UPDATE OF THE NUCLEAR CRITICALITY SLIDE RULE CALCULATIONS
–
SENSITIVITY STUDIES FOR PLUTONIUM SYSTEMS

IDENTIFICATION NUMBER: SR-Pu-UNREFLECTED-GROUND-002, SR-Pu-MOISTURE-GROUND-001, SR-Pu-SKYSHINE-GROUND-001, SR-Pu-SCREEN-GROUND-001,

KEY WORDS: Slide-Rule, plutonium, radiological screen, sensitivity

1 INTRODUCTION

In 1997, Oak Ridge National Laboratory published the reports "An updated Nuclear Criticality Slide rule" (ORNL/TM-13322/V1 and ORNL/TM-13322/V2), as a tool for emergency response to nuclear criticality accident. The "Slide Rule" is designed to provide estimates of the following:

- Magnitude of the number of fissions based on personnel or field radiation measurements,
- Neutron- and gamma-dose at variable unshielded distances from the accident,
- Skyshine component of the dose,
- Time-integrated radiation dose estimates at variable times/distances from the accident,
- 1-minute gamma radiation dose integrals at variable times/distances from the accident,
- Dose-reduction factors for variable thicknesses of steel, concrete, and water.

The initial Slide Rule included five unreflected spherical uranium systems. This document updates and expands the Slide Rule to include five plutonium systems, calculated using modern tools such as MCNP, SCALE, and COG.

2 DESCRIPTION OF THE CONFIGURATIONS

2.1 GEOMETRY

The geometry for the configuration of the slide rule is presented hereafter.

The geometry consists of a simple air-over-ground configuration with a source located at the center of a right-circular cylinder. The radius and the height of the air cylinder is 1530 m. With modern 3-D tools, a square with a half-side of 1530 m might be considered. The ground is now modeled as 50 cm layer of concrete.

The Figure 1 and Figure 2 present the model to be calculated. Additional information is given in the following paragraphs.

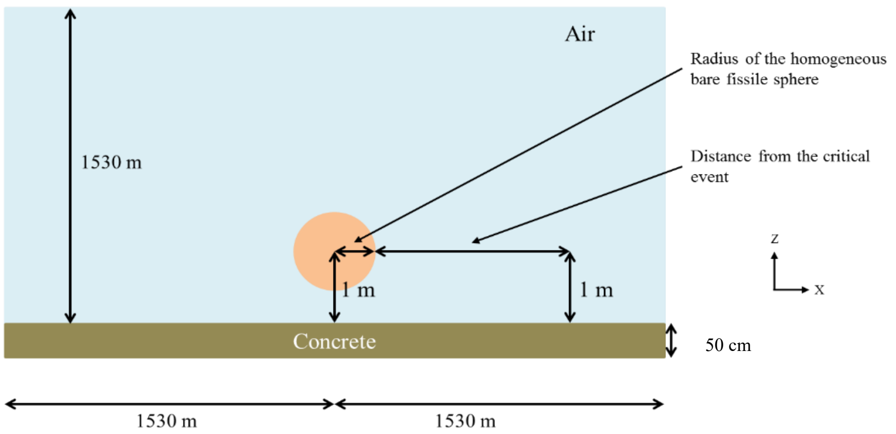


Figure 1: X-Z Plan view of the configuration.

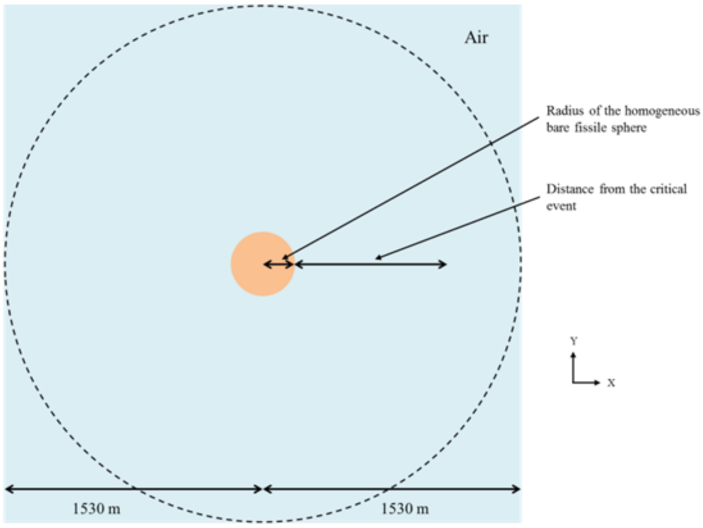


Figure 2: X-Y Plan view of the configuration.

