RADIATION EXPOSURES AT URANIUM MINES – WHAT ARE THE RISKS?

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Historically, uranium mining has resulted in significant radiation exposures to workers, notably if mining was conducted under ground.

Namibian uranium mines are low grade and open cast, and radiation exposures to the workers and the public are well understood, controlled and quantified.

This paper provides an overview of the processes, risks, controls and monitoring programmes at Namibia’s oldest uranium mine, i.e. Rössing Uranium Limited.

1. INTRODUCTION

Uranium was discovered in the Namib Desert in 1928, but it was not until 1976 that Rössing Uranium, Namibia’s first commercial uranium mine, commenced operations. In 2017, Namibia had two significant uranium mines, which together provide for roughly 6 per cent of the world’s uranium oxide mining output. World uranium production is up to 60,000 tonnes uranium per annum, and Rössing produces up to 4,000 tonnes of uranium oxide per year [16].

Uranium mining has historically been associated with lung cancer and other long term health problems among miners [2], [7], [11], [12], [13]. Cohort studies on uranium miners have in the past focused primarily on internal radiation exposures, primarily the risk of radon inhalation, and in some cases the secondary risk of inhaling long-lived radioactive dust. Workers in typical epidemiology cohorts were primarily working in underground mines with very high uranium ore grades (up to 60% uranium in the ore) [17].

Namibia’s uranium mines are open pit and have extremely low ore grades (between 0.01% and 0.06% uranium in the ore) [1], leading to mining conditions significantly different from those encountered in many early uranium mining cohort studies on worker health.

In this paper we provide a summary of the risks relating to radiation exposure in Namibian uranium mines with explicit reference to the Rössing Uranium mine. The potential risks will be put into perspective by comparing these to the actual exposure doses experienced in a work environment where effective controls for managing radiation risks have been implemented.
At Rössing Uranium, the mining operation is in a semi-arid environment with very limited ground cover. Insolation is high, and as a result, daytime ranges of temperatures are wide. Mining is done by blasting, loading and hauling from the open pit, before the uranium-bearing rock is processed in a tank leaching process utilising sulphuric acid combined with continuous ion exchange, solvent extraction and precipitation processes, followed by roasting of yellowcake to uranium oxide [15].

2. RADIATION EXPOSURE DOSE AND RISK

The risk from the exposure to ionising radiation has been quantified by the International Commission on Radiological Protection (ICRP), for example in their 2007 recommendations [6]. The combined detriment factor for cancer and heritable effects proposed by the ICRP is based on a linear biological response to ionising radiation and amounts to roughly 4% per sievert (Sv) for adults.

The ICRP recommendation of an annual occupational effective whole body dose limit of 20 mSv per year, averaged over defined periods of 5 years, is implemented in the international safety standards of the International Atomic Energy Agency (IAEA), for example in the IAEA Basic Safety Standard [5]. The corresponding annual public dose limit is 1 mSv per year, averaged over defined periods of 5 years.

In this paper, risk from exposure to ionising radiation will be quantified in terms of the measured or calculated effective annual whole-body dose of individuals.

3. RADIATION EXPOSURE PATHWAYS FOR WORKERS

Workers can be directly exposed to penetrating gamma radiation if they work close to radioactive materials. Internal exposures may occur through the inhalation of radon and radon decay products, the inhalation of long-lived radioactive dust or through the ingestion of radioactive materials.

3.1 External exposures, controls and potential doses

The mining process leads to uranium ores being exposed in the mining pit or on stockpiles. Blasting, hauling, crushing and processing streams lead to large quantities of uranium bearing material being handled and stored, and hence to workers being exposed to gamma radiation. Because of the low ore grades and the low specific radioactivity of uranium, the ambient dose rates during the mining and crushing streams are relatively low, but rising progressively as the concentration of uranium in the processed materials increases. The highest dose rates from uranium therefore occur where the uranium concentration is highest, i.e. in the uranium recovery areas where uranium is precipitated as yellowcake, roasted to uranium oxide, drummed and packed into containers.

