Public Exposure from Mines Operating on an Igneous Ore Body[1]

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Abstract. The impact on members of the public from the extraction and beneficiation of naturally occurring radioactive materials is of primary concern for responsible operators. In Phalaborwa, South Africa, two companies mine and beneficiate an igneous ore body in close proximity to the community. The unique features of this community allow an integrated look into the radiological impact of these activities. It is shown that the doses received by members of the public in the surrounding community are far below the public dose limit and similar to or less than the statistical variation in natural background.

1. Introduction

The object of the paper is to provide an integrated look at the Phalaborwa region of South Africa and the impact on members of the public of the mining of an igneous ore body, taking cognisance of primary and secondary exposure pathways. It is based on public safety assessments conducted in accordance with the nuclear authorizations of two mining operations in the region and provides some views on the results obtained by the author in his capacity as radiation protection specialist for those operations [1–4].

1.1 The Phalaborwa Igneous Complex

The Phalaborwa Igneous Complex is situated in the Limpopo Province of South Africa (see Fig. 1). One of the unique features of this town is that it is in a fairly pristine environment compared with more urban societies.

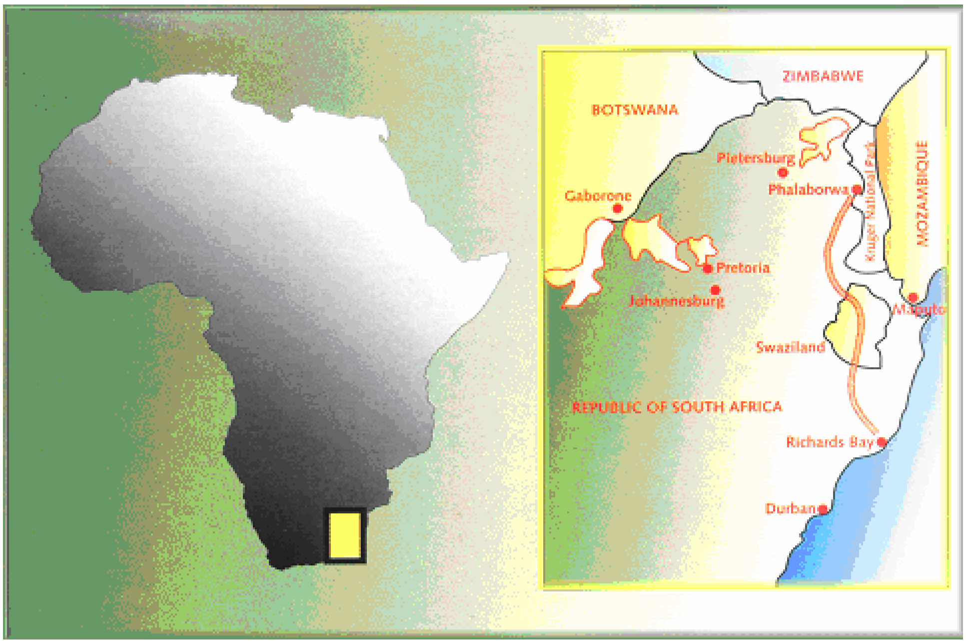

FIG. 1. Location of Phalaborwa

The situation in Phalaborwa is a unique site, with three communities in close proximity to a single source, the igneous mineral deposit, which created both primary extraction and some form of

[1] The work described in the paper was performed within the framework of the nuclear authorization requirements of Palabora Mining Company and Foskor Limited.

beneficiation. The two major facilities are Palabora Mining Company (PMC), a copper mine and smelter, and Foskor Limited, a phosphate mine and ore beneficiation plant. There is also a phosphoric acid plant, but this is relatively minor in terms of source size when compared to the sum of PMC and Foskor. To the immediate east of the igneous formation is the Kruger National Park, while the two mines are located next to one another from east to west. The town of Phalaborwa, meaning "better than the south", is located to the north of the mining complex, while smallholdings and game farms, with another town, Namakgale, are located further to the west and north-west.

