plugs
  mat=11 bunches    (be) 9.016-2                                                             $ Be lower reflector
  mat=12 bunches     (c) 1.128-1                                                             $ Graphite reflector & plugs
  mat=13 bunches (h.h2o) 5.3219-3 o16 4.3892-2 al 7.88-4  si 8.363-3  ca 2.3943-3 fe 1.8771-2  $ Concrete foundation
  mat=14 bunches       c 3.995-4   cr 1.4025-2 ni 6.885-3 ti 8.3555-4 fe 5.083-2               $ Air-steel mixture #1
  mat=15 bunches       c 2.585-4   cr 9.075-3  ni 4.455-3 ti 5.406-4  fe 3.289-2               $ Air-steel mixture #2
  mat=16 bunches       c 9.40-5    cr 3.30-3   ni 1.62-3  ti 1.966-4  fe 1.196-2               $ Air-steel mixture #3
  mat=17 bunches (h.h2o) 6.69-2   o16 3.35-2                                                   $ Water
  mat=18 bunches       c 9.40-6    cr 3.30-4   ni 1.62-4  ti 1.966-5  fe 1.196-3               $ Air-steel mixture #4
  mat=19 bunches (h.h2o) 9.60-3   o16 3.69-2   si 1.17-2  al 4.93-3                            $ Ground
assign-m
   101 4 102 4 103 4 104 4 105 4 106 4 107 4 108 4 109 4
assign-mc
  1 green 2 yellow 3 black 4 white 5 brown 8 black 9 sky 10 orange 11 gray 12 purple 13 lime 17 blue 18 green 19 brown
  101 green 102 lime 103 blue 104 sky 105 red 106 pink 107 orange 108 black 109 gray
geometry
    use unit 3 Lttc   -1
    sector   9 BeB4C   1 -21  $ Homogenized Be and B4C
    sector   8 RXSTL  22 -23  $ Reactor vessel steel
    sector  18 AirStl  1  21  23 -31  $ Air-steel mixture #4
    sector  14 AirStl 31 -32          $ Air-steel mixture #1
    sector  15 AirStl 31  32 -33      $ Air-steel mixture #2
    sector   9 BeB4C  31  32  33 -34  $ Homogenized Be & B4C
    sector   8 RXSTL  32  33  34 -35  $ Rx vessel steel cover
    sector  11 Be      1  21  23 -41  $ Lower Be reflector
    sector  15 AirStl 41 -42          $ Air-steel mixture #2
    sector  13 Cncrt   1  21  23  41  42 -43 $ Concrete foundation
    sector  13 Cncrt  43  61 -62             $ Concrete wall
    sector  13 Cncrt -61  63 -64             $ Concrete wall portion
    sector  12 C      51 -52                 $ Lateral graphite reflector
    sector   9 BeB4C  21  52  53 -54         $ Homogenized Be & B4C
    sector  17 Water  43  51 -55             $ Water
    sector  17 Water  43  56 -57             $ Water
    sector   8 RXSTL  43  65 -66             $ Rx vessel steel
    sector  19 Ground 43 -70 -71             $ Ground
    sector 101 det050m  -101          $ Detector
    sector 102 det100m  -102          $  ditto
    sector 103 det200m  -103          $  ditto
    sector 104 det300m  -104          $  ditto
    sector 105 det400m  -105          $  ditto
    sector 106 det500m  -106          $  ditto
    sector 107 det600m  -107          $  ditto
    sector 108 det800m  -108          $  ditto
    sector 109 det1km   -109          $  ditto
    fill     4                        $ Air
    boundary   vacuum 71              $ BCD
 define unit 1 $ ............... Environs w/o fuel
    sector  11 Be     -1 -2     $ Lower Be reflector
    sector   5 Mdrtr  -1  2 -3  $ Moderator
    sector  12 C      -1  3 -4  $ Graphite reflector
    sector  18 AirStl -1  4 -5  $ Air-steel mixture #4
    sector   4 Air    -1  5     $ Air
 define unit 2 $ ................... Environs w/ fuel
    sector  10 Be    -10              $ Be end plug
    sector   1 Fuel   10 -11          $ Fuel
    sector   2 C      10  11 -12      $ Graphite
    sector   3 FASTL  10  12 -13      $ FA steel vessel
    sector   4 Air    13 -14          $ Air
    use unit 1 Else   14  -1  -4      $ Everything else, lower
    sector  12 C     -15  -1   4      $ Graphite plug
    sector  18 AirStl 15  -1   4  -5  $ Upper reactor cover
 define unit 3 $ ..................... 9x9x1 triangular array
