ASSESSMENTS OF BOUNDARY CONDITIONS AND REQUIREMENTS FOR RARE EARTH UNDERGROUND MINING DUE TO PRESENCE OF NORMS

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Abstract

Rare earths contain NORMs, such as uranium, thorium and their progeny, like radium and radon. The varying concentrations of NORMs are quite often significant enough to result in occupational and environmental radiation exposures during the mining, milling and processing procedures of rare earths and compounds. Ventilation is the primary technique of controlling ambient concentrations of radon. Fresh air volume flow rates, the distribution of airflow within the mine and the radon emanation rate are primary factors affecting such concentrations. In this paper, it is attempted to determine the factors that may result in radiation risks and evaluate the boundary conditions that will contribute to the restriction or even elimination of radon progeny, with a goal to use the evaluations in order to build an overall assessment tool.

Presence of NORMs in Rare Earth Elements

Rare Earth Elements (REEs) in economically exploitable concentrations are mostly found in minerals such as bastnaesite, monazite, xenotime, gadolinite, fergusonite, samarskite and allanite. All of these ore minerals contain low to significant levels of thorium and uranium series nuclides. They are thus typical examples of the Natural Occurring Radioactive Materials (NORMs). Rare earths themselves contain naturally radioactive isotopes as well, such as ^{138}La, ^{142}Ce, ^{144}Nd, ^{145}Nd, ^{147}Sm, ^{148}Sm, ^{149}Sm, ^{152}Gd, ^{156}Dy and ^{176}Lu. The uranium content within rare earth minerals varies from insignificant percentage to 0.8 wt. % while the thorium content varies from 0.1 to 10 wt. % depending on the mineral and occurrence. Bastnaesite (Ce, La)CO_3F contains 0.1–0.2 wt. % thorium (ThO_2) and negligible concentrations of uranium (U_3O_8). Monazite (Ce,La,Pr,Nd,Th,Y)PO_4 contains 0.2–0.4 wt. % U_3O_8 and 4.5–9.5 wt. % ThO_2. Xenotime Y(PO_4) contains almost equal percentages of uranium and thorium, 0.81 wt. % U_3O_8 and 0.83 wt. % ThO_2 respectively[1].

Radioactive Decay Chains of NORMs

NORMs decay with respect to time into many elements called 'daughters', a process associated with the release of radiation. The list of subsequent daughter products is known as the 'decay chain'. Radon is a product of the radioactive decay chain of primordial uranium or thorium (Fig. 1), specifically the isotopes ^{238}U, ^{235}U and ^{232}Th. The isotopes formed from

this decay are, ^{219}Rn ('actinon'), ^{220}Rn ('thoron') and ^{222}Rn ('radon'). Due to the low abundance of ^{235}U and the short half-lives of thoron (55.6 sec) and actinon (3.96 sec), most work concentrates on ^{222}Rn and its progeny.
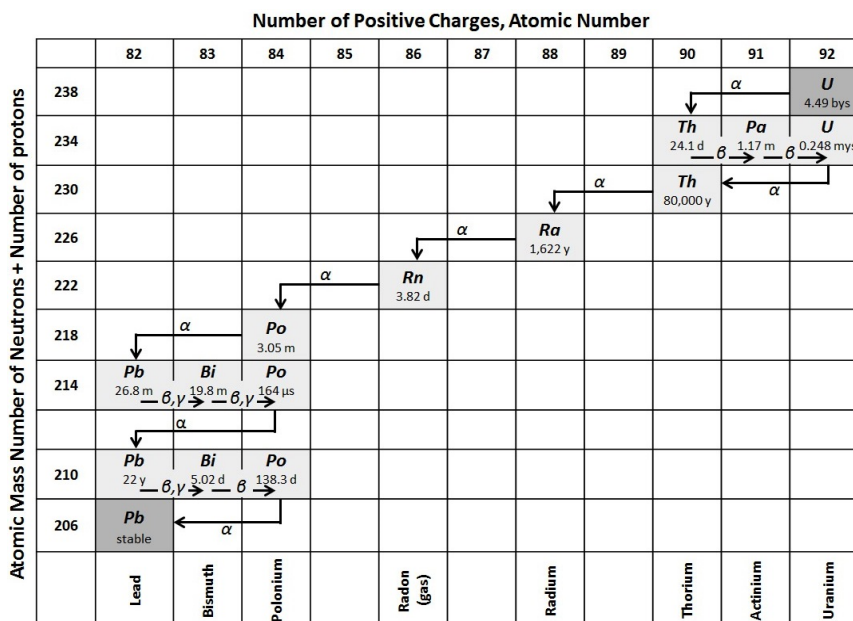

Figure 1: Uranium decay chain with the half-life of progeny (Source: SSVEE).