2.2 PLUTONIUM SYSTEMS (BARE SPHERE)

Five fissile media are separately considered, with plutonium at various moderation ratios (H/Pu). The following table gives atomic concentration of each media.

Table 1: Composition of the homogeneous Pu media.

Number density (atom/barn-cm)	Pu (H/Pu = 0)	Pu (H/Pu = 10)	Pu (H/Pu = 100)	Pu (H/Pu = 900)	Pu (H/Pu = 2000)
Pu-239	5.00305E-02	5.88706E-03	6.58436E-04	7.40255E-05	3.33386E-05
O-16	0	2.94353E-02	3.29218E-02	3.33115E-02	3.33386E-02
H-1	0	5.88706E-02	6.58436E-02	6.66230E-02	6.66772E-02

The following table gives critical radii for these five media. They are calculated using MCNP6.1 with ENDF/B-VII.1 cross sections library. No reflector is considered around the sphere.

Table 2: Radii the bare Pu bare critical spheres

	Pu H/Pu = 0	Pu H/Pu = 10	Pu H/Pu = 100	Pu H/Pu = 900	Pu H/Pu = 2000
Spherical radius (cm)	4.93	12.53	15.36	19.50	29.17

2.3 MATERIAL AND TEMPERATURE DATA

3 media are simulated in the initial configuration:

- One of the 5 homogeneous bare fissile spheres,
- The air,
- The ground made of concrete.

Their atomic compositions are given in Table 1, Table 3 and Table 5.

Table 3: Composition of air.

Number density (atom/barn-cm)	Air
N	4.00E-5
O	1.11E-5

The temperatures for all media are 300 K (26.85 °C).

2.4 SOURCE STRENGTH AND SPECTRA

The magnitude of each source is normalized to correspond to 1.0E+17 fissions. This single information means that the intensity (nubar for neutron) and the energy and space repartition of prompt neutron and prompt gamma inside the sphere must be determined.

3 DESCRIPTION OF THE SENSITIVITY STUDIES

This part presents the sensitivity studies to perform for the additional configurations of the Slide Rule.

3.1 MOISTURE IN AIR

Neutron and gamma prompt dose calculations will be performed with a humidity of 10% and 100%, at the room temperature. The air composition to be used[1] is given in the following table:

Table 4: Composition of air – humidity of 10% and 100%

Number density (atom/barn-cm)	Air Humidity 10%	Air Humidity 100%
N-14	3.9214E-05	3.8397E-05
O-16	1.0798E-05	1.1094E-05
H-1	1.1559E-07	1.1559E-06

3.2 GROUND COMPOSITION AND DIMENSIONS

Calculations will be performed with the regulatory concrete composition, cf. Table 5. Nevertheless, a dry soil composition (without hydrogen) will be also tested for the case 1 and case 4, cf. Table 6. In each case, neutron and gamma prompt dose calculations should be performed. Moreover, the dimension for the ground is changed from **30.48 cm (initial configurations) to 50 cm**. The following tables give atomic concentration of the concrete and the soil[2].

[1] The air composition is based on the reference "Air humide – Notions de base et mesures. Réf : BZ8025 V1. Bernard CRETINON, Bertrand BLANQUART".

[2] Soil composition is taken from the Pacific Northwest National Laboratory "Compendium of Material Composition Data for Radiation Transport Modeling" Revision 1 March, 2011. Concrete composition was defined by the Nuclear Regulatory Commission and it is the standard concrete in SCALE.

