RADIATION PROTECTION CHALLENGES IN A HIGH-GRADE URANIUM MINE

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ABSTRACT

The McArthur River Project in northern Saskatchewan is the largest, highest-grade uranium ore body yet discovered. Current reserves at McArthur River are estimated at 416,000,000 lb U_3O_8 (160,000 t U) at an average grade of 13% U. The high grade of the ore, combined with some characteristics of the structure within which it is found, presents some unusual and challenging radiation protection problems. As in any underground uranium mine, breaking the rock releases trapped radon into the mine air, increasing the radon progeny concentrations. The porous sandstone also allows rapid drainage of water into mine openings. Water that has been in contact with the ore carries high concentrations of radon-222, which is readily released into the mine air, creating very high concentrations of radon progeny, which must be controlled. Ore dust has not generally been a major source of radiation exposure in lower grade uranium mines, but the high specific activity of this ore makes it a significant problem. Finally, the direct gamma radiation from the ore makes handling even drill core an activity to be approached with caution. To complicate the work, Canada was in the process of incorporating the recommendations of ICRP Publication 60 into both the national and provincial regulations for radiation protection at the time this project was being assessed. The methods for dealing with these problems are discussed in some detail.

INTRODUCTION

The McArthur River project is the world's largest known high-grade uranium deposit, with reserves and resources of 416 million pounds of U_3O_8 (160,000 t U) at an average grade of 13% U. Cameco Corporation is the operator of the project on behalf of the joint venture, which is owned by Cameco (55.844%), Uranerz Exploration and Mining Limited (27.922%), and Cogema Resources Inc. (16.234%). The deposit is between 500 and 600 m underground in the eastern part of the Athabasca Basin in northern Saskatchewan, Canada, 80 km northeast of Key Lake and approximately 620 km north of Saskatoon. It is presently being developed to allow the start of production in late 1999, with full production planned at 18 million pounds of U_3O_8 (6,924 t U) per year. Because the Key Lake high-grade ore will be exhausted by the end of 1999, McArthur River ore will be transported by road to Key Lake mill for processing. Since the uranium grades at McArthur River are roughly ten times those at Key Lake and Rabbit Lake and a hundred times the average grades elsewhere in the world, non-entry mining and remote ore-handling techniques will be used.

HISTORY

In 1988, the ore body was discovered following eight years of systematic exploration in the area. Improved electromagnetic methods allowed the identification of a graphitic conductor in the basement fault structure that controls the location of the ore. Several years of core drilling from surface resulted in the outlining of high-grade mineralization over 1.7 km of strike length. By 1991, sixty holes were completed, of which thirty-seven holes intersected uranium mineralization at a depth of 500 to 600 metres. Based on this information, a resource of 260 million pounds U_3O_8 (100,000 t U) at an average grade of 4.2% U was estimated. However, the mineralized zone was very narrow and seventy per cent of the estimated resource was based on only seven drill holes, with eighteen per cent based on a single hole, which graded 36% U over 25 metres. Consequently, in 1992 it was decided to undertake an underground exploration programme to provide detailed information about the shape of the individual ore bodies.

The Atomic Energy Control Board (AECB) had been notified of the intention to develop the project in February, 1991. The AECB referred the project to the Federal Environmental Assessment Review Office (FEARO), which initiated the environmental assessment process. FEARO and the government of Saskatchewan appointed the Joint Federal-Provincial Panel on Uranium Mining Developments in Northern Saskatchewan to look at McArthur River and four other uranium projects.

Although underground exploration did not require a full environmental assessment under any federal or provincial regulations, the Panel felt that allowing the underground exploration to proceed without a detailed examination would harm the credibility of the main hearings. Consequently, the underground exploration was referred to the Panel for review in 1992 and approved in early 1993 (Joint Federal-Provincial Panel, 1993). A shaft was sunk in late 1993 and early 1994, with underground development on one of the two approved levels. The underground drilling over the first 300 m of strike length identified a significant new ore zone, which increased the reserves and resources to the current 416 million pounds U_3O_8 (160,000 t U). During the drilling programme, work proceeded on the environmental studies, and the environmental impact statement (EIS) for the main project was issued in December, 1995 (Wittrup, 1995). Hearings proceeded in 1996, with approval of the project being recommended by the Panel in February, 1997 (Joint Federal-Provincial Panel, 1997). Construction licences were obtained in August , 1997, and construction of the production facility is proceeding.