Radon is unique among the decay products because it is a gas, thus is capable of migrating from the source location into the atmosphere. It is colorless, odorless, tasteless and chemically inert with a half-life of 3.82 days. Radon undergoes 4 rapid decays, forming airborne progeny, starting with ^{218}Po ('polonium') which decays into ^{214}Pb ('lead'), which decays into ^{214}Bi ('bismuth') and finally into ^{214}Po ('polonium'). On entering the mine atmosphere and without sufficient ventilation, this decay chain leads to significant radioactivity (alpha, beta and gamma radiation) in the mine.

Occupational Exposure Limits and Impacts on Human Health

Radon concentration is measured in units of radioactivity rather than mass because the actual mass involved is too small[2]. Common units are; the Becquerel (Bq) for radioactivity and the Sievert (Sv) for the equivalent dose in the human body, while sometimes in mining the historic unit Working Level (WL) is also used. Occupational exposure limits were derived to protect the health of underground miners over a working lifetime. The recommendations issued by the International Commission on Radiological Protection (ICRP), are that no person shall be exposed to more than 14 mJh/m^3 (≈4 WLMs) annually. The effective dose is 20 mSv/year averaged over 5 consecutive years or 50 mSv allowed in any 1 year[3]. The lifetime limit is 400 mSv.

Occupational exposure of underground miners to radon has been related to severe health impacts decades ago, making it the second leading cause of lung cancer after cigarette smoking[4]. It was first identified as a cause of cancer in uranium miners in 1924[5]. But despite the fact that most studies are focused on its bearing risks, it is not the radon itself that is

actually responsible for the health problems, but rather the short lived radon daughters (SLRDs) and their decay products, as described above. The radon may be thought of merely a source for the SLRDs.

Factors Resulting in Radon Spreading in Underground Mining

Radon and progeny emanation can be attributed to their natural occurrence inside the rare earth element bearing minerals. However, the emission of radon from the undisturbed rock can be considered as insignificant compared to the amount of radon released after the rupture of the ore during mining, when the specific surface area of the rock increases. It's spreading in the mine atmosphere, combined with the failure to restrict and/or eliminate it, may be imputed to a series of factors.

It is of utmost importance to evaluate boundary conditions such as dust reduction, the residence time of the excavated ore in the mine sites, the possible bioleaching of the ore, the haulage system, the operation of crushing and grinding mills, as well as the use of tailings in potential backfill mining. Moreover, one of the most important factors responsible for radon concentration is the lack of sufficient air flow in the mine. Inadequate ventilation may result in the insufficiently slow removal of radon gas, thus giving it time to accumulate inside the mine atmosphere (Fig. 2). Another factor is the presence of groundwater in a REE mine. Radon partially dissolves in water and thus can be transported further away by groundwater flow. Water-borne radon will inevitably be outgassed into the air due to de-pressurization and constant agitation[6]. Much of the radon will also decay before it has the opportunity of release.

Assessments for Controlling Radon and Progeny Emanation

The evaluations for maintaining a safe working environment in rare earth mines are basically the same as in conventional mines; however, the occurrence of significant amounts of NORMs, that are the focus of the mining operation, imposes special boundary conditions in order to prevent them from having sufficient time to build up significant quantities of their progeny. These conditions can be established based on those applied to uranium mining operations. However, it needs to be stressed that, different to uranium ore deposits, REE deposits will have, in many cases, a Th rather than a U tenor.
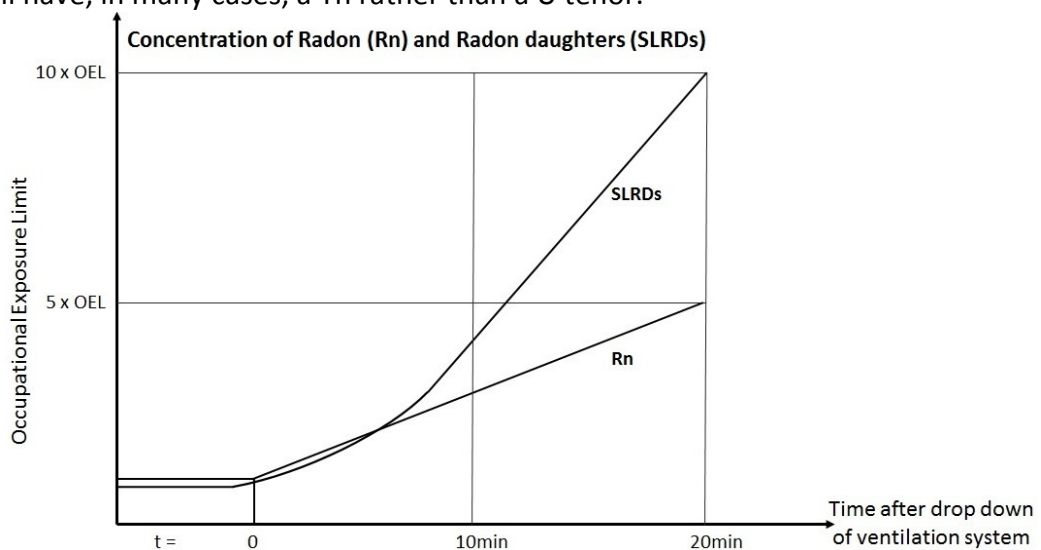
Figure 2: Ascending of radon and radon daughters' concentration versus time after drop down of ventilation (Reinhard Wesely, 1983).

