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Modelled environmental risk-values for low cost housing developments on rehabilitated gold-tailings dams

In view of the current socio economic situation in South Africa, there is a nationwide need for low cost housing, which typically requires low cost land. One such option is land which is situated close to mines or on sites of previously existing mining activities (rehabilitated tailings areas) (NNR, 2002:4). Mining companies need to determine whether rehabilitated areas are contaminated, as well as the degree of contamination. This is necessary in order to adhere to South African legislation (Mineral and Petroleum Resources Development Act (Act 28 of 2002)), which states that tailings areas must be rehabilitated to either their natural state or to a land use which conforms to the principle of sustainable development.

Before a rehabilitated tailings dam arising from mining operations is assigned to a new land use, it is important that potential impacts on human health be determined, particularly impacts arising from residual radioactive material. When houses are built in areas with high radium concentrations, levels of radon gas are an important consideration, as a link has been established between radon and lung cancer in humans (EPA, 2003).

The use of the Residual Radioactive Material Guidelines (RESRAD) modelling programme to determine the environmental risk values for rehabilitated gold-tailings dams was explored. RESRAD is a relatively conservative model for determining radiation dose, radon levels and risk values at a contaminated site.

It was found that the dose rate received by children was higher than that of adults, due to the higher metabolic rate of children. In addition, poor quality building standards of low cost houses may further increase the dose and risk to inhabitants, thus alternative land uses may be more appropriate, where radon mitigation measures could be better controlled.

Keywords: rehabilitation; radiation; radon; exposure modelling; health risk

1. INTRODUCTION

1.1 *The gold mining industry and radioactivity*

Since uranium is a by-product of the gold recovery process, most of the undesired radioactive residue end--s up as waste on tailings dams. Later, once the tailings dams have been reprocessed for the reclamation of residual gold, the remaining footprint may still contain considerable levels of radioactivity, due to the long-term leaching of contaminated rainwater into the subsurface.

In 2002 the National Nuclear Regulator (NNR) stipulated in a guideline document for the release of contaminated sites from regulatory control, that sites may either be released conditionally (for restricted use) or unconditionally (unrestricted use) (NNR, 2002:6). For unrestricted release of land and water the applicant needs to demonstrate that radioactive contamination has been removed from the site and activity concentration levels are below those of the background reference area. For restricted release of contaminated land and water, the applicant needs to prove compliance with an annual effective dose limit (approved by NNR on a case-to-case basis) for an average member of a critical group. The applicant or landowner should therefore prepare a hazard assessment, implement remedial measures to achieve an optimal level of safety on the site, and establish future land use possibilities, in order to receive closure certification after the rehabilitation process.

1.2 *Radon pathway*

In the uranium-238 (238U) decay chain, radium, thorium and their decay products (210Pb, 210Po and 230Th) are some of the most important and potentially harmful radionuclides. The daughter products from radon gas, produced from uranium bearing rock, have half-lives ranging from a few seconds to 20 years, and are alpha, beta and gamma emitters (Shleied, 1998:8-38). Radon gas concentrations in the outside air are generally low as a result of wind dispersion and upper air circulation. Where houses are built in areas with high radium concentrations, however, the enclosed structure may result in the radon levels becoming elevated. At a site contaminated with radium, the release of radon to the environment is controlled by a number of factors, including the radium activity and concentration within the footprint, the rate of emanation of radon from the solid mineral phase, radon diffusion rates, surface cover effects, and meteorological conditions (such as atmospheric temperature, pressure, and rainfall) (IAEA, 1992:6, 12).

When radon is inhaled into the lungs, it is usually exhaled before it decays. Health hazards arise from radon's progeny, which are solid particles with electrical charges, formed as a result of the decay process. These charged species may become attached to aerosol particles which may deposit onto the interior surfaces of the lungs if inhaled. As they emit high-energy alpha particles, which irradiate the cells of the lung tissues, cancer may result. Factors which may influence the dose to an individual include the concentration of radon and its progeny in the air, the fraction of the progeny attached to dust particles, the size of the dust particles and the breathing rate of the individual.