   {tri-x
    -9.5  16.45448
   -28.5 -16.45448
     9.5 -16.45448
     9 9
```

```
     1 -99.9 99.9
    1001 2001 3001 4001
    fill
           1 1 1 1 1 1 1 1 1
          1 2 2 2 2 1 1 1 1
         1 2 2 2 2 2 1 1 1
        1 2 2 2 2 2 2 1 1
       1 2 2 2 2 2 2 2 1
      1 1 2 2 2 2 2 2 1
     1 1 1 2 2 2 2 2 1
    1 1 1 1 2 2 2 2 1
   1 1 1 1 1 1 1 1 1 }
picture cs material color -250 250 100 -250 -250 100 110000 -250 100 title="plane view showing detectors"
picture cs material color    0   0 225    0    0 -30    250    0 -30 title="axial detail: reactor"
picture cs material color  -50   0  85  -50    0 -20     50    0 -20 title="axial detail: core"
picture cs material color   -4   0   2   -4    0  -2      4    0  -2 title="axial detail: lattice"
surfaces
$ --- Entire Problem
   1 c z 17.06   -8.8   67.0  $ Lattice boundary
   2 p z  0.0                 $ Lower Be reflector, top
   3 p z 61.2                 $ Fuel, top
   4 p z 65.0                 $ Graphite reflector, top
   5 p z 66.0                 $ Graphite plugs, middle
$ --- Fuel rod, Be & C plugs, and vessel
  10 c z  1.7    -8.8    0.0  $ Be end plug
  11 c z  1.485   0.0   61.2  $ Fuel
  12 c z  1.7     0.0   61.2  $ Graphite
  13 c z  1.75   -8.8   61.2  $ FA steel vessel
  14 c z  2.05   -8.8   61.2  $ Air
  15 c z  1.75   65.0   67.0  $ Graphite plug
$ --- Reactor vessel internals
  21 c z 27.26   -8.8   65.0  $ Homogenized Be & B4C
  22 c z 28.34   -8.8   65.0  $ RX steel vessel, inner
  23 c z 30.0    -8.8   65.0  $ RX steel vessel, outer
$ --- Structures above the reactor
  31 c z 30.0    65.0   66.0  $ Air-steel mixture #4
  32 c z  5.0    67.0   77.0  $ Air-steel mixture #1
  33 c z 24.0    67.0   77.0  $ Air-steel mixture #2
  34 c z 39.0    67.0   77.0  $ Homogenized Be & B4C
  35 c z 39.0    77.0   79.0  $ Rx vessel steel cover
$ --- Structures beneath the reactor
  41 c z 17.06  -13.2   -8.8  $ Lower Be reflector
  42 c z 17.06  -15.7  -13.2  $ Air-steel mixture #2
  43 c z 243    -25.0   -8.8  $ Concrete foundation
$ --- Lateral structures around the reactor
  51 c z  31
  52 c z  49     11     65    $ Lateral graphite reflector
  53 c z  30
  54 c z  39     65     67    $ Portion of homogenized Be & B4C
  55 c z  65     -8.8    6.2  $ Water
  56 c z  70                  $ Water
  57 c z 163.7   -8.8   21.2  $ Water
  61 rev 14 -8.8 170  41.7 170  41.7  90    72.2  90  72.2 70    79   70    88.1  64.8  88.1  42 $ Concrete
            92.65 42  97.2  35 120.6  35   144    42 144   64.8 180.3 64.8                        $  wall, inner
     tr 0 0 0 0 0 1 0 1 0
  62 rev  8 -8.8 208 65 208 120.6 163.7 120.6 120 144 120 144 130.6 167.4 130.6 180.3 120 $ Concrete
     tr 0 0 0 0 0 1 0 1 0                                                                 $  wall, outer
  63 c z 90
  64 c z 139 26.2 41.7 $ Portion of the concrete wall
  65 rev 8 -8.8 210 70 210 185.3 125.0 185.3 110 199 110 213.4 120 213.4 141 218.7 141 $ Reactor
     tr 0 0 0 0 0 1 0 1 0                                                             $  vessel, inner
  66 rev 4 -8.8 243 79 243 199 151.5 218.7 151.5 $ Reactor
     tr 0 0 0 0 0 1 0 1 0                        $  vessel, outer
$ --- Air/ground
  70 p z -8.8              $ Air/ground interface
  71 c z 120000 -30 120000 $ BCD
$ --- Detector reaction volumes
 101 torus   5000 50 tr 0 0 100 0 0 999 0 999 100 $ Detector at   50 m =   5,000 cm
 102 torus  10000 50 tr 0 0 100 0 0 999 0 999 100 $ Detector at  100 m =  10,000 cm
 103 torus  20000 50 tr 0 0 100 0 0 999 0 999 100 $ Detector at  200 m =  20,000 cm
 104 torus  30000 50 tr 0 0 100 0 0 999 0 999 100 $ Detector at  300 m =  30,000 cm
 105 torus  40000 50 tr 0 0 100 0 0 999 0 999 100 $ Detector at  400 m =  40,000 cm
 106 torus  50000 50 tr 0 0 100 0 0 999 0 999 100 $ Detector at  500 m =  50,000 cm