Table 5: Composition of concrete (REGULAR-CONCRETE-NRC)

Number density (atom/barn-cm)	Concrete
Fe-54	2.02958E-05
Fe-56	3.18600E-04
Fe-57	7.35787E-06
Fe-58	9.79198E-07
H	1.37433E-02
Al-27	1.74538E-03
Ca-40	1.47412E-03
Ca-42	9.83851E-06
Ca-43	2.05286E-06
Ca-44	3.17205E-05
Ca-46	6.08254E-08
Ca-48	2.84359E-06
O	4.60690E-02
Si-28	1.53273E-02
Si-29	7.78639E-04
Si-30	5.13885E-04
Na-23	1.74720E-03

Table 6: Composition of soil (EARTH US average - PNNL)

Number density (atom/barn-cm)	Soil
O-16	2.9391E-02
Na-23	2.4400E-04
Mg-24	3.9053E-04
Mg-25	5.1503E-05
Mg-26	5.8968E-05
Mg-27	2.3260E-03
Mg-28	8.1191E-03
Mg-29	4.2723E-04
Si-30	2.9165E-04
K-39	3.1134E-04
K-40	4.0200E-08
K-41	2.3621E-05
Ca-40	1.1300E-03
Ca-42	7.9141E-06
Ca-43	1.6951E-06

Number density (atom/barn-cm)	Soil
Ca-44	2.6747E-05
Ca-46	5.8450E-08
Ca-48	2.6186E-06
Ti-46	6.9696E-06
Ti-47	6.4222E-06
Ti-48	6.4984E-05
Ti-49	4.8682E-06
Ti-50	4.7564E-06
Mn-55	1.2000E-05
Fe-54	5.2113E-05
Fe-56	8.4826E-04
Fe-57	1.9937E-05
Fe-58	2.7044E-06

3.3 SKYSHINE

The contribution of the skyshine will be determined for height superior to 10 m in each configuration. It means that calculations of the 5 cases will be done again with a height of 10 m (instead of 1530 m). The effect of the skyshine is the different between the two calculations.

3.4 RADIOLOGICAL SCREEN

A radiological screen will be added in each configuration. This screen will be modeled at halfway between the source and the detector[3]. The position of the radiological screen is measured from the external surface of the source to the internal face of the screen. The detector has a spherical shape with default radius of 20 cm.

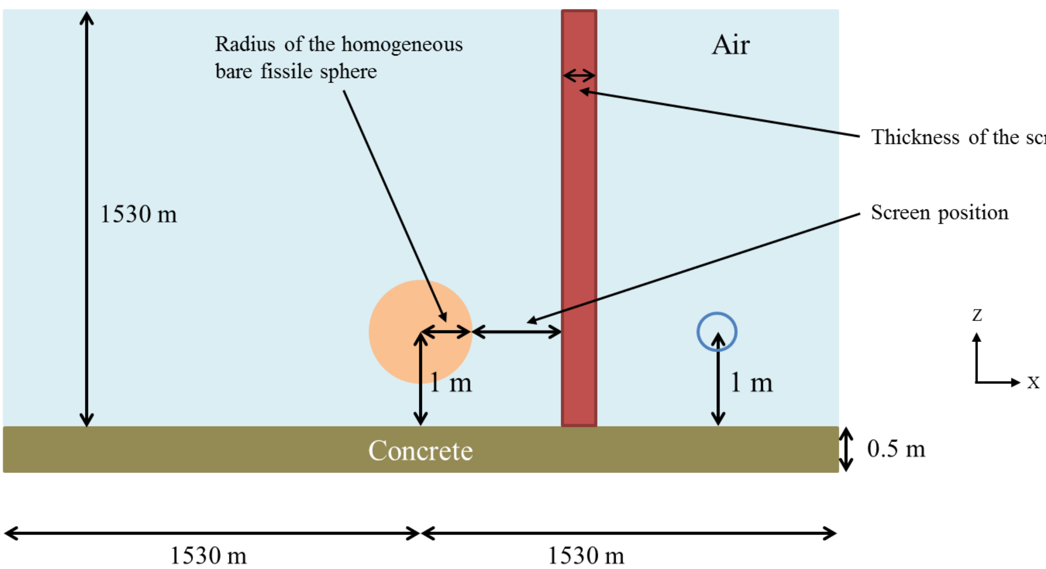


Figure 3: X-Z Plan view of the configuration with a radiological screen.

[3] The distance edge-to-edge between the source and the screen is half the edge-to-edge distance between the source and the detector.

