Modelling and Comparison of Hot Cell Shielding Capabilities during a Criticality Excursion

M R Akbar & T J van Rooyen
South African Nuclear Energy Corporation (Necsa), P.O. Box 582, Pretoria, 0001

A 25 cm thick lead-walled hot cell and an 87 cm magnetite high-density concrete walled hot cell were modelled using MCNP code to determine their respective shielding capabilities in the event of a criticality excursion producing 10^{17}, 10^{18} and 10^{19} number of fissions respectively. Both cells consisted of a lead glass window with layers of different densities. It was assumed that a moderator ingress accident had taken place and that the fissile material present in the hot cell had become homogeneously dispersed in the water moderator. The fissile material was taken as 20% enriched uranium. The shielding capability, or lack thereof, of each type of hot cell was investigated and detector phantoms filled with tissue equivalent material were placed over a range of distances from the hot cell to determine the radiological consequences to operators during a hypothetical criticality excursion. For the lead-walled hot cell it was found that neutrons streamed more easily through the lead walls than the lead glass window. This is due to the borosilicate content of the glass, of which the boron is a strong neutron absorber. However the retention is minimal and the total equivalent radiological dose during such an event would lead to severe deterministic effects and possible death. The total equivalent dose received through the high-density concrete wall at a given distance was approximately 4300 times lower than through the lead-walled hot cell. This is because the magnetite concrete is a better neutron shield than the lead. Therefore in the event of a criticality excursion producing 10^{19} fissions, no person close to the concrete-walled hot cell will suffer any deterministic effects of radiation exposure. It is therefore recommended that for any hot cell operations involving possible criticality, magnetite high-density concrete walls should be used as the material of construction rather than lead.

Key words: criticality, hot cell, shielding, modelling, neutron absorption

1. Introduction

Nuclear criticality refers to the specific state of an assembly of fissionable material in which the neutrons from each fission are able to maintain a self-sustaining chain reaction and produce a large amount of energy per reaction [1, 2].

Nuclear criticality safety is defined as “the prevention or termination of inadvertent nuclear chain reactions in nonreactor environments.” Nuclear criticality safety is a multifaceted discipline consisting of three major components, namely neutron physics, engineering and administration. In practice however, the primary goal should be prevention or to maintain a state of subcriticality. [2]

However, as much as the primary goal should be to prevent criticality, one needs to be aware of the consequences of an inadvertent criticality excursion, so that one can mitigate the consequences and minimize the risk of casualties.

2. Purpose & Scope

The purpose of this study was to compare the shielding capabilities of hot cells, with shielding material of lead and concrete, respectively, during a criticality accident. Two specific existing designs at Necsa where chosen to perform theoretical calculations on. The scope of this study is limited to a specific design and results may vary substantially with other hot cell designs. However, the general principles would remain the same and the conclusions from this study would generally apply to other hot cell designs with similar materials of construction.

3. Methodology

The Monte Carlo code MCNPX 2.6.0 was used to perform the radiation transport simulation in order to investigate radiological doses to the operators during criticality excursions producing 10^{17}, 10^{18} and 10^{19} fissions respectively.

It was assumed that a moderator ingress accident had taken place and that the fissile material present in the hot cell had become homogenously dispersed in the water moderator. The fissile material was taken as 20% enriched ^{235}U and was dispersed in the water such that the effective multiplication factor, k_{eff} entered the range between 1.01 and 1.03. Based on MCNP calculations for relatively fresh fuel enriched to 20%, the value of the fission neutron multiplicity was taken to be 2.49 fission neutrons per fission event.

The investigation involved a comparison between a 25 cm thick lead-walled hot cell and an 87 cm thick magnetite high density concrete-walled hot cell. The interior dimensions of the lead cell was 150 cm × 122.5 cm × 138.5 cm and that of the concrete cell was 800 cm × 290 cm × 660 cm. The models developed in MCNP code are illustrated in figure 1(a) and 1(b) for the lead cell and figure 2(a) and 2(b) for the concrete cell. The concrete roof, floor and four walls of the room surrounding the hot cells were taken to be 30 cm thick ordinary concrete; this is enough to model practically all backscattering of neutrons and photons.