Mine planning

Ore dust presents the dominant source of exposure to radon and progeny, thus a proper mining method selection can reduce the dust production. As in every case, there is no single appropriate mining method that will efficiently deal with all the radiation issues and risks. Excavation techniques, crushing and transportation as well as the long time residence of the broken ore in the mine should be the operations to evaluate so as to keep radon accumulation below the occupational safety standards.

Common excavation practices can be separated into mechanical excavation and use of explosives. With respect to dust production during mechanical excavation, several studies have been made, indicating that the deeper the cut and the larger the chips, the less dust is produced from the ore removed[7]. The sharpness of the cutting tools is also a factor, since worn bits without their carbide tips produce much more dust[8]. When it comes to drilling, dust can be controlled with dry collectors at the tip of the drill bit or with water injection through the drill steel. Foam injection can also be used when excessive water is a problem[9]. Blasting is done when no one is expected to enter the affected area. Consequently, blasting should take place at the end of the shift when all other operations are finished.

During dropping and transporting of the mined ore, dust can also be produced in significant amounts. Depending on the mining method, the broken ore may fall from several meters height to the ground or can travel long distances through conveyor belts, that can be of moderate cost but may be a significant source of dust, or mine railways that usually generate less dust. Enclosure, drenching and ventilation are the primary techniques to deal with these dust emission factors. In the case of wetting the ore on conveyor belts, the amount of water is an issue again for not leaving a sticky mud residue on the belts. Radon-bearing ore dust can be accumulated in areas where crushers and mill plants are installed. In REE mining it would be preferable not to have a crushing plant within the underground mine, yet if inevitable, strict dust control measures should be implemented.

Adequate wetting can be extremely important for dust control. The majority of the dust particles are not released to the air, but stay attached to the surface of the broken ore[10]. The presence of water, though, may be an additional problem and the ample drenching of the ore within the limits of necessity is crucial. Furthermore, remote operation of machinery or cabins in all vehicles for the machine operators, either during mining or mucking of the ore should be evaluated as a condition that reduces human exposure to radioactivity. Personal protection devices such as dust masks can be used. Job rotation is also recommended in high concentration areas.

Some mining methods raise more issues than others. Bioleaching is a cost effective method, but most of the excavated ore is left underground creating high radon levels that are difficult to control. Similarly in shrinkage stoping, the residence of the ore on site will result in radon and progeny accumulation. Among REE mines applying cut and fill methods, those using tailings as backfill are found to have higher radon levels than those using rocks or cement. Concrete can be used to reduce radiation from the exposed ore on the back or walls;

therefore it could also be used as part of the backfill mixture. In sublevel stoping the broken ore is falling from significant height, creating the "piston effect" that leads to generation of big amounts of ore dust. The sublevel caving method is well suited for a high degree of automation and remote operations with corresponding high productivity; however this method may result to high radon progeny concentration levels and should thus possibly be avoided.

Ventilation

The design of the overall ventilation system in a REE mine is based on the mining operation; on ventilation-air-transit time; on radon emissions from the wall-rock and broken ore, the haulage, the tailings backfill and the groundwater. The aim is to lower radon residence times to 10-15 minutes, in order to attain a limit of 10-20% of the theoretical yield of progeny in the atmosphere[11]. It is the total air volume flow rate through the mine that determines the time air takes to travel from the inlet to the production areas and to the outlet of the mine. The primary applications are main fan and multi-fan ventilation systems. Main ventilation can either be forced (blowing), exhaust (suction) or a combination of the two. Multi-fan ventilation uses forced, exhaust, main and auxiliary fans, and a parallel multiple fan operation technique based on energy saving and building partition ventilation[12].