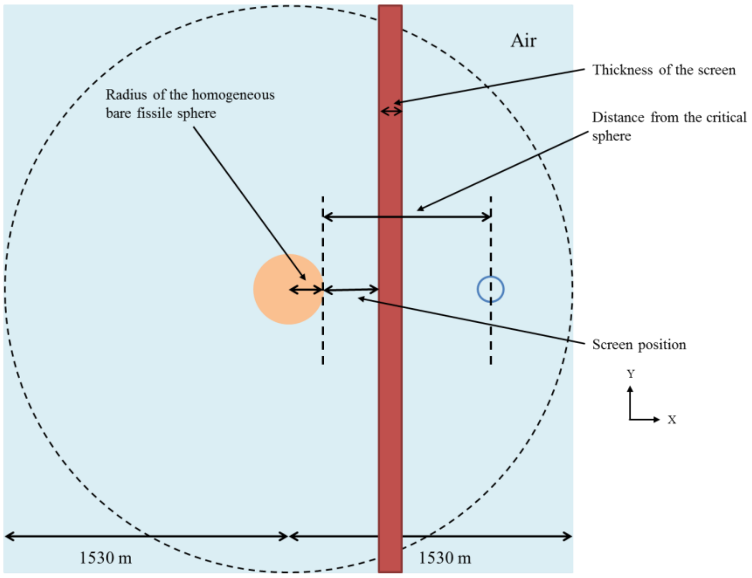


Figure 4: X-Y Plan view of the configuration with a radiological screen.

The following table presents screen positions for each detector distance.

Table 7: Screen position for each detector

Detector position (m)	Screen position (m)
0.3	
0.5	
1	0.50
2	1.00
5	2.50
10	5.00
20	10.00
50	25.00
100	50.00
200	100.00
300	150.00
500	250.00
700	350.00
1000	500.00
1200	600.00

Compositions[4] for the radiological screen are presented in the following table.

[4] Compositions (except concrete) are taken from the Pacific Northwest National Laboratory 'Compendium of Material Composition Data for Radiation Transport Modeling' Revision 1 March, 2011

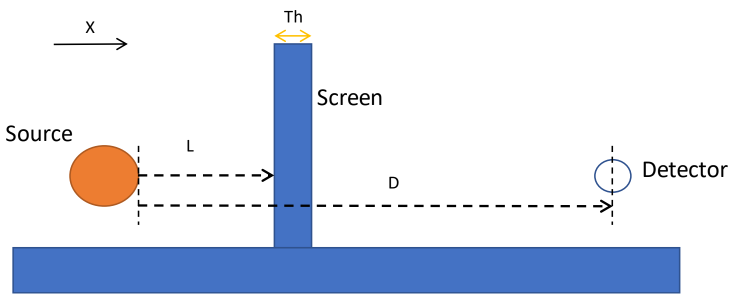
Table 8: Compositions for the radiological screen

Number density (atom/barn-cm)	Steel 304 PNNL	Number density (atom/barn-cm)	Water PNNL	Number density (atom/barn-cm)	Lead PNNL	Number density (atom/barn-cm)	Concrete
C-6	1.6000E-04	H	6.6733E-02	Pb-204	4.6183E-04	Fe-54	2.02958E-05
P-31	3.6000E-05	O-16	3.3368E-02	Pb-206	7.9501E-03	Fe-56	3.18600E-04
Mn-55	8.7700E-04			Pb-207	7.2903E-03	Fe-57	7.35787E-06
Si-28	7.8821E-04			Pb-208	1.7286E-02	Fe-58	9.79198E-07
Si-29	4.1476E-05					H	1.37433E-02
Si-30	2.8314E-05					Al-27	1.74538E-03
S-32	2.1784E-05					Ca-40	1.47412E-03
S-33	1.7733E-07					Ca-42	9.83851E-06
S-34	1.0355E-06					Ca-43	2.05286E-06
S-35	2.5300E-09					Ca-44	3.17205E-05
Cr-50	7.6494E-04					Ca-46	6.08254E-08
Cr-52	1.4751E-02					Ca-48	2.84359E-06
Cr-53	1.6727E-03					O	4.60690E-02
Cr-54	4.1636E-04					Si-28	1.53273E-02
Fe-54	3.4180E-03					Si-29	7.78639E-04
Fe-56	5.5636E-02					Si-30	5.13885E-04
Fe-57	1.3076E-03					Na-23	1.74720E-03
Fe-58	1.7738E-04						
Ni-58	5.1691E-03						
Ni-60	1.9911E-03						
Ni-61	8.6553E-05						
Ni-62	2.7597E-04						
Ni-64	7.0281E-05						

The thickness of the screen is related to its composition. The thicknesses of the radiological screen to be considered will be 1, 5, 10, 20, and 40 cm for each type of screen. Those thicknesses are representative of the different kind of wall, tank etc., that could be found in a nuclear facility.