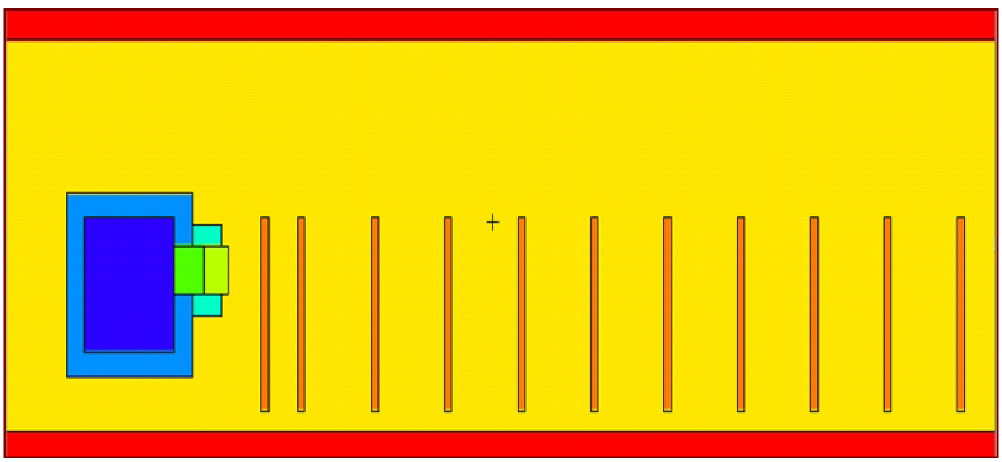

Figure 1(a): Side view of the lead cell

	Air
	Concrete
	Detector-phantoms composed of tissue-equivalent material (TEM)
	Lead
	Steel support for window
	Lead glass, higher density
	Lead glass of lower density
	Fissile material mixed with water moderator, inside hotcell

Figure 1(b): Legend for the lead cell MCNP model

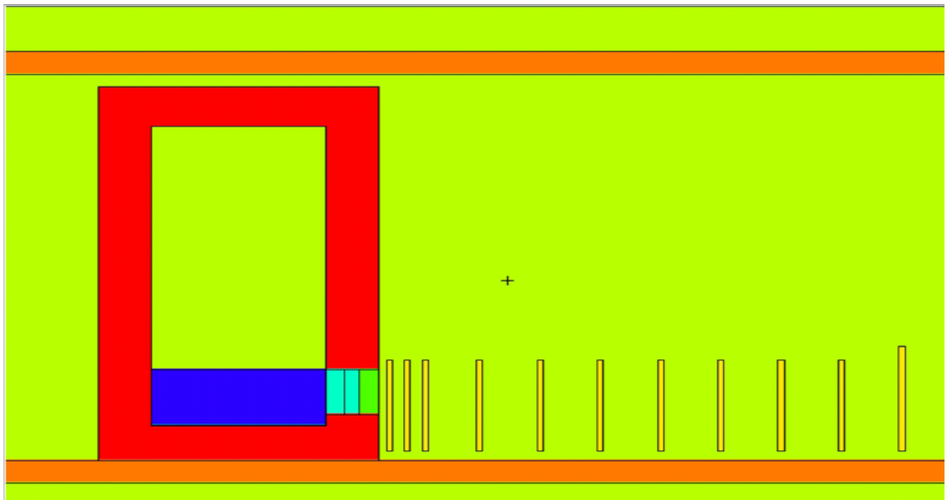

Figure 2(a): Side view of the concrete cell

	Air
	Concrete
	Detector-phantoms composed of tissue-equivalent material (TEM)
	Lead glass, higher density
	Lead glass of lower density
	Fissile material mixed with water moderator, inside hotcell

Figure 2(b): Legend for the concrete cell MCNP model

Detector-phantoms filled with tissue equivalent material (TEM) were placed over a range of distances from the lead glass window in front of the hot cells, where operators and workers may be standing during a hypothetical criticality excursion. Note that these detector-phantoms widen further away from the hot cell, in the interest of better detector efficiency. The material composition of the anthropomorphic detector phantoms was taken to be standard tissue-equivalent material (TEM), i.e. the average composition of the tissues inside the human body.

