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Doses and Dose Rates from CBRN Attacks in Subterranean Environments

ALEX PARKER[1], ALEXANDER BRANDL[1], PETER HOFER[2], ROBERT GALLER[3]
[1]*Colorado State University*
[2]*Theresian Military Academy*
[3]*Montanuniversität Leoben / Zentrum am Berg*
✉ alex.parker@colostate.edu
alexander.brandl@colostate.edu
peter.hofer@bmlv.gv.at
robert.galler@unileoben.ac.at

Abstract

Industrial and military structures, civilian and military installations and facilities, and civilian infrastructure and public transport increasingly utilize the space below Earth's surface. Subterranean infrastructure can provide some shelter from the elements and potential military adversaries and can ease surface traffic concerns. In major metropolitan areas, subsurface public transport has become the most convenient and expedite means of transportation. Provided their importance and large number of regular users of subterranean structures, emergency situations, including those which may result in mass casualty events and require combined efforts by first responders, civilian authorities, and security forces, have become increasingly probable. The Austrian "Zentrum am Berg" (ZaB) facility was designed as a research and training center for the construction and operation of subterranean structures and also provides similar opportunities for first responders and security forces in the case of accidents in or terrorist attacks on subterranean structures. We are investigating mass casualty events, and the force protection and operation-specific means and measures to be employed if radiological or nuclear CBRN agents have been deployed in the event. Our preliminary studies utilize small-scale models of tunnel geometries as they exist at the ZaB and in other subterranean structures to assess dose rates and doses for first responders and security forces for a variety of operational situations, including staging and approach, first aid to and rescue of victims, and apprehension of the perpetrators. We are investigating the radiation fields emanating from a radiological exposure device as a function of the structure geometries, materials and vehicles present in the structures, and protective equipment at hand for first responders and security forces. Streaming of ionizing radiation by the structure walls may enhance radiation fields in the direction of the deployed personnel, or even outside the direct line-of-sight. We are providing data on the expected effects to properly inform the commanders and personnel conducting the subterranean operation.

Introduction

Underground infrastructures pose special challenges for the emergency forces as well as the personnel of infrastructure constructors and operators due to their extraordinary framework conditions. Since public transport is highly attractive for attackers, and the knowledge required for the realization of technically sophisticated attacks can be assumed to exist (Fischer and Pelzer 2015, 105&137) it is necessary to deal with complex operations in underground infrastructures. The assessment of such an emergency in subsurface service structures is difficult, which is why the cooperation of several actors is indispensable and depending on the own forces' capabilities within Safety and Security Strategies for Subsurface Service Structures - S^6 (Hofer 2019). Associated risks include a skilled and initiative opponent, (unfavourable) ventilation, geotechnical impacts, water ingress, gas outbursts, hazardous materials of different kinds, electricity, and CBRN threats.

Radiation Scattering

Radiation fields emanating from isotropic point sources have been well characterized by systematic studies for free air and various shielding configurations. In these studies, the inverse square law is readily observed and attenuation coefficients (and half-value layers) can easily be determined as functions of the distance from the source to the response personnel and the radiation energy and attenuator material, respectively. The well documented free air measurements provide important information that can help operators estimate characteristics of radiation sources encountered in the field and develop plans to mitigate risk to personnel. In cases of high scattering potential, these published and repeatedly utilized values may not be as useful. If a radiation source is well shielded in the line of sight of the observer, but not shielded in other directions, then the inverse square law may be invalidated due to scatter in air. This phenomenon, coined sky shine, results in an increasing radiation dose rate as an observer moves away from the radiation source and shielding. At some distance behind the shielding, the radiation dose rate peaks and begins to decrease at a rate eventually resembling the inverse square law. As photons emitted from a radiation source travel in a direction other than towards the shielding, there is a probability that they will interact with electrons in air resulting in a Compton Scatter event and a new direction of travel (Figure 1). This new direction of travel post scatter can be in the direction of the observer or detector, contributing to the radiation dose, despite being behind thick shielding (Mann 2018).

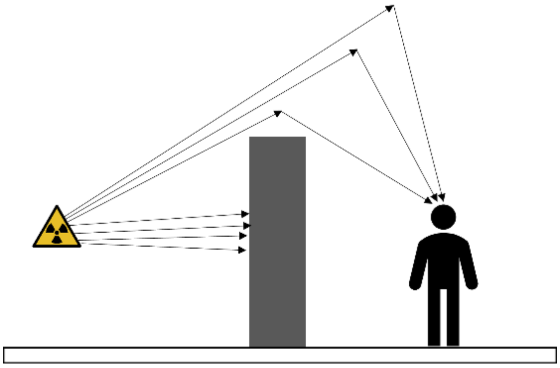

Illustration 1: Radiation Scattering in Air to Cause 'Sky Shine'

Similar in concept to sky shine, streaming is a phenomenon associated with narrow paths that allow photons to traverse shielding material that would otherwise be thick enough to absorb the energy of the emitted gamma rays. One example of a narrow pathway which could allow radiation streaming is the interface between two flat surfaces, like shielding blocks of lead. In order to prevent radiation streaming through these interfaces, shielding materials are often notched to eliminate the straight path between two flat surfaces. Along a narrow straight path, photons can scatter repeatedly in the direction of the pathway in order to traverse even very thick shielding.