Impact of Radiological Screen Position Study

In addition to initially modeling the radiological screen halfway between the source and the detector, this study will evaluate the impact of the screen's position on radiation protection effectiveness. The results will help evaluate the influence of the screen position on the measured doses.



The screen will be placed at six different positions relative to the total distance "D" (distance between the source edge and the center of the detector), corresponding respectively to 1/4, 1/3, 1/2, 2/3, 3/4, and 4/5 of "D". These positions will be numbered from 1 to 6. The neutron and gamma (prompt) dose will be determined for six detector distances: 1 m, 2 m, 5 m, 10 m, 50 m, and 100 m. Calculations will be performed for screen thickness of 20 cm. These calculations will only be conducted for cases 1 and 4.

3.5 RESPONSE FUNCTIONS AND DETECTORS

The additional configurations should be performed using the following conversion factors:

- ANSI/HPS N13.3-2013 conversion factors (personal adsorbed dose per neutron unit fluence, Table B1 p. 18 and personal adsorbed dose per photon unit fluence, Table B2 p. 19),
- Fine group structures for neutron and gamma spectra, defined in the Table **9** and
- Table **10** (only a measurement of the flux with these factors). With these structures, it will be possible to apply any kind of flux-to-dose conversion factors in the future.

Table 9: Upper bounds for neutron fine group structures (from left to right and top to bottom)

Upper bounds in MeV						
1.00E-11	1.00E-09	2.15E-09	4.64E-09	1.00E-08	2.15E-08	2.50E-08
2.60E-08	3.00E-08	4.64E-08	5.00E-08	1.00E-07	2.00E-07	2.15E-07
2.25E-07	3.25E-07	4.15E-07	4.64E-07	5.00E-07	8.00E-07	1.00E-06
1.13E-06	1.30E-06	1.86E-06	2.00E-06	2.15E-06	3.06E-06	4.64E-06
5.00E-06	1.00E-05	1.07E-05	1.10E-05	2.00E-05	2.15E-05	2.90E-05
3.60E-05	4.64E-05	5.00E-05	6.30E-05	1.00E-04	1.01E-04	1.10E-04
2.00E-04	2.15E-04	3.60E-04	4.64E-04	5.00E-04	5.83E-04	6.30E-04
1.00E-03	1.10E-03	2.00E-03	2.15E-03	3.04E-03	3.60E-03	4.64E-03
5.00E-03	6.30E-03	1.00E-02	1.10E-02	1.25E-02	1.50E-02	1.58E-02
2.00E-02	2.51E-02	3.00E-02	3.16E-02	3.60E-02	3.98E-02	5.00E-02
5.01E-02	6.30E-02	7.00E-02	7.94E-02	8.20E-02	8.60E-02	9.00E-02
9.40E-02	9.80E-02	1.00E-01	1.05E-01	1.11E-01	1.15E-01	1.25E-01
1.35E-01	1.45E-01	1.50E-01	1.55E-01	1.58E-01	1.65E-01	1.75E-01
1.85E-01	1.95E-01	2.00E-01	2.10E-01	2.30E-01	2.50E-01	2.51E-01
2.70E-01	2.90E-01	3.00E-01	3.10E-01	3.16E-01	3.30E-01	3.50E-01
3.70E-01	3.90E-01	3.98E-01	4.00E-01	4.08E-01	4.20E-01	4.50E-01
4.60E-01	5.00E-01	5.01E-01	5.40E-01	5.50E-01	5.80E-01	6.00E-01
6.20E-01	6.30E-01	6.60E-01	7.00E-01	7.40E-01	7.80E-01	7.94E-01
8.00E-01	8.20E-01	8.60E-01	9.00E-01	9.07E-01	9.40E-01	9.80E-01
1.00E+00	1.05E+00	1.10E+00	1.15E+00	1.20E+00	1.25E+00	1.30E+00
1.35E+00	1.40E+00	1.43E+00	1.45E+00	1.50E+00	1.55E+00	1.58E+00
1.60E+00	1.65E+00	1.70E+00	1.75E+00	1.80E+00	1.83E+00	1.85E+00
1.90E+00	1.95E+00	2.00E+00	2.10E+00	2.20E+00	2.30E+00	2.40E+00
2.50E+00	2.60E+00	2.70E+00	2.80E+00	2.90E+00	3.00E+00	3.10E+00
3.15E+00	3.20E+00	3.30E+00	3.40E+00	3.50E+00	3.60E+00	3.70E+00
3.75E+00	3.80E+00	3.90E+00	4.00E+00	4.10E+00	4.20E+00	4.30E+00