1.2 Geology of the igneous orebody

The dominating rock type in the Phalaborwa area, older than 3000 million years, is granite–gneiss of the Archaic Complex. Intrusive in this are younger rock types of the Phalaborwa Igneous Complex. Inclusions of serpentine, talc and amphibole schist are found in the granite–gneiss and igneous rock. The major mineral content of the ore is as follows:

- Apatite: $Ca_2 (PO_4)_3F$
- Magnetite: Fe_3O_3
- Phlogopite: $KMg_3 (AlSi_3O_{10}) (FOH)_2$
- Copper sulphide: CuS
- Baddeleyite: ZrO_2

Table 1 summarizes the typical radionuclide activity concentrations associated with mining operations at the complex, presented as an average of various samples analysed by the Nuclear Energy Corporation of South Africa on behalf of the companies involved. A unique feature of this complex is the predominance of thorium decay series radionuclides.

TABLE 1. TYPICAL ACTIVITY CONENTRATIONS

	Activity concentration (Bq/g)				
	Phosphate rock	Phosphate tailings	Copper concentrate	Magnetite	Copper extraction tailings
^{238}U	0.14	0.26	1.43	0.14	3.52
^{226}Ra	0.14	0.27	1.14	0.14	1.81
^{210}Pb	0.12	—	0.56	0.08	8.84
^{232}Th	0.47	0.31	0.56	0.11	2.09
^{228}Ra	0.55	0.33	1.04	0.16	1.60
^{228}Th, ^{224}Ra	0.55	0.35	1.04	0.16	1.60

1.3 Mining operations

1.3.1 PMC

The ore was initially removed from an open pit, once the largest in the world. Currently the orebody lies below the open pit and is mined by the block caving method. The main process is the mining and beneficiation of copper. The process is depicted in Fig. 2.

1.3.2 Foskor Limited

Foskor is primarily a phosphate mine and beneficiation plant. The mining method is typical of opencast hard rock mining. Drilling of 250 mm blast holes is accomplished using electrically driven rotary drills. Explosives are then used to loosen the 12–15 m high benches. After blasting, an electrically driven loading shovel loads rock onto 100–180 t diesel-electric trucks that transport it to the primary crusher or the waste dumps. Rocks that are to big for the shovel are pushed to one side and crushed by mechanical impact or explosives. From the primary crushers, the rock passes through secondary and tertiary crushers before entering the milling section where the ore is ground to a fine pulp. The pulp is put through a flotation and filtration process to extract the phosphate rock and, depending on the ore stream, then put through a magnetic separation and secondary flotation process to extract magnetite and copper concentrate. The final product is stockpiled and dried before loading it on rail cars for delivery. The tailings are pumped to two tailings dams for final disposal.