In addition to gamma radiation arising from the presence of uranium, the radioactive decay products of uranium are present in the ore, and therefore throughout the leaching process. Some of the daughter products of uranium have a tendency to be deposited in scales developing on the linings of tanks and pipes, in particular radium, Ra-226. The specific activity of Ra-226 at roughly 37 GBq/g is significantly higher than that of natural uranium, at roughly 25 kBq/g (excluding daughters other than uranium). Radium scales can therefore present the highest dose rates in areas of the processing plant where liquid processing streams occur.
In some cases, where high ambient dose rates in heavily frequented areas occur, for example in tank or pipe scales, engineered controls may be employed, e.g. shielding of areas using high density materials such as lead or concrete. Where relevant, an additional reduction of ambient dose rate may be achieved through the utilization of preferential geometry, for example by stacking uranium drums in single layers behind each other on the floor, rather than double stacking (Figure 1). This practice optimises the dose rate by reducing the surface area emitting radiation into a direction where work may occur, and utilises the shielding properties of uranium to shield radiation emitted from the drums in rows behind the front row.

![Figure 1. Single-layer stacking of uranium drums can be used to reduce the nearest exposure area shielding the sources further away](image1)

Where engineered controls are not feasible, the administrative controls of time restrictions and distance optimization must be employed. If ambient dose rates pose a risk, access restriction helps to reduce exposures to occur only for authorized workers on a supervised schedule (Figure 2). Additional time restrictions for specific tasks can help to ensure that doses remain as low as reasonably achievable.

![Figure 2: Area classification and access restriction help reducing exposures to unauthorised personnel](image2)
For the estimation of potential exposure doses to workers, a standard 2,000-hour working year is assumed, and the subtraction of any background radiation is avoided.

Potential gamma dose rates in micro-sieverts per hour (μSv/h), associated annual doses and actual worker doses in milli-sieverts per annum (mSv/a) as measured when utilizing controls, are summarized in Table 1.

<table>
<thead>
<tr>
<th>Process</th>
<th>Maximum dose rate, μSv/h</th>
<th>Maximum potential annual dose, mSv/a</th>
<th>Annual occupational dose observed, average, mSv/a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mining</td>
<td>2</td>
<td>4</td>
<td>0.2 – 3</td>
</tr>
<tr>
<td>Crushing</td>
<td>2</td>
<td>4</td>
<td>0.5 – 2</td>
</tr>
<tr>
<td>Extraction</td>
<td>100</td>
<td>200</td>
<td>1 – 5</td>
</tr>
<tr>
<td>Recovery</td>
<td>100</td>
<td>200</td>
<td>1 – 6</td>
</tr>
<tr>
<td>Waste Management</td>
<td>3</td>
<td>6</td>
<td>1 – 2</td>
</tr>
<tr>
<td>Packing</td>
<td>50</td>
<td>100</td>
<td>1 – 3</td>
</tr>
<tr>
<td>Transport</td>
<td>1</td>
<td>2</td>
<td>up to 0.5</td>
</tr>
<tr>
<td>Administration</td>
<td>0.5</td>
<td>1</td>
<td>up to 0.5</td>
</tr>
</tbody>
</table>

Table 1: Potential maximum gamma dose rates, annual dose and average exposure doses when applying controls

3.2 Internal exposures, controls and potential doses – radon

From early human history, the mining of minerals was associated with dangerous working conditions for people, often underground, in narrow unstable passages, with minimal lighting and ventilation. Five centuries ago, it was already known that underground miners in the Erzgebirge in Europe, where silver was mined, often died of lung disease. Historically, this lung disease was ascribed to the “pestilence of the air”, for example in the 1500’s by Paracelsus. The lung disease of underground miners was finally identified in 1879 as bronchial cancer, and first studies suggested radon and particularly the short-lived radon daughter products as cause of lung cancer in the 1930’s in the Schneeberg and Joachimsthal (today Czech Republic) silver mines.

Radon, a member of the uranium and actinium decay chains, is a gas emitted from uranium bearing ores, low-grade or waste rock stockpiles (Figure 3) and tailings materials (Figure 4) alike. As it diffuses into the air from sources in the ground, it mixes with radon-poor air. The primary control for reducing radon concentrations is therefore ventilation, for diluting radon concentrations in the air and removing short-lived radon decay products attached to aerosols and dust particles from the air.