This study was designed to explore the impact of radiation streaming through tunnels of various dimensions. Subterranean tunnels are well shielded by earth and rock, which provides opportunity for scattering along the tunnel path length. Utilizing a suite of software, radiation fields can be modeled very accurately for various tunnel designs and radiation sources. The results of computer simulations can then be graphically displayed to quickly communicate relative risk within specified environments to help make informed response decisions. Before full scale road or pedestrian tunnels are modeled, real measurements on a smaller scale were required as a proof of concept. These results should provide some insight to the behavior of radiation fields within well shielded and narrow spaces that have become increasingly common within public infrastructure.

Methods and Materials

To investigate the impact of radiation streaming and how radiation fields are impacted in well shielded tunnels, three small scale geometries were created for testing. The experimental set up and subsequent measurements were performed in Korneuburg, Austria. The radiation source used was a 28.3 GBq Cs-137 source (SN 0401GN) which emits a 0.662 MeV gamma with a yield of 85%. The detector used was a Radeye PRD-ER (ThermoFisher Scientific, Waltham, MA) with an infrared readout to a PC. Prior to conducting measurements in any of the tunnel assemblies, a free air measurement was taken in order to compare detector response with the accepted gamma ray constant. A subsequent measurement with the source and detector one meter apart, just above the ground was intended to quantify radiation scattering from the ground.

The first experimental set up was created to simulate a well shielded straight tunnel. Lead bricks were aligned to create a 120 cm long tunnel with a width of 10 cm and a height of 10 cm (Figure 2). The bottom or ground of the tunnel was asphalt. The Cs-137 source was positioned at one entrance of the tunnel, approximately 5 cm from the opening. The detector was then positioned in various locations in the tunnel for measurements.

Illustration 2: Small Scale Straight Tunnel Made with Lead Shielding Bricks

The second experimental set up was designed to simulate a 'T' intersection in a tunnel. A 40 cm straight tunnel with a width of 10 cm and a height of 10 cm was built leading to a crossing tunnel with a width of 15 cm and a height of 10 cm (Figure 3). The intersecting tunnel was built wider so measurements could be taken at both the near wall and far wall for comparison. For this set up, measurements were taken at three points along the near wall of the intersecting tunnel and three points along the far wall.

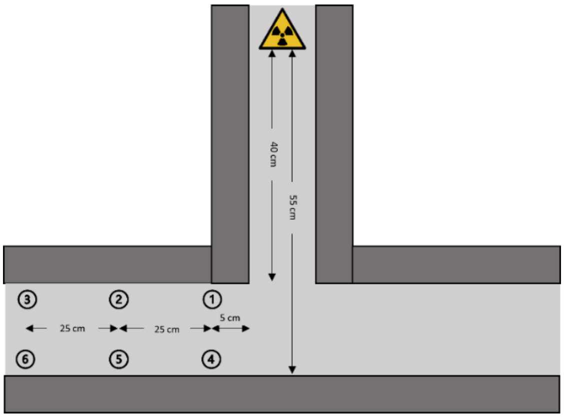

Illustration 3: 'T' Intersection Tunnel with Dimensions and Detector Positions

The final experimental set up was created to simulate a curved tunnel (Figure 4). In the curved tunnel set up, the detector was placed out of line-of-sight at three different positions along the path of the tunnel. The tunnel had a total path length of 120 cm with a width of 10 cm and a height of 10 cm.

Illustration 4: Small Scale Curved Tunnel Made with Lead Shielding Bricks

In each of the tunnel arrangements, the Radeye detector was placed in various positions of interest and the exposure rate was measured for 60 seconds in order to obtain an average rate over 5 second intervals. Additional detectors were positioned around the radiation source throughout the measurements for the safety of the operators present.

Results and Discussion

The measurements taken outside any of the lead tunnel shielding were recorded in order to compare to the accepted gamma ray constant and validate the function of the detector. For the first measurement, the detector and source were both one meter off the ground and supported only by wood to minimize scattering effects. In this configuration, the measured steady state exposure rate at one meter from the source was 225 mR/h. Using the gamma constant, $\Gamma = 0.343\ \frac{R\cdot m^2}{Ci\cdot h}$ (Smith 2012), and activity, A_0 = 28.3 GBq (0.765 Ci), the expected exposure rate at one meter is 262 mR/h. The expected exposure rate is 16.4% greater than the rate measured by the detector, which is within the 20% error margin described by the manufacturer. When the detector and source were both placed near the ground, the measured exposure rate at one meter increased to 235 mR/h.