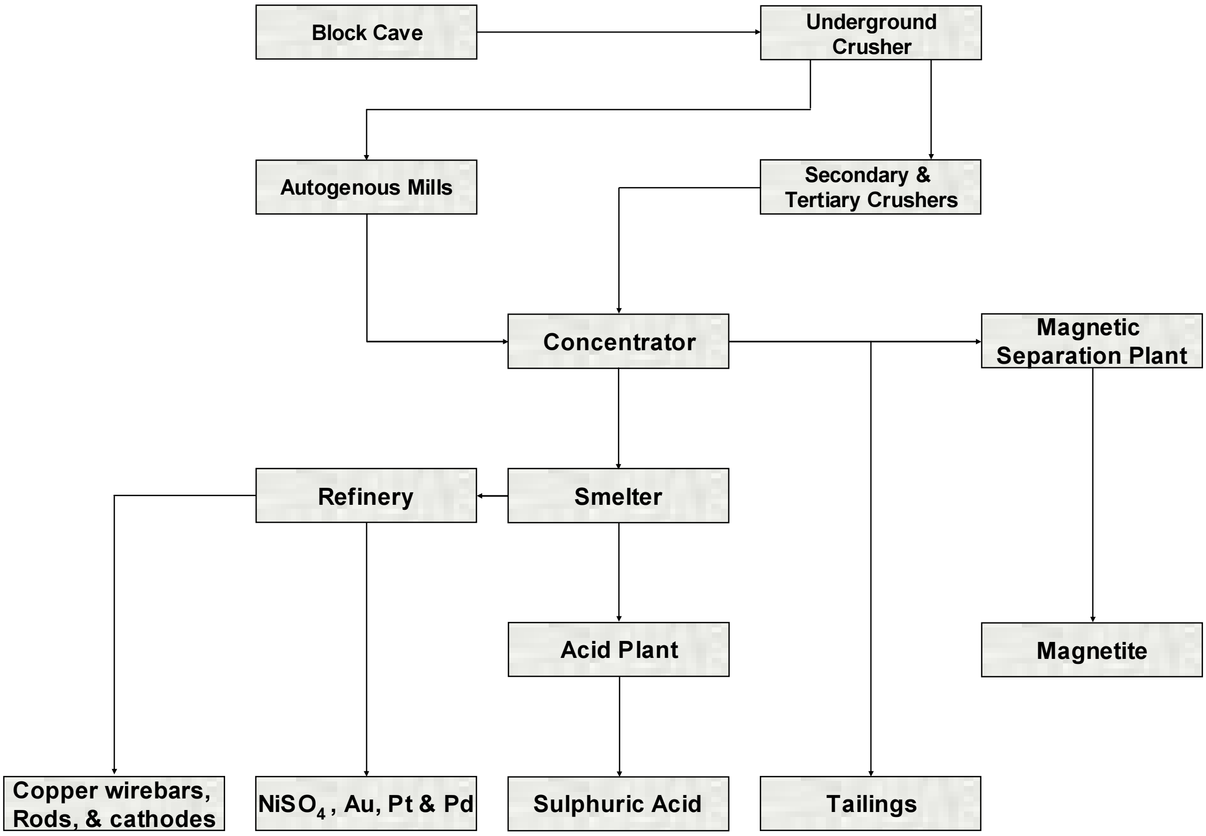

FIG. 2. PMC mining and beneficiation process

2. Public safety assessment

2.1 Methodology

Empirical equations were used for activity concentration points along the secondary pathways where actual measurements were not available. Generally, average radionuclide concentrations in air, food and water were combined with the annual rates of intake to obtain an estimate of the total radionuclide intake during that year.

2.2 Critical groups

A critical group is defined as a group of members of the public which is reasonably homogenous with respect to its exposure for a given radiation source and given exposure pathway and is typical of individuals receiving the highest dose by the given exposure pathway from the given source. For the purpose of this assessment several actual and hypothetical groups were considered to ensure an appropriate estimation of the incremental public dose as a result of the mining activities in the complex. All age groups were assumed to be present in the critical group of each scenario, with homogeneous exposure from the applicable sources. A clear distinction needs to be made between the actual and hypothetical groups. The focus of the current monitoring programme was on the actual critical groups and compliance with dose limitation requirements was determined annually for these groups. Hypothetical critical groups are seen as possible future variations that might need consideration in any future planning, especially the planning for mine closure and town development. The following critical groups were considered:

Exposure primarily from the phosphate mine

1. Actual critical group north of the site, on the site border; includes a family living in Phalaborwa.
2. Actual critical group represented by a family living in Namakgale, approximately 10 km north-west of the site.
3. Actual critical group living on the south-east border of the Selati Tailings Dam.
4. Actual critical group situated on smallholdings to the west and north-west of the Selati tailings dam, between the tailings dam and the critical group described in (2) above.
5. Disruptive or unplanned flood event.

Exposure primarily from the copper mine

6. Actual critical group north of the site, on the site border; includes a family living in Phalaborwa.
7. Actual critical group represented by a family living in Namakgale, approximately 10 km north-west of the site.
8. Hypothetical group represented by a small farm community located to the south-east on the banks of the Selati River, utilizing river water.
9. Hypothetical group represented by a small farm community located to the south-east on the banks of the Selati River, utilizing ground water.
10. Hypothetical group representing a small farm community located to the east, utilizing different boreholes from those included in (9) above.
11. Hypothetical event, e.g. an abnormal rainfall event equal to a 1 in 100 years flood.

The locations of the critical groups are shown on the satellite photograph in Fig. 3.