In an open pit mining environment with low ore grades, ventilation or dilution in most working areas is high and the risk from radon progeny accumulating is correspondingly low. Exceptions are all areas that are deficient in ventilation, and which have sources of radon in the underlying soil or in the containment structure. It is therefore essential to ensure that radon sources are not used for building purposes. For example, using tailings materials for building foundations greatly increases the risks from radon inhalation in these buildings if occupied by people. Tunnels used for conveying crushed ore or tailings material must be suitably ventilated if frequented by workers. Access to confined spaces,
particularly if they contain uranium bearing ores or waste materials, must be restricted pending risk assessments (including those from radon). Buildings housing ore or core samples, product samples or tailings or rock samples must be ventilated if used by people. Uranium bearing materials should not be stored in buildings used for regular working activities.

![Exposed ore body (open pit) and waste rock dumps, sources for radon emissions (photo: A Terblanche)](image)

If a few simple guidelines are followed, such as refraining from the use of tailings material for building structures, providing adequate ventilation in enclosed spaces and providing rigorous confined space entry procedures, the inhalation dose from radon and radon progeny can be kept remarkably low. A summary of the potential maximum radon concentration, maximum potential annual dose and actual representative dose is provided in Table 2 [14]. The occupational dose is measured directly by using personal radon progeny dosimeters. Representative doses can also be calculated from radon concentrations using an equilibrium factor of 0.4, which is fairly typical for this region as confirmed through direct measurements of radon and radon progeny concentrations.

![Tailings storage facility, source for radon emissions (photo: A Terblanche)](image)
<table>
<thead>
<tr>
<th>Process</th>
<th>Typical radon concentration, Bq/m³</th>
<th>Maximum potential annual dose, mSv/a</th>
<th>Annual occupational dose observed, average, mSv/a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background at mine site</td>
<td>10 – 70</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Extraction &amp; Recovery</td>
<td>70 – 100</td>
<td>0.6</td>
<td>up to 0.6</td>
</tr>
<tr>
<td>Crushing plant</td>
<td>50 – 150</td>
<td>1</td>
<td>up to 0.8</td>
</tr>
<tr>
<td>Open pit</td>
<td>100 – 300</td>
<td>2</td>
<td>up to 0.8</td>
</tr>
<tr>
<td>Tailings Storage Facility</td>
<td>60 – 260</td>
<td>2</td>
<td>up to 1.5</td>
</tr>
<tr>
<td>Offices, labs</td>
<td>50 – 1500</td>
<td>9</td>
<td>up to 3</td>
</tr>
<tr>
<td>Ore tunnels</td>
<td>up to 1500</td>
<td>up to 9</td>
<td>up to 3</td>
</tr>
</tbody>
</table>

Table 2: Potential maximum radon concentrations, associated annual dose and average dose measured when utilising controls, at Rössing Uranium

3.3 Internal exposures, controls and potential doses – long-lived radioactive dust

Uranium mining in Namibia results in potentially very dusty workplaces, as the region is poor in vegetation, often windy, and exposed to temperature extremes. In addition, the processes of blasting (Figure 5), mining and hauling (Figure 6), crushing, stockpiling (Figure 7) and mineral waste deposition enhance the potential for dust generation and distribution, and hence the inhalation of the radioactive particles contained in the dust.

Figure 5: Blasting distributes significant amounts of ore dust in the air
In addition to ore dust containing uranium and thorium, which are prevalent in the mining processes from blasting up to wet chemical extraction processes, at Rössing Uranium the end product is uranium oxide, which is obtained by roasting yellowcake at high temperatures in roasters. Because of the very low ore grades, the radioactivity concentration in the ore dust is relatively low, while the roasted uranium oxide has significantly higher concentration of radioactivity.
In order to assess the internal exposures from the inhalation of long-lived radioactive dust, personal sampling of dust inhalation is followed by an analysis of the dust filters in order to assess the radioactivity of the filter. The filter activity can then be used to calculate the dose resulting from the inhalation of the air breathed, knowing the air volume pumped through the filter during the sampling process.

Following the dose calculation method proposed by the IAEA [4], the information needed for a dose calculation is then the radioactive concentration of the dust.