4. Results & Discussion

Table 1 and 2 illustrate the total equivalent doses received by the detector-phantoms at various distances from the lead and concrete-walled hot cells and for the different number of fissions. In order to interpret these results one needs to understand the somatic effects of radiation.

Short term radiation effects are those that occur in the period between a few hours up to a few weeks after an acute exposure. The effects are due to a major decrease in the number of cells in the body organs, due to cell death and the prevention or delay of cell division [3].

A dose above 1 Sv will lead to deterministic tissue reactions such as radiation sickness and will give rise to nausea and vomiting. Doses above 2 Sv can lead to death probably 10 to 15 days after exposure. Chances of surviving an acute dose of 8 Sv would be very low above 10 Sv, the cerebrovascular syndrome will dominate; this syndrome is not survivable, and death will occur within approximately 3 to 5 days. [3]

Table 1: Total equivalent doses for the lead-walled hot cell

TOTAL EQUIVALENT DOSE								
1E19 fissions					1E18 fissions		1E17 fissions	
Distance (m) from hotcell outer surface	Total Equivalent Dose (Sv)	Total Equivalent Dose (mSv)	Rel error	Abs error (mSv)	Total Equivalent Dose (mSv)	Abs error	Total Equivalent Dose (mSv)	Abs error
0.5	451	4.51E+05	0.0131	5.91E+03	4.51E+04	590.6	4508	59.1
1	321	3.21E+05	0.0153	4.91E+03	3.21E+04	491.3	3211	49.1
2	200	2.00E+05	0.0201	4.03E+03	2.00E+04	402.7	2003	40.3
3	127	1.27E+05	0.0235	2.99E+03	1.27E+04	299.5	1274	29.9
4	88.3	8.83E+04	0.0296	2.61E+03	8.83E+03	261.4	883	26.1
5	66.2	6.62E+04	0.0325	2.15E+03	6.62E+03	215.3	662	21.5
6	49.4	4.94E+04	0.0306	1.51E+03	4.94E+03	151.3	494	15.1
7	39.7	3.97E+04	0.0327	1.30E+03	3.97E+03	129.7	397	13.0
8	31.9	3.19E+04	0.0331	1.05E+03	3.19E+03	105.5	319	10.5
9	25.4	2.54E+04	0.0301	7.64E+02	2.54E+03	76.4	254	7.64
10	21.5	2.15E+04	0.0345	7.40E+02	2.15E+03	74.0	215	7.40
15	10.1	1.01E+04	0.0531	5.37E+02	1.01E+03	53.7	101	5.37
20	5.6	5.64E+03	0.0648	3.65E+02	5.64E+02	36.5	56	3.65

Table 2: Total equivalent doses for the concrete-walled hot cell

TOTAL EQUIVALENT DOSE								
1E19 fissions					1E18 fissions		1E17 fissions	
Distance (m) from hotcell outer surface	Total Equivvalent Dose (Sv)	Total Equivalent Dose (mSv)	Rel error	Abs error (mSv)	Total Equivalent Dose (mSv)	Abs error	Total Absorbed Dose (mSv)	Abs error
0.2	1.23E-01	122.7	4.06E-02	4.98E+00	1.23E+01	4.98E-01	1.23E+00	4.98E-02
0.5	1.03E-01	102.6	4.11E-02	4.22E+00	1.03E+01	4.22E-01	1.03E+00	4.22E-02
0.8	8.53E-02	85.3	4.79E-02	4.09E+00	8.53E+00	4.09E-01	8.53E-01	4.09E-02
1.7	5.55E-02	55.5	4.90E-02	2.72E+00	5.55E+00	2.72E-01	5.55E-01	2.72E-02
2.7	3.96E-02	39.6	5.98E-02	2.37E+00	3.96E+00	2.37E-01	3.96E-01	2.37E-02
3.7	3.05E-02	30.5	6.41E-02	1.95E+00	3.05E+00	1.95E-01	3.05E-01	1.95E-02
4.7	2.35E-02	23.5	5.28E-02	1.24E+00	2.35E+00	1.24E-01	2.35E-01	1.24E-02
5.7	2.09E-02	20.9	5.53E-02	1.16E+00	2.09E+00	1.16E-01	2.09E-01	1.16E-02
6.7	1.66E-02	16.6	5.37E-02	8.90E-01	1.66E+00	8.90E-02	1.66E-01	8.90E-03
7.7	1.29E-02	12.9	4.80E-02	6.21E-01	1.29E+00	6.21E-02	1.29E-01	6.21E-03
8.7	1.09E-02	10.9	4.80E-02	5.25E-01	1.09E+00	5.25E-02	1.09E-01	5.25E-03
18.7	2.97E-03	2.97	6.54E-02	1.95E-01	2.97E-01	1.95E-02	2.97E-02	1.95E-03