THE PROBLEMS

From the results of the surface drilling programme, it was apparent that high-grade ore would be encountered and that conventional mining methods would not give adequate control of radiation exposures. Exploration drill core that showed average grades of 20% to 30% U had sections of almost pure U_3O_8. Gamma radiation from such material arises from some of the uranium chain radioisotopes, notably ^{214}Bi with energies over 2 MeV, and radiation fields of 3.5×10^{-5} C/kg (equivalent to 1.2 mGy/h) could be expected. Conventional mining has workers within the stope and directly exposed to ore. Such an approach would clearly have led to overexposures in a short time. Hence, mining methods had to be devised that would not involve entry into the stope and that would not involve manual handling of ore or direct exposure to open loads of ore in haulage equipment.

Radon progeny generally represent the most significant airborne radiation hazard in uranium mines, and ventilation is commonly used for control. At McArthur River, the high grade of the ore results in a ^{222}Rn source that is far higher than that encountered in previous mines. In addition, the McArthur River ore occurs at the contact between the Athabasca sandstone and the underlying basement rock of the Canadian Shield. The sandstone is porous and large water flows continue to be experienced during mine development. This water has been in contact with the high-grade ore and contains dissolved radon concentrations up to 1.8×10^{10} Bq/m^3. When this water splashes into a mine opening, it releases the radon in unprecedented concentrations. At these concentrations (up to 70,000 Bq/m^3 predicted in the downwind sections of some drifts with full ventilation), the uptake of radon itself becomes a significant source of radiation exposure. Hence, much higher air volumes would be needed than for similar-sized mines that are not handling radioactive materials. At the present time there is one shaft at McArthur River, with a second one being sunk and a third planned. At full development, Shafts 1 and 2 will supply fresh air and Shaft 3 will be the main ventilation exhaust. In the northern location with its harsh climate, mine ventilation is particularly expensive, because mine air must be heated for much of the year.

Experience from the underground exploration showed that local exhaust ventilation would also be essential to control exposures. Drill holes and water flowing from them could be significant point sources of radon, which if not controlled would cause very high exposures of workers in the vicinity.

Ore dust has not generally been a major source of radiation exposure in lower-grade uranium mines. Usually, other factors have dictated ventilation rates. For example, where diesel equipment is used, the ventilation requirements of the diesel exhaust have been stricter than the requirements due to airborne radioactivity. The assessment of the Eagle Point underground mine, operated by Cameco at Rabbit Lake, showed that the silica content of the ore would limit the dust exposure until the ore grade exceeded 4.8% U_3O_8 (4.1% U) (Cameco, 1992). At McArthur River with its 13% U average ore grade, the high specific activity of the ore clearly changed this situation.

BASIC MINE DESIGN

At the time that the preliminary mine design was being developed, new radiation protection regulations were being drafted in Canada. Although we were not permitted to see the draft before it was formally released, we knew that the new regulations would incorporate the general philosophy of ICRP Publication 60 (ICRP, 1991). This meant that Canada would change from the old critical organ concept, with separate limits for external whole body dose, lung dose and radon progeny, to the effective dose concept, with a 60% lower five-year average dose limit.

From the outset of mine design, it was clear that non-entry mining methods would be required. Strict adherence to the principles of limiting the time of exposure, maximizing the distance between the workers and the ore, and placing shielding between the workers and the ore was necessary in order to limit worker gamma radiation exposures. Mining methods were screened for radiation protection, general safety, flexibility, productivity and maximum use of conventional equipment. Seven potential mining methods were proposed in the EIS submitted for McArthur River, with final selection dependent upon ore grades and ground conditions. These methods were:

1) Raise boring
2) Box-hole boring
3) Remote box-hole stoping
4) Blast-hole stoping, including vertical crater retreat
5) Remote raise-bore stoping
6) Jet boring
7) Remote box-hole stoping with “Viscaria” raise mining

Three of these, raise boring, box-hole boring and remote box-hole stoping, were recommended in the EIS, with raise boring being the choice for the first zone to be mined. The jet-boring method favoured for Cigar Lake was not recommended because of the harder rock at McArthur River; however, it has been retained as a potential secondary method.