For ore dust, secular equilibrium can be safely assumed. The ratio of uranium to thorium in the ore needs to be established, as all the radionuclides from the uranium, actinium and thorium decay chains must be considered when calculating the inhalation dose. At Rössing Uranium, the thorium content of the ore is relatively low; the dose conversion coefficient for uranium bearing ore is calculated to be 3.6 µSv per Bq of alpha radiation counted [15].

While the radiological risk from the inhalation of general ore dust at Rössing is very low, additional occupational risks are presented by the contents of silica in the dust. The most effective controls for reducing dust are presented by engineered controls, including enclosures of dust prone areas such as stockpiles (Figure 8), and road stabilization. Additionally, wetting of crushing and conveying processes (Figure 9) helps to reduce the emission of dust at source.

Where engineered and administrative controls are not adequate, personal protective equipment (PPE) in the form of respiratory protection is used as a last resort. For this to be effective, dust masks must be replaced regularly, fit testing must establish the suitability of the type of dust masks issued, and a clean-shaven policy for all workers in the relevant areas must be enforced.
For areas where yellowcake dust and uranium oxide dust occur, precautions must be stricter as the inhalation risks can be significant. Due to the slow lung absorption properties, low solubility uranium oxide can remain in the lung for extended periods once inhaled. It is therefore essential to have effective engineered controls ensuring a separation of workers from dust generating areas as much as possible. Automation of drum filling and packing processes can reduce the exposure of workers to very low levels if implemented effectively.

Uranium oxide has a lung absorption type of S (slow), which results in long retention times of uranium in the lung. The corresponding dose conversion coefficient corresponding to a mean aerodynamic diameter of uranium dust particles of 5 microns is 6.2 µSv per Bq of alpha radiation counted [15]. Yellowcake is classified as lung absorption type M (medium). The higher solubility leads to lower retention times in the lung and consequently a lower dust conversion coefficient of 1.8 µSv per Bq of alpha radiation.

For additional control, an effective respiratory protection program is needed. This can be full face respirators paired with regular respirator cleaning and maintenance services, fit testing and clean-shaven policy, or the use of positive pressure or air supplied respiratory protection.

A summary of typical uranium dust concentrations, potential maximum occupational dose and average dose calculated from measured dust concentrations when utilizing controls, is provided in Table 3.
### Table 3: Potential maximum radon concentrations, associated annual dose and average dose measured when utilising controls, at Rössing Uranium

<table>
<thead>
<tr>
<th>Process</th>
<th>Typical LLRD dose rate, μSv/h</th>
<th>Maximum potential annual dose, mSv/a</th>
<th>Annual occupational dose observed, average, mSv/a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offices, labs (ore)</td>
<td>up to 0.1</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Tailings (tailings)</td>
<td>up to 1</td>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>Open pit (ore)</td>
<td>up to 0.3</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Extraction (ore)</td>
<td>up to 0.6</td>
<td>1.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Crushing plant (ore)</td>
<td>up to 5</td>
<td>10</td>
<td>0.3</td>
</tr>
<tr>
<td>Recovery (uranium oxide)</td>
<td>up to 50</td>
<td>100</td>
<td>1</td>
</tr>
</tbody>
</table>

#### 3.4 Internal exposures, controls and potential doses – uranium ingestion

The potential for ingesting uranium yellowcake or uranium oxide is limited to those areas of the processing plant which should be access restricted radiation-controlled areas.

Accidental ingestion is best controlled by providing adequate hygiene facilities, physically separating work areas from kitchens and meeting rooms, retaining all working clothes in contaminated areas for washing, and providing contamination checks at exit points.

A common check for internal contamination with uranium (either through inhalation or through ingestion) is provided by urine bioassays analysing for uranium content of the urine. Although this method provides some ease of mind, it is not possible to accurately assess the dose resulting from ingestion from urine sampling results, as it is important to know the pathway and the exact time of ingestion before sampling took place. Urine bioassays are therefore not a control or dose assessment tool, but merely serve as an additional check to confirm the absence of internal contamination.