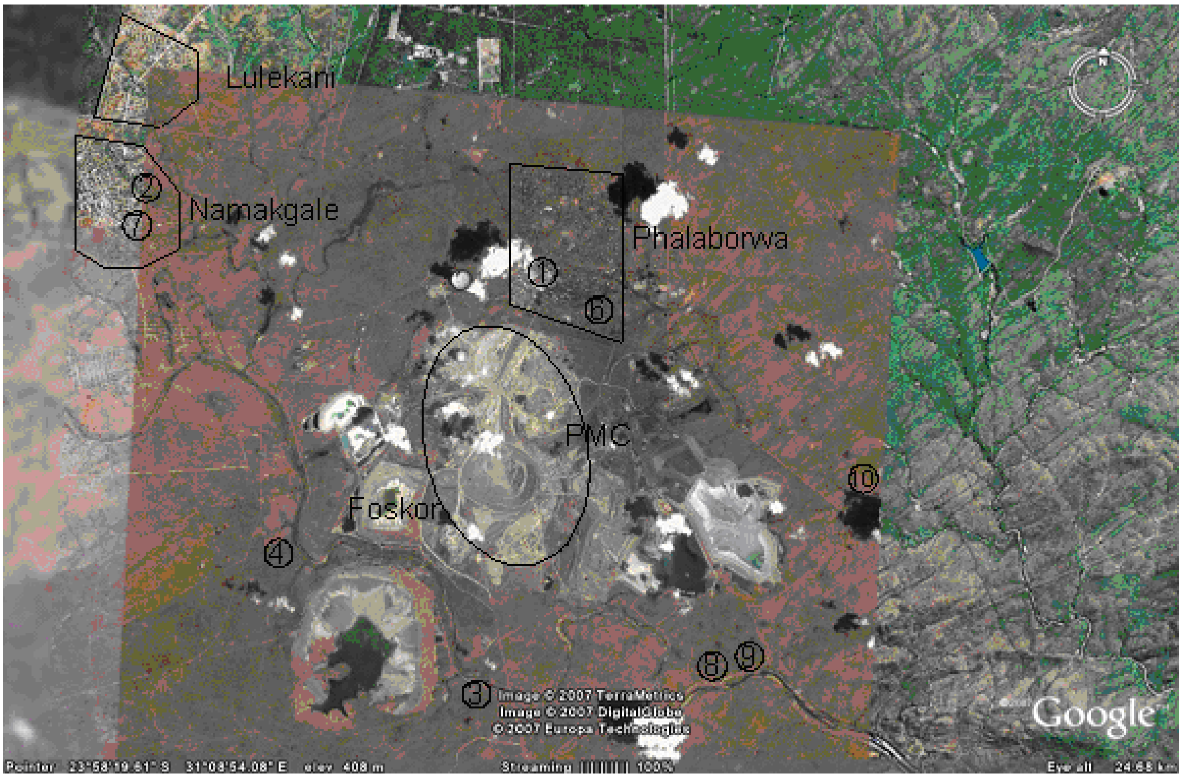

FIG. 3. Locations of critical groups

2.3 Exposure pathways

The principal exposure pathways considered for most of the critical groups listed in Section 2.2 are shown in Table 2.

TABLE 2. EXPOSURE PATHWAYS

Critical group	Exposure pathway		
	External radiation	Inhalation	Ingestion
1	Soil, plume immersion	Dust, radon, thoron	Fish, leafy vegetables, root vegetables, fruit
2	Soil, plume immersion	Dust, radon, thoron	Fish, leafy vegetables, root vegetables, maize, cereal, poultry, eggs, meat, milk
3	Soil, plume immersion	Dust, radon, thoron	Fish, leafy vegetables, root vegetables, maize, cereal, poultry, eggs, meat, milk
4	Soil, plume immersion	Dust, radon, thoron	Fish, leafy vegetables, root vegetables, maize, cereal, poultry, eggs, meat, milk
6	Soil, plume immersion	Dust, radon	Fish, leafy vegetables, root vegetables, fruit
7	Soil, plume immersion	Dust, radon	Fish, leafy vegetables, root vegetables, maize, cereal, poultry, eggs, meat, milk
8	—	Radon	Surface water, leafy vegetables, root vegetables, maize, cereal, poultry, eggs, meat, milk
9	—	Radon	Groundwater, leafy vegetables, root vegetables, maize, cereal, poultry, eggs, meat, milk
10	Soil, plume immersion	Dust, radon	Groundwater, leafy vegetables, root vegetables, maize, cereal, poultry, eggs, meat, milk

2.4 Wind direction and water flow

The wind direction at Phalaborwa is represented by the wind rose shown in Fig. 4. The wind blows from a south-easterly direction for approximately 70% of the time.