With respect to radon confinement, forced ventilation is more effective, even mandatory in many cases and countries. In forced ventilation the positive pressure on the intake airway not only prohibits radon from being released from rocks but also blocks it from entering into airways that channel fresh air into working faces. The effectiveness of the method increases as the fracturing of the rock is growing. Nevertheless, air leakage due to positive pressure state can be a significant issue, even more if air doors are not well maintained. Infrastructure costs are relatively high, as an independent intake shaft has to be built, in addition to a return airshaft. On the contrary, in a state of negative pressure due to suction ventilation, where fresh air moves into the mine because the pressure is lower, the release of radon and progeny is speed up either because of the operations or the wall rock emission.

Development headings are areas of higher risk and their proper ventilation is critical. Auxiliary ventilation is to be used in such areas[11]. Continuous air change should be planned for headings. During production, flow-through ventilation must be employed to keep the working staff in clean fresh air. Moreover, a forcing ventilation system should be used to deliver fresh air to the faces. This air from production areas is, of course, not to be reused to ventilate other areas. The distribution of pressure is harder to manage when multiple operations are taking place at the same time at various levels. Ideally, a retreat system should be implemented with a minimum possible number of working faces ventilated in series, decreasing the effective surface in intake airways. If this is not possible, then each mining area could be designed as an independent ventilation block. A split system of ventilation should be employed, in which fresh intake air is distributed to working blocks with respect to relative needs. Air from each section is afterwards collected in an isolated return airway without contaminating other active mining areas. The number of personnel required to work or travel in return airways should be kept to a minimum.

Beyond production areas, ventilation assessments should be made for all rooms and facilities

in a rare earth underground mine. Primary airways should be kept free from mining activity, so that relatively high air velocities can be readily maintained. Air speed depends on local regulations. Mined-out areas should be kept on the return side of the ventilation system and be sealed whenever possible. Ramps are likely to be contaminated, for the airflow is not stable and is likely to change with the development of the mine. Conveyor ways, crushing facilities and ore passes in general should be ventilated so that exhaust air can be directed to the return air system quickly. Warehouses, repair shops and laboratories should be positively ventilated by controlled air volume flow rate. All unventilated areas in the mine must be sealed and marked, stating the hazard, to prohibit inadvertent entries. Moreover, to prevent radon flow from goaf areas or old drifts, hermetisation with sealing dams or concrete platforms in raise drifts should be evaluated. Last to consider is the maintenance of such a complicated system. Surveys and safety inspections are used to verify if the ventilation system is in compliance and if it meets all defined objectives. Determination of airflow and the proof that the minimum limits are kept; evidence that air velocity is within the minimum and maximum limits; proof that the climate limits are met, are evaluations of primary importance. Any deficiencies found during an inspection should be acted upon promptly.

Monitoring

The principal objectives of monitoring are to evaluate occupational exposures with respect to the accepted standards and limitations and to provide data for adequate control. This can be done by collecting samples in short time periods, primarily in the working faces, where human exposure is more frequent. Thereby, there will be better detection and evaluation of the principal sources of exposure, assessment of the effectiveness of the control equipment, detection of anomalies in the mining operation and prediction of the effect of future operations on contamination levels.

Personal protection measures

Thorough personal hygiene should be required of all personnel and personal cleanliness should be mandatory at the end of each work shift. Resting and changing rooms should be isolated from working areas, and provided with convenient access to washing facilities. Personal protective equipment such as respirators, dust masks or air helmets should be used in areas where airborne dust is high or in exceptional circumstances when the ventilation has dropped down or during a maintenance task for which adequate ventilation is not available. Gloves should be worn for any direct contact with concentrates. Dosimeters should also be carried from all personnel.

Groundwater assessments

Confining water from coming in contact with airborne radon can be accomplished by using pipes for sealing or by applying grout covers ahead of development[11] to divert water flow from the dust production areas. Furthermore, sufficient mine drainage can prevent the creation of stagnant pools of water contaminated with radon.

Conclusions

The presence of NORMs, especially of radon, is a paramount safety and health issue for the

underground mining industry. This poses challenges for ventilation engineers to minimize the radiation contamination of the air and thus the human exposure. The most efficient methods to achieve control are; mechanical dilution ventilation, confinement or suspension of radiation source, dust reduction and control as well as personal protection measures. The improvements made so far have reduced radon concentration in underground mines, however, the work to further improve the evaluations continues. In an ideal underground rare earth mine radon accumulation is prevented and radiation concentration is kept to very low levels with respect to safety and cost efficiency. For this reason, a thorough investigation was made in this paper to evaluate the primary boundary conditions and requirements. What can be done further on is to use these evaluations in order to build an overall assessment tool, to adjust and apply special techniques in mining of radon-emitting deposits.

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