Upper bounds in MeV						
4.50E+00	4.60E+00	4.70E+00	4.80E+00	4.90E+00	5.00E+00	5.10E+00
5.20E+00	5.30E+00	5.40E+00	5.50E+00	5.60E+00	5.80E+00	6.00E+00
6.20E+00	6.30E+00	6.40E+00	6.50E+00	6.60E+00	6.70E+00	7.00E+00
7.30E+00	7.40E+00	7.50E+00	7.70E+00	7.80E+00	7.94E+00	8.00E+00
8.20E+00	8.30E+00	8.50E+00	8.60E+00	9.00E+00	9.40E+00	9.80E+00
1.00E+01	1.05E+01	1.10E+01	1.15E+01	1.20E+01	1.25E+01	1.30E+01
1.35E+01	1.40E+01	1.45E+01	1.50E+01	1.60E+01	1.70E+01	1.80E+01
2.00E+01						

Table 10: Upper bounds for gamma fine group structures (from left to right and top to bottom)

Upper bounds in MeV						
1.00E-02	1.25E-02	1.50E-02	1.75E-02	2.00E-02	2.50E-02	3.00E-02
4.00E-02	4.50E-02	5.00E-02	6.00E-02	7.00E-02	8.00E-02	1.00E-01
1.25E-01	1.50E-01	2.00E-01	2.50E-01	3.00E-01	3.50E-01	4.00E-01
4.50E-01	5.00E-01	5.50E-01	6.00E-01	6.50E-01	7.00E-01	8.00E-01
1.00E+00	1.10E+00	1.20E+00	1.33E+00	1.40E+00	1.50E+00	1.66E+00
1.80E+00	2.00E+00	2.20E+00	2.50E+00	2.60E+00	2.80E+00	3.00E+00
3.25E+00	3.50E+00	3.75E+00	4.00E+00	4.25E+00	4.50E+00	4.75E+00
5.00E+00	5.25E+00	5.50E+00	5.75E+00	6.00E+00	6.25E+00	6.50E+00
6.75E+00	7.50E+00	8.00E+00	8.50E+00	9.00E+00	9.50E+00	1.00E+01
1.10E+01	1.30E+01	1.50E+01	2.00E+01			

Doses are calculated (see Figure 1) at 1 m above the ground as a function of distance (between 30 cm and 1 200 m) from the external surface of the source to the center of the detector. The detector used (type and geometry) might be specified. By default (for configurations without a radiological screen), the detector geometry is a shape of a cylindrical shell with a square cross-section of 5 cm x 5 cm. The center of the detector is also at a height of 1 m above the ground.

4 RESULTS

All options and data necessary to analyze the results (for instance, cross section libraries, kind of detector, use of variance reduction technique, etc.) might be specified.

For more clarity, a common file naming convention may be adopted. An example is the following:

SR-Pu-S-UN-G1-C1-D10-L1-N.inp stands for:

- SR: Slide-Rule,
- Pu: plutonium[5],
- S: sphere[6],
- UN: unreflected (no shielding)[7],
- G1: first case with a ground[8],
- C1: first case with the plutonium system (H/Pu = 0)[9],
- D10: distance 10 m,
- L1: screen position corresponding to ¼ of the distance 'D',
- N: prompt neutron[10].

[5] Pu is for Plutonium.

[6] CYL1, CYL2 or CYL3 stands for cylinders.

[7] R stands for reflected configurations.

[8] G1 is for concrete ground, G2 stand for a soil ground.

[9] C2 is H/Pu = 10; C3 is H/Pu = 100; C4 is H/Pu = 900; C5 is H/Pu = 2000.

[10] « G » stands for prompt gamma.