#### 4. RADIATION EXPOSURE CONTROLS

##### 4.1 Equipment contamination

The presence of radioactive materials in uranium processing plants can lead to contamination of equipment. In order to prevent equipment or materials contaminated with radioactive materials from leaving the mine site, a comprehensive clearance protocol is required, which is stringently applied. A breakdown in compliance with this requirement can easily lead to members of the public suffering exposures far exceeding the public dose limit of 1 mSv/a. In particular, scrap metal can only be recycled if proven to be free of contamination. If such materials are discarded on the mine site, for example by burying in the tailings storage facility, then care must be taken that recovery of these items by members of the public is not viable, even after closure of the mine has occurred.
4.2 Awareness

Because of the negative connotations of atomic energy with nuclear war, communication about radiation risk must focus on much more than explaining the numbers behind monitoring programs [3]. Appropriate awareness programs therefore form the core of any radiation safety program at uranium mines. The foundation of any effective awareness program is a thorough appreciation of risk perceptions of people, designing communication that is consistent with respecting fears, using plain language and openly presenting the risks and what is done about their mitigation. Awareness sessions about radiation risk must always be presented by experts suitably trained in communication skills.

4.3 Incident preparedness

Incidents involving spills of uranium oxide in transit, or spills of effluents from the processing plant, have the potential to expose both workers and members of the public to radiation. Possible scenarios must therefore be risk assessed appropriately, and regular drills be performed to practices preparedness for these events (Figure 11).

![Figure 11: Uranium spill drill, Rössing Uranium, 2015](image)

5. Radiation exposure pathways for members of the public

Members of the public may be exposed to radiation from the inhalation of radon emitted from exposed radon sources at the mine, from the inhalation of radioactive dust emitted through mining activities, or through the ingestion of food or water directly or indirectly contaminated through mining activities.

The dose limit for public exposure resulting from mining activities is 1 mSv per year on average. This dose limit does not include background sources, be they natural (from the environment) or man-made (such as medical procedures or the use of consumables containing radioactive materials). The natural background radiation in the Erongo Region is approximately 1.8 mSv/a, while the dose to critical groups in the public from mining activities is generally very low to negligible. It is therefore not possible
to measure the public dose directly – it must be calculated from first principles, after determining the factors potentially contributing to it.

This principle is illustrated in Figure 12: For each potential public exposure pathway, the critical group (i.e. the group that may potentially receive the largest possible public dose from this pathway) is determined. The resulting maximum (‘worst case scenario’) dose is then calculated for this pathway and critical group. The procedure is repeated for each pathway and critical group.

For some pathways, such as the inhalation of dust and radon progeny, the critical groups may be identical and hence the public dose for these pathways must be added to yield the total public dose for this critical group.

Regular public dose assessments include those performed for impact assessments [1], closure planning [8], [9], and annual performance reporting to the National Radiation Protection Authority [10], and show that the public doses to all critical groups remain well below the public dose limit.

Figure 12: Schematic summary of pathways and critical groups contributing to potential public exposure doses

5.1 Water quality

Seepage from processing streams or from tailings disposal may lead to groundwater contamination. Members of the public using contaminated groundwater for drinking, crop irrigation or as a source of water for animals may therefore be exposed to radiation from ingested radionuclides.

Seepage can be controlled by lining tailings disposal areas. At Rössing Uranium, seepage is recovered through a series of seepage recovery boreholes situated downstream of the tailings facility.
Groundwater contamination is controlled by using a system of trenches intercepting the natural flow of water towards the Khan River aquifer, and regular groundwater monitoring confirms the effectiveness of this program.

5.2 Air quality – dust

Dust emitted from the Rössing mine is suppressed as much as possible at source, through the utilization of engineered controls. A series of dust monitoring stations provides continuous feedback on the effectiveness of dust controls at public receptor locations.

5.3 Air quality – radon

The emission of radon from uranium mine sites is a risk if communities live close to the mine, or after closure when the community settles in areas on or close to tailings or waste rock dumps. At Rössing Uranium, the closest critical group at Arandis is not exposed to additional radon from the mine. However, after closure the site will require remediation activities to reduce radon levels to those consistent with background levels.

6. CONCLUSION

Uranium mining results in a series of radiation risks, both internal and external, to workers and to the public, that can be significant if they are not effectively controlled. When utilising a regime of layered controls, both public and occupational exposures can be kept well below the legal limits, and are sufficiently low to be of minor concern, noting ore grades are low and that mining takes place in an open pit environment, as is common practice in Namibia.

7. REFERENCES