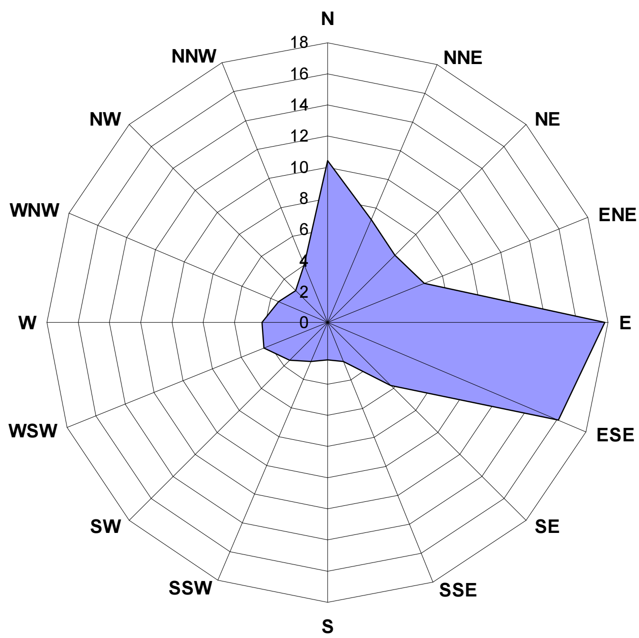

FIG. 4. Wind rose for Phalaborwa

A major difference between the PMC risk assessment and the Foskor risk assessment was that actual receptor fall-out dust measurements were not available for the former. It was therefore assumed for the PMC assessment that the concentration at source equalled the concentration at the receptor (i.e. no resuspension of dust) and that the wind direction was the only factor determining the concentration at the receptor.

The direction of surface water flow is opposite to the predominant wind direction, away from the site and into the neighbouring national park. The surface water thus affects only the hypothetical critical groups in terms of drinking water and irrigation. However, the actual critical groups were affected by the uptake of radionuclides in fish. Groundwater also flows away from the community, through the mine sites towards the Selati River and therefore only affects the hypothetical critical groups.

3. Results of initial assessment

The results of the initial public safety assessment are summarized in Table 3.

TABLE 3. RESULTS OF THE INITIAL ASSESSMENT

Critical group	Annual effective dose, by age group (μSv)					Exposure pathway	
	0–2 a	2–7 a	7–12 a	12–17 a	>17 a	Primary contribution	Secondary contribution
1	52.4	112	147	122	144	Ingestion: fish	Ingestion: leafy vegetables
2	43.7	105	138	108	137	Ingestion: fish	Ingestion: leafy vegetables
3	242	271	355	481	254	Ingestion: leafy vegetables	Ingestion: fish
4	60.0	118	153	131	146	Ingestion: fish	Ingestion: leafy vegetables
5	Similar to (3) which is already conservative and the most restrictive, hence no further calculations made						
6	72.7	65.8	73.7	97.9	73.0	Inhalation	Ingestion: leafy vegetables
7	126	111	132	195	107	Inhalation	Ingestion: leafy vegetables
8	60.6	56.1	61.9	98.9	58.3	Ingestion, water	Meat, milk for infants
9	431	292	233	256	181	Ingestion: water	Meat, milk for infants
10	136	111	109	140	99.4	Ingestion: water	Meat, milk for infants
11	Similar to (8) which is already conservative and the most restrictive, hence no further calculations made						

4. Discussion of results and revised assessment

Owing to the proximity of the mines to three communities, it is necessary to fully quantify the impacts on these communities, actual and potential, to ensure responsible management. This assessment was very conservative in its approach, in that it assumed that a critical group received all of its consumables from a potentially affected area, but this is very unlikely in the Phalaborwa region. The shallow soils and low crop potential prevent any extensive agricultural use and farming consists mainly of game and cattle farming. In addition, the areas available for growing crops are limited, with only one smallholding producing leafy or root vegetables in marketable quantities. This smallholding does not have cattle to provide meat and milk, nor does it produce cereals and maize in addition to vegetables. However, for the purpose of the initial assessment, it was assumed that large scale farming was possible, hence the inclusion of the various pathways.