Table 1: Summary of exposure pathways considered for the different receptor description scenarios

	Pathways Considered								
	External gamma exposure	Inhalation of dust	Ingestion of plant foods	Ingestion of meat	Ingestion of milk	Ingestion of aquatic food	Ingestion of water	Ingestion of soil	Radon exposure
Residential farmer	x	x	x	x	x	x	x	x	x
Sub-residential farmer	x	x	x	–	–	–	–	x	x
Urban resident	x	x	–	–	–	–	–	x	x
Industrial worker	x	x	–	–	–	–	–	x	x
Recreationist	x	x	–	–	–	–	–	x	x

2. METHODOLOGY

The RESidual RADioactive Material Guidelines (RESRAD) modelling program was developed in 1989 by the US Department of Energy (DOE) as a user-friendly, multiple pathway analysis programme for the calculation of radiation dose and the risk to hypothetical individuals, living on a contaminated site, from the exposure to residual radioactive material (RESRAD, 2001:1-2).

The basic criterion for final closure certification is the dose limit. In RESRAD, the dose limit (legal requirement of 0.25 mSv per year in South Africa (CNS, 1997:32)) is converted to soil guidelines, or more specifically radionuclide concentrations, with the use of dose/source ratios (DSR) or visa versa. Radium activity (within soil) is measured and is used in RESRAD to calculate the total dose received by an individual living on-site. In RESRAD, the radon pathway considers both indoor and outdoor concentrations for radon as well as its decay products.

In order to derive soil concentration guidelines in RESRAD from a dose limit, the exposure pathway analysis consists of four parts: source analysis, environmental transport analysis, dose/exposure analysis, and scenario analysis.

Factors which would influence the external radiation dose in a housing development include shielding by a cover of uncontaminated soil over the contaminated area, or by means of a concrete floor and walls of a house built on such an area, as well as the percentage occupancy within the house. Internal exposure through inhalation arises primarily from radon, the radon-progeny, and inhalation of contaminated dust. Four different ingestion pathways are considered: the food pathway, water pathway, drinking water pathway and soil ingestion pathway.

The scenario analysis consists of the pattern of human activity which may affect the release of radioactivity from the contaminated zone, the amount of exposure received at the exposure location, and the exposure scenario. Permanent residents were chosen as the critical population since their exposure is more likely to be long-term and involve more exposure pathways. The non-resident group, receiving a smaller dose due to less time spent on-site, would consist of construction workers and individuals who visit the area. For residents living in the vicinity of the contaminated site, the external radiation would decrease rapidly with distance from the site. Five exposure situations or receptor types were investigated (Table 1).

2.1 *Residential farmer (family-farm scenario)*

In this worst-case scenario (consisting of all nine exposure pathways) a family moves onto the radioactive contaminated site, builds a house, raises cattle, crops and/or vegetables as sources of food, and uses water on-site for both drinking and irrigation purposes.

2.2 Sub-residential farmer

The site is situated within an urban area and it is therefore highly unlikely that livestock would be raised by the residents as a source of meat and milk. For the water pathway, groundwater from the rehabilitated site is used for irrigation of plants grown on site. The food pathway is included since residents of the specific area would possibly grow their own vegetables or crops to provide half their total plant diet. Drinking water (uncontaminated water) would be provided by the local Municipality. The aquatic food pathway would be ignored, since this would not serve as a source of food. The pathways included are: external radiation, dust inhalation, radon and soil ingestion, as well as plant food ingestion.

2.3 *Urban resident*

The area of investigation falls within Municipal boundaries. In this case the Municipality will supply all water for irrigation, drinking water and other uses. No food will be cultivated or grown on the area. This would be the most probable scenario and receptor for the area. The pathways included are: external radiation, inhalation of contaminated dust, inhalation of radon and its decay products, and soil ingestion.