Ground and Water Control

Experience from the sinking of Number 1 Shaft and from the underground exploration programme has shown that high water flows and occasional poor ground conditions may be expected. The Athabasca sandstone is very porous and water at full hydrostatic pressure occurs in many places. At 600 m below the surface, the water pressure can be 60 atmospheres. Freezing will be used to stabilise the ground to permit safe extraction of the ore. Both grouting and freezing will be used to control water; however, freezing has the added benefit of stopping the flow of radon-laden water into mine openings, greatly reducing the radon source.

Freezing will be accomplished by circulating chilled brine at -30° C through freeze pipes surrounding the ore zones. Since it must be implemented approximately nine months prior to mining, the 85 holes needed for the freezing of the first two mining areas will be drilled during 1998 to allow the freezing to start in early 1999.

Raise-bore Mining

Raise-bore mining (See Figure 1) requires the establishment of mine openings in non-radioactive waste rock above and below the ore zone. The raise-bore machine is set up in the production chamber above the ore zone. The machine drills a 300 mm pilot hole from the upper chamber, through the ore zone into the lower extraction chamber. The drill bit is replaced with a 2.4 m diameter reaming head, which then reams upward through the ore. The reamed ore is funnelled downward through a sizing screen to the semi-autogenous mill in underground ore-grinding area. The raise-boring machine is removed and the raise filled with concrete. After the concrete fill has cured, adjacent ore will be extracted by repeating the sequence. By overlapping the raises, a high percentage extraction of the ore zone is achieved.

McARTHUR RIVER PROJECT
RAISE BORE MINING AND BACKFILLING SEQUENCE

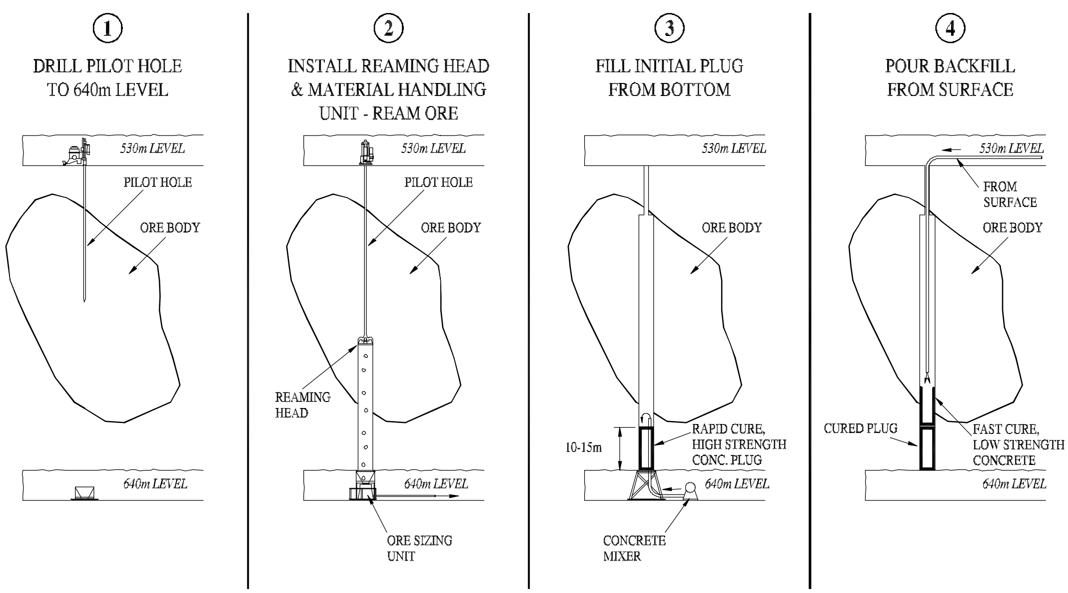

FIGURE: 1

The raise-boring method will produce, on average, from each raise approximately 190,000 pounds of U_3O_8 (73 t U) from within the initial mining areas of the zone providing most of the production planned during the first years of mining. Due to the high grade of the ore, an average of only 125 t must be mined per day. The total time necessary to mine and fill a raise is currently expected to be about 15 days, of which only three days will likely be spent reaming ore. Four raise-bore machines are planned for full production.

