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## **Cigar Lake's Jet Boring Mining Method**

Barry W Schmitke

### **Abstract**

Cameco Corporation, on behalf of a joint venture, is preparing surface and underground facilities at their northern Saskatchewan property in preparation for the future operation of a high grade uranium mine.

The Cigar Lake orebody is situated about 430 metres below surface at the unconformity between metamorphic basement rocks and flat lying sandstone. Major technical factors influencing the mining method selection include ground stability, control of ground water, radiation exposure and ore handling and storage. A decade-long test mine program resulted in the selection and validation of "jet boring", a non-entry mining method.

Cigar Lake's jet boring mining method involves several major steps: artificial ground freezing of the orebody and surrounding rock; TBM (tunnel boring) type development of access crosscuts below the orebody; installation of cased pilot holes upwards through the ore; and ore extraction using a rotating high pressure water jet within the pilot holes. The resulting cavities are surveyed and backfilled with concrete. The ore slurry will be processed underground and pumped to surface.

This Paper discusses the jet boring mining method in general terms and includes highlights of the Cigar Lake test mine program completed in 2000.

### **Introduction**

The Cigar Lake deposit occurs in northern Saskatchewan, 660km north of Saskatoon (*Figure 1*) and is jointly owned by Cameco Corporation, Cogema Resources Inc., Idemitsu Uranium Exploration Canada Ltd., and Tepco Electric Power Corporation.

The deposit is of the unconformity type, similar geologically to the Key Lake, McArthur River, and Collins Bay B-Zone deposits. It occurs about 430m below

surface at the unconformity contact between the overlying Athabasca Group sandstones and the metamorphic basement rocks of the Pre-cambrian shield.

The deposit is from 20m to 100m wide and about 2150m long. It is crescent-shaped in cross-section and averages about 6m thick, with a maximum thickness of 15m.

The Cigar Lake deposit is one of the two highest grade known uranium orebodies in the world. The higher grade Phase 1 eastern area contains mine recoverable proven reserves of about 226 million lbs  $U_3O_8$  at a grade of 20.7%  $U_3O_8$ . The lower grade Phase 2 western area contains recoverable resources estimated to be 118 million lbs  $U_3O_8$  at a grade of 16.9%.

### **Geotechnical characteristics of the deposit**

The pertinent geotechnical aspects of the deposit are shown schematically in *Figure 2*.

The eastern area of the deposit consists of a massive high-grade core of mineralization surrounded by a narrow lower grade envelope and concentric zones of hydrothermal alteration of the original rocks.

The massive high-grade core is formed by metal oxides, arsenides and sulphides in a matrix of generally well indurated greenish clay, or claystone. Metals include uranium, nickel, cobalt, iron, lead, zinc, molybdenum.

The high-grade core is capped by a layer of similarly indurated clay but with only low values of U mineralization. This clay cap is variably 1-5m thick and hematitic red colour.

This cap is succeeded upwards by a highly heterogeneous, highly permeable zone from 20m to 50m thick consisting variably of soft to moderately indurated sandy clay, unconsolidated sand, and variably altered sandstone.

Above this zone and elsewhere in the immediate vicinity of the deposit, alteration is primarily restricted to fractures and fault zones.

The deposit and area are highly fractured. Post-mineralization fracturing is the dominant control of hydraulic conductivity and, where it transects the otherwise impervious claystone core of the deposit, fracturing acts as conduits for water, sand, and soft clay. The basement rocks are much tighter, with very minimal groundwater flow.

Two of the primary geotechnical challenges in constructing the test mine have been control of groundwater, and ground support in areas of weak rock. These challenges occur concurrently in the immediate area of the massive mineralization

and the overlying saturated alteration zone, and within fracture zones in the sandstone.

### **Cigar Lake challenges**

The major technical factors influencing the mining method selection included ground stability, control of ground water, radiation exposure, and ore handling and storage. Various studies on ground conditioning and non-entry mining methods were conducted and field testing was recommended. Thus, a test mine program was launched to demonstrate that the ore could be safely and economically mined.

### **Test mine highlights 1987-1999**

#### *INITIAL DEVELOPMENT*

Construction began in 1987 on various surface facilities and a 500-meter shaft. Initial underground development included levels above and below the ore to facilitate testing mining methods including raise boring and blind boring.