From this it is clear that in the event of a criticality excursion producing a flash of 10^{19} fissions, all people standing closer than about 20 m to the lead-walled hot cell will be expected to die as a result of radiation exposure.

In the event of a criticality excursion producing a flash of 10^{18} fissions, all people standing closer than about 8 m from the cell will be expected to die as a result of radiation exposure. All people standing between 8 m and 20 m from the cell will be expected to suffer from a degree of acute radiation sickness.

In the event of a criticality excursion with 10^{17} fissions, nobody close to the hot cell will be expected to die as a result of radiation exposure. All people standing between 1.5 m and 3.5 m from the hot cell will be expected to suffer from a non-lethal degree of acute radiation sickness.

With regard to the concrete-walled cell, even in the worst-case event of a criticality excursion producing a flash of 10^{19} fissions, no person close to the hot cell will suffer any deterministic effects of radiation exposure, with the maximum equivalent dose closest to the cell being 0.12 Sv.

With the lead cell it was found that the prompt fission neutrons are generated inside the fissile mixture in the interior of the hot cell and very few neutrons are generated within the hot cell walls by other neutron producing reactions. Prompt fission gamma-rays as well as bremsstrahlung ionizing photons from electrons slowing down, are generated inside the fissile mixture in the interior of the hot cell, as well as throughout the hot cell walls. Almost no ionizing photons are generated in the air outside the hot cell.

The simulation demonstrated that neutrons stream more easily through the lead walls than through the lead glass window due to the presence of a proportion of borosilicate in the lead glass. The ^{10}B isotope is excellent at capturing thermal neutrons [4] and the relatively better shielding capabilities of the lead glass can be attributed to it. Therefore a worker standing in front of the window will receive a significantly lower dose than one facing the lead wall.

Furthermore, the dominant lead isotope in the lead shield is ^{208}Pb, which has a closed shell of 82 protons and also a closed shell of 126 neutrons, and is a double magic number nucleus. Such nuclei have low neutron absorption cross-sections and also contribute significantly less to neutron slowing down than for example non-magic numbered stable heavy nuclei. [5] In fact, neutrons slowing-down from 0.1 MeV to 0.5 eV require between 12 and 102 elastic collisions with light nuclides while the same neutrons require about 1270 elastic collisions with ^{208}Pb. Seeing that with lead, neutrons are captured with a higher probability during the slowing down process, the poor neutron capture capabilities of lead becomes obvious [6].

It was also found that the cell was able to attenuate ionizing photons efficiently and therefore during a criticality excursion, the dose field around such a lead-walled hot cell will be dominated by neutrons.

The concrete hot cell on the other hand was able to attenuate much of the neutrons emanating from the criticality excursion. This can be attributed to the high hydrogen content of the concrete and its density, which influences the shielding effects of the concrete [7]. The magnetite concrete is also efficient in attenuating ionizing photons [7] and therefore both neutrons and photons were significantly attenuated by the magnetite concrete wall.

Figure 3(a) and 3(b) illustrate the attenuation capabilities of both the lead and concrete-walled cells respectively.

Figure 3(a) illustrates that lead is a much better photon shield than a neutron shield. However, compared to the shielding capabilities of magnetite concrete illustrated in figure 3(b), lead overall has poor shielding capabilities. Magnetite concrete has excellent attenuation properties and was able to reduce the equivalent dose due to both photons and neutrons extensively. In fact, the total equivalent dose received at a given perpendicular distance outside the concrete-walled hot cell was found to be approximately 4300 times lower than at the same distance from the lead-walled cell.