Box-hole Boring

The box-hole boring machine is set up in barren waste rock below the ore body and pushes the reamer upwards through the ore. The ore falls down the raise to a chute above the box-hole machine and is diverted to the sizing screen and grinding area. All further ore processing is as described for the raise-boring method.

Remote Box-hole Stoping

This mining method combines the productivity improvements offered by stoping with the control and containment provided by box-hole boring. The raise is reamed as described in the box-hole boring method. Blast holes are then drilled from drill drifts in waste rock lateral to the raise and above the mining chamber. These blast holes intersect the raise, and are loaded with explosive and blasted, as required, to provide broken ore to the box-hole boring unit. The reamer head is kept within the lower section of the raise. It reduces the size of the broken ore falling from the stope and regulates the ore flow to the sizing screen below.

Ore Transport

At Eagle Point, with an average grade of about 1.3% U and some small zones ranging over 5% U, non-entry mining has been employed. Ore haulage has been by conventional truck, with loading being done by remote-controlled scoop-tram, with the operator remaining within sight of the equipment. However, it became apparent that even at these grades ore spillage from the trucks on the access ramp resulted in unacceptable levels of contamination and created an additional source of radon to contaminate the mine air. The higher grades at McArthur River would only exacerbate these problems. The solution was to develop an ore-transport system that did not involve direct exposure of the miners and would keep the ore generally enclosed. The ore from the underground grinding circuit will be pumped to surface in a slurry pipeline using positive displacement pumps, eliminating the need to hoist the high-grade ore in the shaft used to move men and material and to supply fresh air. On surface, the ore slurry will be blended by grade, thickened to 50% solids and placed in purpose-built containers. The containers will be shipped, four to a truck, to Key Lake, carrying 18 t of ore (21.2 m^3 of slurry) per trip. Approximately eight trips per day will be required.

Ore Processing

After examining various options for processing the high-grade ore, it was decided to blend it with low-grade mineralized material at Key Lake to produce a feed grade into the mill of 4%. Material of this grade can be handled in the existing equipment without added shielding. This option has the benefit of recovering uranium from the low-grade material, which otherwise would have become a decommissioning liability.

EXPOSURE MODELLING

For the EIS, 60 separate jobs were identified and time and motion studies were assembled for each job. Mine ventilation was modelled with the MINEVENT software developed by SENES Consultants (SENES, 1995a), using the conceptual mine design and placing an upper limit on radon progeny exposure of 1 working level month (WLM) *versus* the current Canadian standard of 4 WLM. Potential gamma radiation exposures were modelled using the GRADEX software developed by SENES Consultants (SENES, 1995b). Consideration was given to breakdown maintenance requirements and spill clean-ups, as well as normal operations. The highest effective dose (6 mSv) was predicted for the raise-boring operator.

To refine the equipment design, the software MicroShield v5.01 (Grove, 1996) has been used to calculate shielding requirements. Shielding has been designed for tanks, for separate rooms and for piping. To test the theory, field tests were done using ore at 30% U_3O_8 from the test mining of Cigar Lake. Six-metre long pipes of various standard wall thicknesses (defined by pipe Schedule) were filled with the high-grade ore and radiation fields were measured. This information essentially confirmed the calculations done with MicroShield. From this work, the decision was to use Schedule 160 pipes, which are the thickest-walled pipes commercially available without a special production run. In the two primary pipe sizes specified in the design, the Schedule 160 wall thicknesses are 0.531 in. (13.3 mm) for 4-inch and 0.719 in. (18.2 mm) for 6-inch pipe. Design calculations were also confirmed by physical measurements of radiation fields around equipment at the existing Key Lake and Rabbit Lake mills. Tank shielding was based on an average operator distance from equipment of 2 m and an objective of keeping doses below 5 mSv per year with generously estimated occupancy times.