 107 torus  60000 50 tr 0 0 100 0 0 999 0 999 100 $ Detector at  600 m =  60,000 cm
 108 torus  80000 50 tr 0 0 100 0 0 999 0 999 100 $ Detector at  800 m =  80,000 cm
 109 torus 100000 50 tr 0 0 100 0 0 999 0 999 100 $ Detector at 1000 m = 100,000 cm
detector
  number=#0000001 title="Neutron dose rate at  50m, Rem/s"
    reaction 101 2.46740E+8  $ Reaction detector in air, V=(2*PI*5000)(PI*(50**2))
    drf-e neutron dose77     $ Dose in Rem/sec
  number=#0000002 title="Neutron dose rate at  100m, Rem/s"
    reaction 102 4.93480E+8  $ Reaction detector in air, V=(2*PI*10000)(PI*(50**2))
    drf-e neutron dose77     $ Dose in Rem/sec
  number=#0000003 title="Neutron dose rate at  200m, Rem/s"
    reaction 103 9.86960E+8  $ Reaction detector in air, V=(2*PI*20000)(PI*(50**2))
    drf-e neutron dose77     $ Dose in Rem/sec
  number=#0000004 title="Neutron dose rate at  300m, Rem/s"
    reaction 104 1.48044E+9  $ Reaction detector in air, V=(2*PI*30000)(PI*(50**2))
    drf-e neutron dose77     $ Dose in Rem/sec
  number=#0000005 title="Neutron dose rate at  400m, Rem/s"
```

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    reaction 105 1.97392E+9  $ Reaction detector in air, V=(2*PI*40000)(PI*(50**2))
    drf-e neutron dose77     $ Dose in Rem/sec
  number=#0000006 title="Neutron dose rate at  500m, Rem/s"
    reaction 106 2.46740E+9  $ Reaction detector in air, V=(2*PI*50000)(PI*(50**2))
    drf-e neutron dose77     $ Dose in Rem/sec
  number=#0000007 title="Neutron dose rate at  600m, Rem/s"
    reaction 107 2.96088+9   $ Reaction detector in air, V=(2*PI*60000)(PI*(50**2))
    drf-e neutron dose77     $ Dose in Rem/sec
  number=#0000008 title="Neutron dose rate at  800m, Rem/s"
    reaction 108 3.94784+9   $ Reaction detector in air, V=(2*PI*80000)(PI*(50**2))
    drf-e neutron dose77     $ Dose in Rem/sec
  number=#0000009 title="Neutron dose rate at 1000m, Rem/s"
    reaction 109 4.93480+9   $ Reaction detector in air, V=(2*PI*100000)(PI*(50**2))
    drf-e neutron dose77     $ Dose in Rem/sec
  number=#0000011 title="Photon dose rate at  50m, Rem/s"
    reaction 101 2.46740E+8  $ Reaction detector in air, V=(2*PI*5000)(PI*(50**2))
    drf-e photon dose77      $ Dose in Rem/sec
  number=#0000012 title="Photon dose rate at  100m, Rem/s"
    reaction 102 4.93480E+8  $ Reaction detector in air, V=(2*PI*10000)(PI*(50**2))
    drf-e photon dose77      $ Dose in Rem/sec
  number=#0000013 title="Photon dose rate at  200m, Rem/s"
    reaction 103 9.86960E+8  $ Reaction detector in air, V=(2*PI*20000)(PI*(50**2))
    drf-e photon dose77      $ Dose in Rem/sec
  number=#0000014 title="Photon dose rate at  300m, Rem/s"
    reaction 104 1.48044E+9  $ Reaction detector in air, V=(2*PI*30000)(PI*(50**2))
    drf-e photon dose77      $ Dose in Rem/sec
  number=#0000015 title="Photon dose rate at  400m, Rem/s"
    reaction 105 1.97392E+9  $ Reaction detector in air, V=(2*PI*40000)(PI*(50**2))
    drf-e photon dose77      $ Dose in Rem/sec
  number=#0000016 title="Photon dose rate at  500m, Rem/s"
    reaction 106 2.46740E+9  $ Reaction detector in air, V=(2*PI*50000)(PI*(50**2))
    drf-e photon dose77      $ Dose in Rem/sec
  number=#0000017 title="Photon dose rate at  600m, Rem/s"
    reaction 107 2.96088+9   $ Reaction detector in air, V=(2*PI*60000)(PI*(50**2))
    drf-e photon dose77      $ Dose in Rem/sec
  number=#0000018 title="Photon dose rate at  800m, Rem/s"
    reaction 108 3.94784+9   $ Reaction detector in air, V=(2*PI*80000)(PI*(50**2))
    drf-e photon dose77      $ Dose in Rem/sec
  number=#0000019 title="Photon dose rate at 1000m, Rem/s"
    reaction 109 4.93480+9   $ Reaction detector in air, V=(2*PI*100000)(PI*(50**2))
    drf-e photon dose77      $ Dose in Rem/sec
end
```