Extremely poor ground encountered on the upper level (420m level) was frozen to advance development. After this expensive advance, the decision was made to concentrate the test mine program on methods which could extract the ore from below the orebody. Conventional and enhanced rock support methods were used in the development of headings on the level below the ore body (480m level).

#### *OREBODY FREEZING*

The support of the weak rock associated with the orebody and the minimization of the potential for a large inrush of water while mining the ore was addressed through ground freezing. The ground freezing also eliminated the majority of the free water from exiting the orebody and assisted in reducing the overall radiation exposure. Near vertical freeze pipes were installed through the orebody and calcium chloride brine, at about  $-40^{\circ}\text{C}$ , was circulated through the freeze pipes. This enabled the 6 metre wide orebody panel to be frozen to a temperature of about  $-10^{\circ}\text{C}$  after a period of about 4 months. Future production panels of 12 to 18 metre width will require 1.5 to 2.5 years of freezing.

#### *BOXHOLE BORING*

In 1991, a boxhole boring test was successfully completed in frozen ore. Two vertical pilot holes and 1.5m diameter boxholes were drilled upward using a customized Robbins drill set up on the 480m level. A chute diverted the cuttings into ore cars which were subsequently transported to the cage in the shaft using a remote controlled locomotive.

### *JET BORING 1991*

Adjacent to the two boxholes, two jet mining tests were conducted. The Robbins drill bored the pilot holes through the ore and installed steel casing to the bottom of the ore. A rotary freeze hole drill was fitted with a high pressure swivel and rotated a single, side firing nozzle at the top end of a drill string, positioned above the casing within the ore.

A 520kW pump supplied about 300 litres per minute of jet water at 80 MPa pressure. A “preventer”, comprising of seals around the jet rod and a shut off valve on the outlet, was fixed to the pilot hole casing and contained the slurry. The preventer, rated at one-and-a-half times formation water pressure, also provided collar security in the event of ice wall failure above orebody. These initial tests demonstrated the jet mining method's potential but also its slurry handling challenges.

### *JET BORING 1992*

A ramp was developed from the 480m level up to the 460m level and a crosscut closer to the ore was developed. Two rows of freeze pipes were installed from the 480m level and a larger test mining zone was frozen in about 5 months.

Due to its potential advantages, jet boring was selected for the first tests in the new test zone. In addition to the equipment used in previous jetting tests, a rolls crusher, pump box and slurry pipeline to the 420m level were installed. The test included the excavation of 4 cavities up to 2m in diameter.

Although some slurry handling difficulties persisted, the test was considered a success and the jet mining method was considered technically feasible and safe with respect to radiation protection and mine water control.

### *MINING METHOD EVALUATION*

Upon completion of these initial tests, an evaluation of the two processes indicated the following significant advantages with the jet boring mining method.

- The cutting of ore with high pressure water produces a slurry which can be handled in pipelines. This provides containment for radiation control while utilizing the relatively simple and cost effective method of pumping to move the slurry away from the mining equipment.
- The elimination of dust since the cutting and material transport are wet processes.

- The incorporation of a preventer system into the jet boring machine, to provide a final point of control should an inrush of water occur during mining. This is not possible with the boxhole boring mining method.
- The ability of the water jets to extract the ore next to a backfilled cavity without significant dilution of the ore with concrete. The boxhole boring mining method could require a significant overlap of holes to maximize the recovery of the orebody.
- Due to the ability to mine in a fan pattern with the jet boring mining method, there is a reduction in the amount of drifting which may be required which enhances the economics of the method.
- The jet boring mining method requires the installation of a small diameter casing (approximately 0.3m in diameter) to access the ore, whereas the boxhole boring mining method requires the drilling of a 1.5m diameter hole. Thus, the boxhole boring mining method significantly increases the amount of waste which must be stored and increases the operating cost of the mining method.

### *STUDY AND DEVELOPMENT PHASE 1993-1997*

Numerous environmental, engineering, and feasibility studies followed to determine production approaches and economics and to support regulatory submissions. In 1995, an Environmental Impact Statement was submitted based on the jet boring mining method with two levels of development below the orebody; a lower level for freeze pipe drilling and an upper level for jet mining (*Figures 3 and 4*).

Key study recommendations included a jetting system with four times the previous jet power and the construction of concrete segment lined tunnels immediately below the orebody in the weakest rock.