2.4 *Industrial workers*

This applies to an eight hour working day and where no contaminated food or water is obtained from the site. Exposure pathways include external exposure, inhalation of airborne radioactive materials, and ingestion of radioactive soil.

2.5 *Recreational scenario*

Here exposure relates to people who spend a limited amount of time at or near a site. For example a recreationist such as a jogger or soccer player usually spends a limited period of time on site (two hours a day, three days a week). Pathways to be considered are: external radiation, inhalation of contaminated dust, radon, and soil ingestion.

3. *SITE INFORMATION AND RESULTS*

The rehabilitated footprint in this case study had an area of 3 000 000 m2 (300 ha), with the contaminated zone having a depth of 0.3 m (effected area due to leaching). The length of the aquifer flow was set at the approximate diameter of the contaminated area, namely 1730 m. The density of the contaminated zone for rehabilitated footprints is 1.6 g.cm-3 and the total porosity of the contaminated area is 0.44. Meteorological data was obtained for the area in question from the South African Weather Service, in order to calculate the average wind speed (2.75 m.s-1) and annual rainfall (0.4232 m.yr-1). The occupancy parameters for the inhalation and external gamma pathways are set out in the guidelines on assessment of radiation hazards to members of the public from mining and minerals processing facilities (CNS, 1997). These South African values are specific in terms of the

Ra-226 soil conc. Bq.g^{-1}	Dose mSv.yr^{-1}	Cancer risk	Outdoors Radon flux Bq.m^{-2}.s^{-1}	Outdoors Radon conc. Bq.m^{-3}	Indoors Radon flux Bq.m^{-2}.s^{-1}	Indoors Radon conc. Bq.m^{-3}
Residential farmer scenario						
1	9.362	0.01348	0.229	49.567	0.048	177.820
0.5	4.681	0.00674	0.115	24.783	0.024	88.908
0.2	1.873	0.00269	0.046	9.913	0.010	35.563
0.1	0.936	0.00135	0.023	4.957	0.005	17.782
Sub-residential farmer scenario						
1	8.393	0.01247	0.229	49.567	0.048	177.820
0.5	4.196	0.00624	0.115	24.783	0.024	88.908
0.2	1.679	0.00250	0.046	9.913	0.010	35.563
0.1	0.839	0.00124	0.023	4.957	0.005	17.782
Urban scenario						
1	8.196	0.01220	0.229	49.567	0.048	177.820
0.5	4.098	0.00610	0.115	24.783	0.024	88.908
0.2	1.639	0.00240	0.046	9.913	0.010	35.563
0.1	0.820	0.00120	0.023	4.957	0.005	17.782
South African conditions for the sub-residential scenario (living in brick houses)						
0.119	1.235	0.00155	0.028	4.362	0.005	18.893

Table 2:
Summary of modelling results for rehabilitated footprint areas, for scenarios where people live on the site, for the first year of exposure

shielding factors and time spent indoors (65%) and outdoors (35%). Annual food consumption parameters and element specific transfer factors for terrestrial food were also obtained from this document. The age specific ingestion and inhalation dose coefficients were obtained from the ICRP (1996). In the case of low cost housing, the area of the house was determined as 45 m2 (room height of 2.5 m) with a building foundation thickness of 0.35 m and foundation depth of 0.1 m within the contaminated area.

The average radium soil concentration for the soil samples from the rehabilitated footprint area, was 0.119 Bq.g-1. Control samples from background reference areas were also taken and radium soil concentrations were 0.09 Bq.g-1. Radium soil concentrations of 1, 0.5, 0.2 and 0.1 Bq.g-1 respectively, were used as input parameters to determine a trend in possible future soil concentrations.