For ventilation design, the minimum air supply was that required for diesel engine operation, 3.8 m^3/min/kW of engine power. For radon progeny control a nominal supply rate of 15 m^3/s was developed. Modelling of radon progeny concentrations was done using the software MINEVENT. Refined operator doses have been calculated as the equipment designs have been specified in greater detail. Currently, the highest exposed worker is predicted to receive an annual effective dose of 7.0 mSv.

ALARA CONSIDERATIONS

The dose calculations have shown that all personnel will meet the ICRP Publication 60 dose limit recommendations. To assess the efficacy of the design, an ALARA analysis has been performed on general underground ventilation, the ventilation of the surface slurry handling facility, concrete shielding specified for various pieces of equipment, and pipe shielding. The analysis used as the base case the doses calculated for the Addendum to the McArthur River EIS (Wittrup, 1996). Dose reductions for various design modifications were calculated conservatively, i.e., overestimating the dose reduction to be achieved. The costs of these modifications were realistically estimated and the costs per unit dose reduction were calculated. These costs of dose reduction were then compared with the upper-end justifiable cost criterion of \$100,000[1] per person-sievert (p-Sv) given in AECB Regulatory Guide G-129 (AECB, 1997). In the course of this analysis some low-dose jobs, which had been omitted from the EIS for brevity, were included, so that the collective dose was as complete as possible.

In assessing the effects of ventilation changes, it was assumed that radon gas would contribute the same dose as radon progeny, and ore dust inhalation dose was included. The conversion factor from radon progeny exposure to effective dose was 5 mSv/WLM, as recommended in ICRP Publication 65 (ICRP, 1993). Ventilation costs arise from the capital costs of mine openings and mine fans and the operating costs of electricity to run the fans and fuel to heat the mine supply air in winter. There is some flexibility in fan operation, but as air volume is increased, the limit on any particular size of motor is reached. There is also a limit on the amount of air that can be pushed through a given size of mine opening. When that limit is reached, more power to the fan does not move more air; the fan blades merely start to stall aerodynamically. At this point the only option is to increase the size of the mine opening, which is an enormous capital cost. In this exercise, an estimate was made of the additional air that could be moved by the design fans without additional capital cost. The electricity and heating cost of this additional air was calculated to be \$5,900 per year per m^3/s. The effect of the additional air on air changes in the mining and ore-handling drifts was calculated using the tunnel formula for radon progeny calculation, i.e. $WL \propto t^{1.86}$, where t is the residence time of the air (Schroeder and Evans, 1969). The effects on radon gas and dust concentrations were simply the linear reduction in concentration due to additional dilution. The resulting

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[1]All costs are given in Canadian dollars.

cost per unit dose avoided by the additional ventilation was $4.5 million /p-Sv, far in excess of anything that could be justified by the Regulatory Guide.

A similar calculation for the surface ore-handling facility resulted in a cost per unit dose avoided of $3.0 million/p-Sv, again far exceeding the criterion.

A design thickness of 30 cm of concrete shielding is being used for the various tanks used for handling the ore slurry. The cost of an increment of 5 cm in concrete thickness was estimated. Because of the varying tank geometries, an individual concrete volume and cost had to be calculated for each tank. In addition, the tank location was important, because it costs more to transport and place concrete underground than it does on surface. MicroShield was used to calculate the reduction in gamma radiation field achieved by the additional shielding. The result showed an average reduction in dose rate at 2 m of 1 μSv/h, but the average reduction over the entire work area would have been less than this. The collective dose to the entire workforce over a 20-year operating life was calculated. The resultant cost of dose reduction was $365,000/p-Sv, again well above the criterion.