Unique tunneling and freeze pipe drilling equipment was constructed and field tested. A custom designed tunnelling machine excavated two crosscuts in weak ground on the 480m level, erecting a concrete segment tunnel liner for ground support while advancing. Lastly, design began on a production “Jet Bore System” capable of performing the complete mining cycle.

The production “Jet Bore System” is a complex system comprised of the following sub-systems:

- High pressure pumping system
- In-hole jetting tools
- Surveying systems
- Jet boring system (JBS): “drilling” rig

- Slurry circuit
- Backfilling system
- Overall control and monitoring system.

Several companies including Tamrock, Voest-Alpine, Waterjet Technology, BCP Engineering, and Saskatchewan Research Council worked closely together on design and shop tests to address the numerous subsystems' inter-related issues.

Shop tests of jetting equipment provided insight to production rates and confirmed jetting power requirements. Surveying tools and the collar preventer were also shop tested.

### *JETTING TOOLS TEST 1999*

Prototype jetting production tools were successfully tested in an underground culvert lined raise. The culvert was three metres in diameter and was filled with simulated ore around a destructible fiberglass cased pilot hole. The culvert was fitted with a removable lid permitting access for viewing mining progress as well as inspecting and modifying tools.

Four 600kW Hammelman five piston pumps were installed underground near the mining area and fed high pressure oil field piping routed to the JBS. In parallel, these pumps supply one 7mm diameter nozzle a total of 1000 litres per minute at 100 Mpa (total power of 2.4MW).

With the JBS still in the manufacturing stage, a freeze hole drill was used for nozzle motion for this test. A redesigned complex high pressure swivel, fitted to the drill's rotation head, allowed the passage of jetting and flush water flows through the rotating drill head and up through dual wall jet rods to a nozzle sub in the cavity. A "blade" screen attached to the nozzle sub provided a choke point and controlled the size of ore leaving the cavity. This screen consisted of several radial plates in the annular space between the jet rods and the casing (*Figure 5*).

An improved preventer, complete with flushing jets, was installed at the collar and instrumentation monitored the cavity environment during and after jetting for future cavity survey tool development.

The full three-metre diameter filled culvert was excavated including 250 MPa boulders, the preventer passed the slurry without plugging, and productivity expectations were met.

## *JET BORING SYSTEM AND SECOND CULVERT TEST*

Voest-Alpine in conjunction with Tamrock, manufactured a production “Jet Boring System” (JBS), consisting of five cars connected on rails (*Figures 6, 11 and 12*). The five cars include a drill car, slurry car with pumpbox, and three storage cars for drill rods, jet rods and casings. The main tasks of the JBS are:

- Drilling pilot hole and installing casing (fiberglass in ore, steel below ore, *Figure 7*);
- Jet boring the cavity;
- Containing the slurry and pumping it to the process circuits.

The JBS drill and slurry cars were set up beneath the culvert lined raise and the culvert was re-filled with simulated ore. Subsequent jetting tests successfully demonstrated most of the functionality of the JBS drill car and the survivability of a cavity survey tool.

The survey tool is mounted to the top of the nozzle sub and is within the cavity during jetting operations. Between periods of jetting, the survey tool is remotely activated and sends survey data down the dual wall jet rods (electrically isolated) and out through brushes in the high pressure swivel. These tools also transmit DC voltage up to power the survey tool.

### **Industrial Jet Boring Test in ore 2000**

#### *OBJECTIVES*

The objectives for the 2000 Jet Boring Test in ore are summarized as follows:

- In a production environment, test the complete jet boring system including jet boring cars, high pressure pumping system, jetting tools, slurry circuit, water handling and treatment systems and backfilling equipment.
- Test the jet boring procedures including pilot hole drilling, casing installation, jet mining and techniques, slurry transport, cavity surveying, backfilling, ore recovery, and water treatment.
- Determine productivity rates, cycle times and potential cavity sizes; assess the ability to mine, size and transport uranium ore (including ability of the slurry to flow from the cavity to storage without plugging process circuit).
- Reconfirm the mining method with respect to radiation and safety issues.

## *TEST ARRANGEMENT*

An existing 460m level crosscut was re-established and fitted with a circular steel liner (4.25 meter inside diameter) and rails (*Figure 6*). The liner simulated a future production crosscut and accommodated the complete five car JBS and associated piping.