The dose, received by inhabitants living on a rehabilitated footprint area, was modeled, and the results are presented in Table 2. The highest dosage received by an individual was found to be 9.362 mSv.yr-1 (at an excess cancer risk of 1348 in 100 000) for the first year, for a radium soil concentration of 1 Bq.g-1 for the residential farm scenario. The lowest dose received, an average of 0.820 mSv.yr-1 (at an excess cancer risk of 12 in 100 000) for the first year, was calculated for a radium soil concentration of
0.1 Bq.g-1 for the urban scenario.

4. DISCUSSION

4.1 Evaluation of possible final land uses

for the South African scenario

In SA, the dose constraint from authorised facilities for members of the public is 0.25 mSv.yr^{-1} above the dose received from the background reference area (DME, 2006: section 4.5.2.2). For a background value of 1.2 mSv.yr-1, the total dose rate of 1.45 mSv.yr^{-1} (calculated regulatory dose limit) would be the cut-off dose rate for restricted release of contaminated land and water (NNR, 2002:6). The total dose thus received by adults in each of the different future land use scenarios is presented in Figure 1.

4.2 Dose rates for different age groups

Figure 2 indicates the relationship between the residential farm scenario for raising chickens; the sub-residential scenario; and urban scenario; and the dose received by individuals of different ages. The dose from the external pathway would be the same for all age groups regardless of the scenario, since the external radiation dose values are dependant on the spatial distribution of the radioactivity; the radionuclide concentrations in the soil; and the bulk density of the soil. All of these values are independent of the habits of an individual. Food consumption parameters as indicated by the NNR for different age groups need to be evaluated, since these parameters vary not only for different cultures, but also for different countries of residence. From Figure 2 it is evident that children (age 15 years and younger) are at higher risk than adults. This is mainly due to different dose coefficients and the higher metabolic rates of children compared to those of adults.

The radon pathway contributes ~70 % to the total dose, thus it would be advisable to implement further mitigation measures to reduce indoor radon concentrations.

4.3 Sensitivity and uncertainty of parameters

In RESRAD, the built-in sensitivity and uncertainty analysis helps to determine the relative importance of input parameters in terms of their contribution to the total uncertainty. Sensitivity analyses for certain parameters were performed with the use of a built-in Monte-Carlo based tool. Parameters with little sensitivity included the thickness of the contaminated zone (values less than 0.5 m), the cover depth, the soil-to-plant transfer factors, and indoor dust filtration. Input parameters of higher sensitivity included the area of the contaminated zone, and the distribution coefficient of the radionuclides within the contaminated zone.

5. CONCLUSION AND RECOMMENDATIONS

Outdoor radon concentration values changed with meteorological conditions, as a consequence of differences in moisture and atmospheric mixing phenomena. Solar heating during the day induces turbulence that causes radon to be transported more readily upwards and away from the ground surface. During the night and early morning, temperature inversions may occur, which tend to trap radon closer to the surface of the ground (UNSCEAR, 2000:102). There are also seasonal variations related to the effects of precipitation or changes in the prevailing wind (changing the location of the highest radon concentration).

By comparing the results with the South African standards, the most plausible scenarios for future land use are: the residential chicken farm scenario (using municipal water); the sub-residential farmer scenario; the urban scenario; the industrial scenario; and the recreational scenario. During this investigation the dose rate received by children was higher than that of adults due to the higher metabolic rate of children.

It should be noted that the food consumption param-

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Figure 1:
Total dose received by adults in the case of different land use scenarios