In the straight lead tunnel, exposure rate measurements were taken at 25 cm, 50 cm and 100 cm from the radiation source. The results of these measurements (Table 1) show that the exposure rate at one meter was 214 mR/h or 4.8% less than the free air measurement at the same distance. The exposure rate as a function of distance from the source took the form $\frac{1}{r^{2.39}}$ therefore the exposure rate increased more rapidly on approach to the source than the inverse square law would predict in free air.

Table 1: Exposure Rates at Various Positions in Straight Tunnel

Position	Distance (cm)	Mean Exposure Rate (mR/h)
1	25	5849
2	50	1228
3	100	214

In the lead tunnel with a 'T' intersection, measurements were taken around the corner from the source at three different locations along both the near and far walls. The results of these measurements (Table 2) show that photons did not evenly scatter down the crossing tunnel passage. The exposure rates along the near wall were smaller than the corresponding rates on the far wall at each distance. For the near wall, the exposure rate decreased with distance following the function $\frac{1}{r^{1.96}}$ while exposure rates along the far wall decreased following the function $\frac{1}{r^{2.1}}$.

Table 2: Exposure Rates at Various Positions in 'T' Intersection

Position	Distance from Intersection (cm)	Mean Exposure Rate (mR/h)
1	5	22.7
2	25	1.4
3	50	0.2
4	5	42.7
5	25	2.2
6	50	0.3

In the curved lead tunnel, the first measurement was taken 5 cm beyond line of sight (at 55 cm path length) of the radiation source. Subsequent measurements were taken at 75 cm and 100 cm path length from the source (Table 3). Exposure rates along the tunnel path length were substantially larger than similar path lengths in the 'T' intersection tunnel. At a path length of 90 cm (50 cm from intersection), the far wall exposure rate was about 10 times less (0.3 mR/h) than the exposure rate at a path length of 100 cm in the curved tunnel (3.2 mR/h). If the first measurement at 55 cm path length is included, the radiation exposure rate follows the form $\frac{1}{r^{5.7}}$. Excluding the 55 cm measurement yields an even steeper relationship of the form $\frac{1}{r^{6.4}}$.

Table 3: Exposure Rates at Various Positions in Curved Tunnel

Position	Distance (cm)	Mean Exposure Rate (mR/h)
1	55	94.8
2	75	19.9
3	100	3.2

Conclusions

The data acquired in this benchmark study were a good first step in investigating radiation streaming and the impact of scatter in narrow, well shielded tunnels. There were two main preliminary findings that were of interest in the context of a radiation exposure device in a subterranean environment.

First, the inverse square law did not accurately represent most of the scenarios tested. Functional dependency on distance ranged from $\frac{1}{r^{1.9}}$ for the near wall after the 'T' intersection to $\frac{1}{r^{5.7}}$ for the curved tunnel. This result shows that the inverse square law should not be used in well shielded subterranean spaces to estimate source strength or position. Operators relying on the standard relationship between distance and radiation source position should understand how tunnel geometries can impact the data being reported to incident commanders.

Secondly, radiation exposure rates remained relatively high beyond the line of sight of the source, despite the very thick shielding between the source and the detector. The thickness of the lead attenuator between the source and the detector was large enough that virtually none of the primary beam made it to the detector yet scatter down the length of the tunnel still contributed to a significant exposure hazard. The eased curve of the third tunnel set up provided favorable scattering angles over the 'T' intersection which resulted in higher exposure rates at similar path lengths from the source. Operators cannot rely on corner, curves or being out of line of sight for force protection from a radiation exposure device placed in a tunnel system.

The results of this benchmark study show that traditional first responder training for radiological hazards may be inadequate in subterranean environments. Shielding and distance will not always provide the protection expected and could lead to increased radiation dose rates in unexpected areas.

Outlook

The results of this benchmark study will be compared against a computer model of the same physical specification using SpaceClaim®, Attila4MC and MCNP®. Large scale models of real tunnel systems will then be modeled based on the benchmark results obtained in this study.

Computer modeling of radiological exposure devices in subterranean environments based on these findings will greatly improve situational awareness for incident commanders by providing visualization tools that rapidly convey important risk information.

The development of a “Mini-ZaB” model will enable further experiments within a down-scaled system prior the in-situ test in the full-scale “Zentrum am Berg”[1] laboratory.

The integration of this study into the NIKE Research & Development Program[2] enables highly efficient interaction between the different projects and ensures the integration into the curriculum for training of subsurface operators (Galler et.al. 2021).

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