5. Conclusion

From the modelling and simulation performed, it is evident that lead is not an effective shield against neutrons, which dominate during an inadvertent criticality excursion and in most cases the operator will receive a lethal dose of radiation. Magnetite concrete on the other hand is very efficient in shielding against neutrons and no operator even in the worst-case modelled, will suffer from any deterministic effects during a criticality excursion.

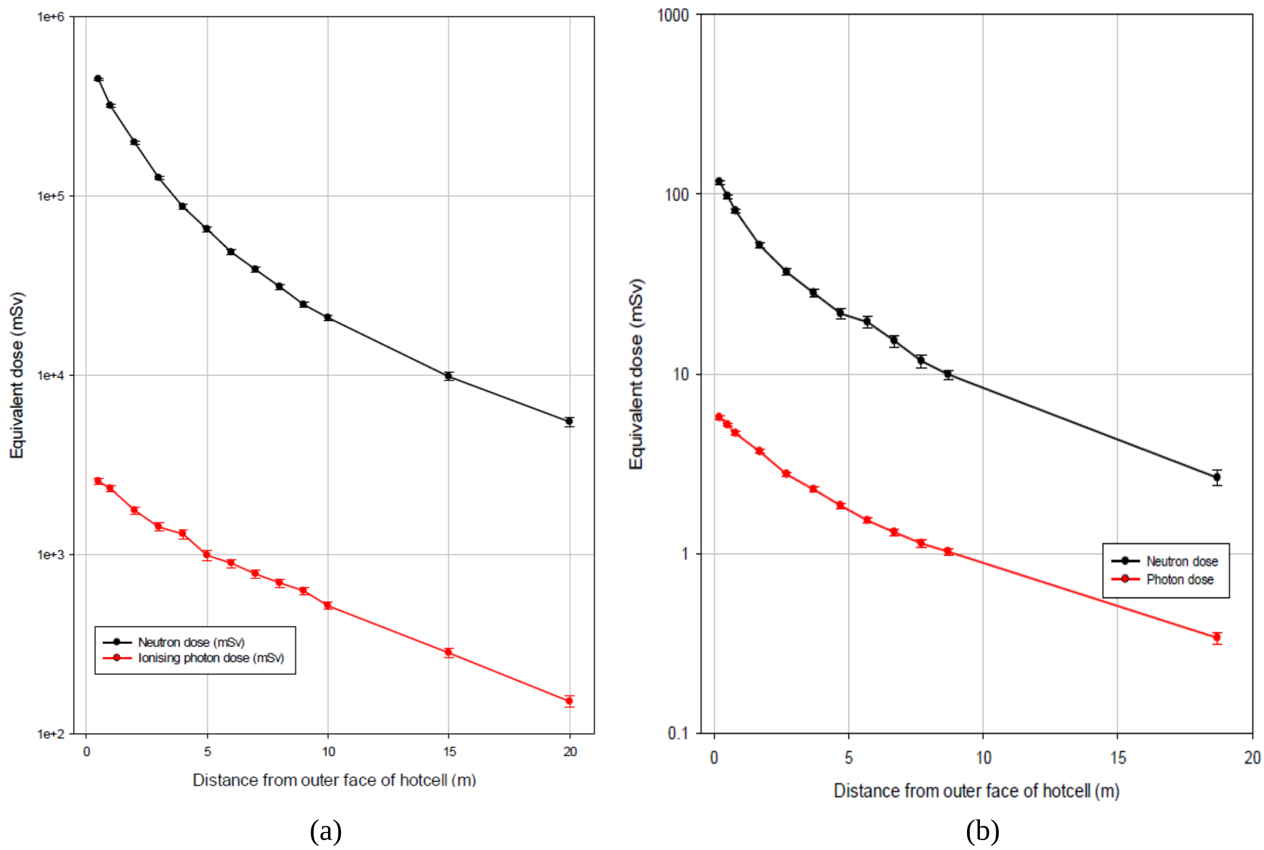

Figure 3: Attenuation capabilities of lead and magnetite concrete hot cells

It can therefore be concluded that for operations involving possible criticality, the material of construction should rather be magnetite concrete instead of lead, since the latter will not do much to prevent the operator from being exposed to harmful levels of radiation.

6. Acknowledgments

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7. References

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