Since Schedule 160 is the thickest-walled pipe commercially available, there are only two options for increasing the shielding on pipes: add external shielding by wrapping with lead sheet or placing the pipes in a concrete utilidor, or buy thicker pipe by special order. The former option was deemed not to be useful, because any maintenance would require greater time in close proximity to the pipe as the shielding is removed and replaced, resulting in higher doses to the maintenance staff who are generally the most exposed anyway. In the pipe sizes being used for the ore slurry, the next thickness of pipe is Schedule XXS. The reduction in gamma fields around the pipes with this wall thickness was calculated and the collective dose to all personnel over 20 years of operation was calculated. The additional cost of this pipe resulted in a cost per unit dose avoided of $1.7 million/p-Sv, again far exceeding the criterion.

Although it would be possible to meet the dose limits using less protection than has been specified in the mine design, it is considered prudent to have some capacity to accommodate upset conditions that may not have been considered in the basic design analysis. This is particularly true of mine ventilation. For concrete shielding, the thickness specified is a standard size for which forming materials are readily available. The cost of fabricating and placing shielding below the standard size could well exceed the savings in concrete cost and result in a net negative benefit in the ALARA analysis. Similarly, the savings in reducing the pipe wall thickness by one Schedule could only be marginally justified in the ALARA analysis.

CONCLUSIONS

McArthur River is the largest, highest-grade uranium deposit yet discovered. In developing the mine design, radiation protection has been paramount. Wherever possible standard sizes of equipment have been used in the mine design to avoid the extra costs of items that are not routinely manufactured. The dose predictions that have been done for all jobs in the operation, including upset conditions, maintenance, and spill clean-up, indicate that all employees will be well below the recommended dose limits of ICRP Publication 60. The ALARA analysis has demonstrated that additional measures to further reduce dose are not justified on a cost -benefit basis, because all results far exceed the $100,000/p-Sv criterion of AECB Regulatory Guide G-129. Nevertheless, when the mine goes into operation, radiation doses associated with the various activities will be carefully monitored to look for additional opportunities to reduce doses to personnel.

REFERENCES

Atomic Energy Control Board. Guidelines on How to Meet the Requirement to Keep All Exposures As Low As Reasonably Achievable. Regulatory Guide G-129 (E). AECB, Ottawa, September 26, 1997.

Cameco Corporation. “Environmental Impact Statement, Collins Bay A-zone, D-zone and Eagle Point Development, Revised 1992.” Cameco Corporation, June, 1992.

Grove Engineering. “MicroShield Version 5 User’s Manual”. December, 1996.

International Commission on Radiological Protection 1991. *1990 Recommendations of the international Commission on Radiological Protection*. ICRP Publication 60, Annals of the ICRP, Volume 21, No. 1-3. Pergamon Press, Oxford.

International Commission on Radiological Protection 1993. *Protection Against Radon-222 at Home and at Work*. ICRP Publication 65, Annals of the ICRP, Volume 23, No. 2. Pergamon Press, Oxford.

Joint Federal-Provincial Panel on Uranium Mining Developments in Northern Saskatchewan. *McArthur River Underground Exploration Program*. Federal Environmental Assessment Review Office, January, 1993.

Joint Federal-Provincial Panel on Uranium Mining Developments in Northern Saskatchewan. *McArthur River Uranium Mine Project*. Canadian Environmental Assessment Agency, February, 1997.

Schroeder, G.L. and R.D. Evans. “Some Basic Concepts in Uranium Mine Ventilation”. *Transactions SME/AIME*. Vol. 244, 1969.

SENES Consultants Ltd 1995a. “Appendix D.1, MINEVENT Model Description”, *Workplace Radiation Health Risk Study*. Prepared for Cameco Corporation, McArthur River Environmental Impact Statement, October 1995.

SENES Consultants Ltd 1995b. “Appendix D.3, Design for Radiation Protection in the Mining of High Grade Uranium Ore (GRADEX)”, *Workplace Radiation Health Risk Study*. Prepared for Cameco Corporation, McArthur River Environmental Impact Statement, October, 1995.

Wittrup, M.B. “Environmental Impact Statement, McArthur River Project.” Cameco Corporation, October, 1995.

Wittrup, M.B. “Addendum, Environmental Impact Statement, McArthur River Project.” Cameco Corporation, June, 1996.

KEY WORDS

Uranium, mining, McArthur River Project, radiation protection, ALARA.