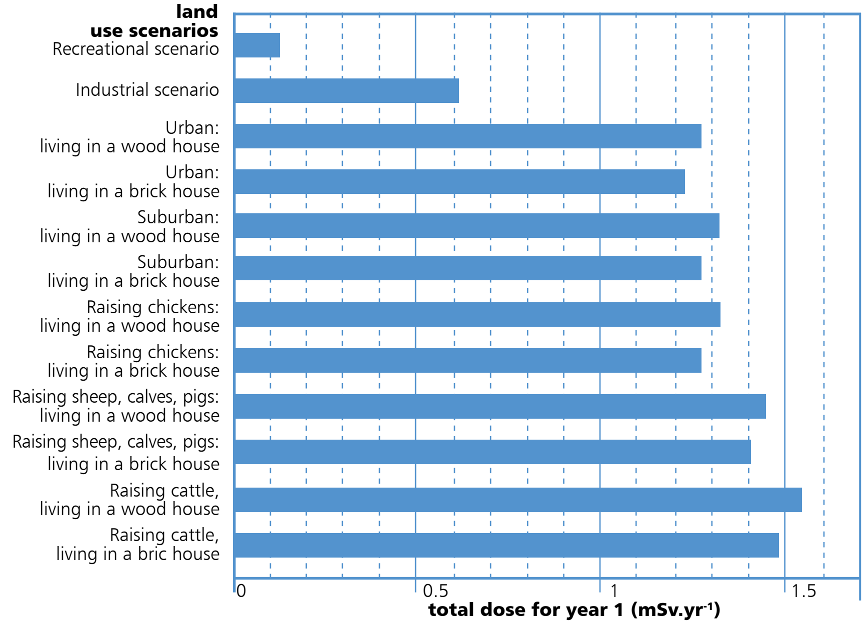
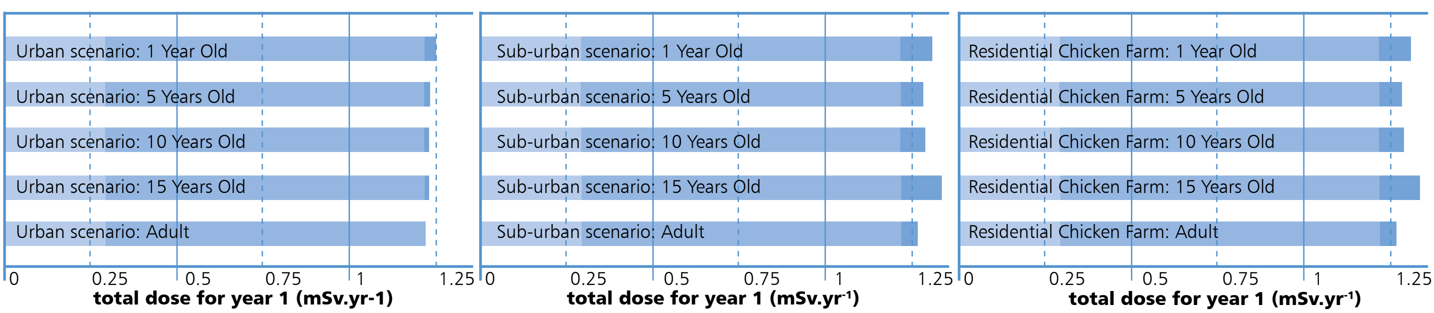


Figure 2:
Different age group scenarios and associated annual dose rates



eters are values that need to be further evaluated since they vary not only for different cultures but also according to the country of residence.

A limitation of RESRAD is that it can only be applied to on-site scenarios, as it does not explicitly model releases to the atmosphere. It does, however, model the effect of dust releases (inhalation and foliar deposition), by use of mass loading factors. In the RESRAD-OFFSITE programme, however, this is extended to include an atmospheric transport model.

It would be advisable to implement additional mitigation measures to reduce the indoor radon concentrations and thereby the risk. The most cost effective mitigation measure would be an increase in the air exchange rate within a house (achieved by opening windows, doors, etc.), which would require no additional cost but rather a change in the habits of the individuals living in such an area. It should, however, be noted that due to poor living conditions and the associated crime in low-cost housing areas, this may not be a feasible mitigation measure. Poor quality building standards may result in large cracks not only in the foundation but also in the walls, which may greatly influence the dose values and risk to the inhabitants. As a result, other land use scenarios, such as the industrial or the recreational scenario, where radon mitigation measures within a building can be more easily implemented, should preferably be considered. ❑

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