The initial assessments for both facilities utilized measured data, and only reverted to conservative assumptions where such data were not available. A good example is the inhalation dose at the receptor locations. Foskor's programme was structured around its impact on air quality, a primary concern for the company, and radionuclide-specific airborne dust measurements were therefore available. However, PMC was more concerned with its impacts on surface water and groundwater, so more emphasis was placed on gaining a good understanding of these impacts. In the case of PMC, therefore, airborne dust measurements at receptor locations were not made. Instead, it was conservatively assumed that the air concentration at source was not reduced over time and distance and only the wind direction accounted for any reduction in exposure at the receptor location compared with that at the source. It should be noted that physical location and other physical parameters played an important part in the difference in focus by the two companies.

For Foskor, the initial assessment indicated that critical group 3 received the highest dose, but further investigations showed that the occupants do not use the land for any type of farming, thus removing ingestion as a possible pathway. Broadly the same principal applied to critical group 9 (of concern for PMC), for whom the primary dose contribution in the initial assessment was from the use of borehole water for drinking purposes. In this instance, the effect of the poor groundwater quality was recognized. The groundwater in the Phalaborwa region is not suitable for human consumption and should thus be excluded for the second iteration of the assessment.

It should also be noted that the airborne dust activity concentration measured by Foskor in Phalaborwa and Namakgale includes not only the impact of Foskor but also the contribution from PMC. It should thus be seen as the total impact of both facilities on Phalaborwa and Namakgale. The impacts from each facility could have been assessed separately, but this would have required the same comprehensive airborne dispersion model, using the same assumptions, to be applied to each facility and the results used to determine the relative dose contributions. Since the impact determined for critical groups 1 and 2 was small (<200 μSv/a), it was not considered necessary to proceed along this line. However, it is important to note that a significant amount of conservatism was introduced by assuming that the activity concentrations at the receptor and source were the same.

A revised impact assessment was therefore made, in order to take account of the following:

- Dust sampling in Phalaborwa and Namakgale represents the combined impact of PMC and Foskor. (The difference between the two is that Foskor allows fishing in the company dams and such fish may therefore be consumed);
- Ingestion does not contribute to the dose received by critical group 3;
- Fish consumption does not contribute to the dose received by critical group 4, as these individuals do not fish on the Foskor site;
- Groundwater does not contribute to the doses received by critical groups 9 and 10.

The results of this revised assessment are shown in Table 4. It is clear from these results that the doses received by all critical groups are significantly less than the 1 mSv limit on annual dose for members of the public and, moreover, are less than or close to the statistical variation (about 100 μSv) in the natural background in South Africa. This implies that public exposure is not a factor in determining whether the operations should be subject to regulatory control.

TABLE 4. RESULTS OF THE REVISED ASSESSMENT

Critical group	Annual effective dose, by age group (μSv)				
	0–2 a	2–7 a	7–12 a	12–17 a	>17 a
1	52.4	112	147	122	144
2	43.7	105	138	108	137
3	70.1	134	173	153	189
4	20.6	16.6	19.4	30.1	11.8
6	30.0	28.1	30.2	37.4	26.7
7	8.26	7.77	8.50	1.07	7.27
8	60.6	56.1	61.9	98.9	58.3
9	156	128	108	96.5	68.8
10	72.2	70.0	75.5	93.9	60.7

An interesting aspect of the responsible management approach to radiation protection by both companies was an initial community belief that the ambient radiation level was caused by the mines and that this had caused an increased cancer rate amongst the local population. Notwithstanding almost constant communication with the community through different forums to alleviate this anxiety, one person did attempt to utilize the 'radiation coming from the mines' as an argument in a court action claim. It was realized that it is very important not to resort to generic assumptions, but to be realistic, using scenarios and parameters to which the community can relate. A shortcoming is also that the radiation protection process remains somewhat unfamiliar and that a common denominator, such as a management system similar to ISO 9001 or ISO 14001, could be helpful in convincing the public that an authorized facility is responsible in terms of its management of this particular risk.

5. Conclusions

– The annual effective dose received by the various critical groups, attributable to the mining operations, is significantly below the limit of 1 mSv that is applicable in terms of international standards.

– The radiological impact is generally less than or marginally above the statistical variation in natural background.

– Based on experience in Phalaborwa, it is advisable to present the radiation protection management system in the same terms as ISO 14001, a system known to the general public.

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