The freeze pipes used in 1992 tests were re-activated and the ore and surrounding rock was re-frozen. On the 480m level, an ore storage sump was developed and slurry piping from the JBS to this sump was installed.

## *TEST RESULTS*

### *Frozen Waste Cavities and Tools Improvements*

In mid 2000, four cavities were excavated in frozen waste rock, just below the ore, and included the first tests of the complete five car JBS, casing hole drilling and installation procedure, and slurry circuit operation.

Jetting tools improvements continued during the frozen waste tests. The original blade screen was stationary within the fiberglass casing and the nozzle would traverse to and from the blades while jetting. On several occasions, the blade screen became plugged, broke away from the nozzle sub and was propelled down the casing annulus. The blade screen was modified to traverse with the nozzle sub allowing the nozzle to continuously clean the blade screen openings (*Figure 8*).

The laser surveying tool was unable to operate reliably through the cavity fog generated by the jet in frozen ground. The survey tool was modified to accommodate an ultrasonic sensor, a sensing technology unaffected by fog.

Fiberglass plugging below the blade screen was attributed to one or more of the following: minimal overlap of blade screen within casing, damaged end of casing, casings connections coming apart, and blade screen extending beyond casing end. These issues were addressed by incorporating a blade screen extension, one metre in length.

Acting as flow meter, a load cell weigh scale was installed in the slurry tank to forewarn the operator of plugging situations (i.e. blade screen). Traditional flow meters were not utilized due to flow conditions, particle size and space constraints but will be considered for production as an alternative or addition to load cell.

### *Frozen Ore Cavities*

Four cavities were successfully excavated in frozen ore where an estimated 600 tonnes of ore containing 90 tonnes uranium was mined (*Figure 9*). The average grade of the ore mined was 15% U, but some massive pitchblende up to 50% U was successfully extracted.

The cavities were fairly circular in shape and were 4-5m in diameter, confirmed by follow-up laser surveys. The cavities were mined using a “recipe” of jetting parameters and no diameter limitation or maximization was attempted. This approach contrasted the initial plan of jetting in specific directions based on surveys to achieve the target diameter. In production, it is anticipated that jetting parameters will more often be selected based on gamma logs and experience from adjacent cavities rather than interim cavity surveys.

The upper part of most cavities continued to grow in diameter while jetting occurs in the lower part of the cavity. This “after mining” phenomenon, attributed to the high kinetic energy of the deflected jet and loose ore in a small space, may prove advantageous while mining cavities at steep angles and by reducing initial jetting duration and overall mining height.

Video inspection indicated the cavities were stable at least in the short term (i.e. several days). Therefore, until more experience is obtained, the maximum cavity size will be limited to 5-5.5m in diameter by selecting the appropriate jetting duration and parameters per mining increment. This control is supplemented by the nature of the jet to significantly diminish in cutting power beyond a certain distance.

### *Productivity and Limiting Factors*

The estimated productivity rate of ten tonnes per hour while jetting was confirmed and will be the benchmark for operations. With two JBS’s in operation, this jetting productivity rate equates to an average daily production of 100 to 150 tonnes of ore.

The jet performs four functions. It mines ore from the cavity wall, reduces the size of the loose ore, cleans the blade screen openings, and flushes the ore from the cavity. The observed rubble pile in some cavities suggests the jet’s sizing function in conjunction with the component clearances may likely be the main limiting factor affecting productivity. Related equipment parameters include the blade screen and casing sizes, preventer clearances, and slurry piping sizes.

The hardness or grade of the ore is also assumed to be a limiting factor. However, the limited test data was inconclusive and further jetting experience in all ore types is required to determine sensitivity.

The slurry circuit operated as expected and all 600 tonnes of the mined ore was pumped to the ore storage sump. Key features of this circuit include a sweeping suction pipe in the slurry car pump box and a very high flow rate to move the larger, heavy pieces of ore.

#### *Cavity Backfilling*

Six of the eight cavities jetted during the JBS test were backfilled with concrete while two cavities were back backfilled with cement grout. A special concrete mix was designed for cavity backfilling. This mix was designed to achieve an early high compressive strength of 40 MPa, to set up in frozen conditions, remain pumpable after being transported from surface to underground and be capable of being batched on site with available aggregate.

Videos and rangefinder surveys obtained in the cavities following jetting, showed that the backfill stood up well with only minimal erosion when jetting was carried out in an adjacent cavity.

#### *Ore Recovery Test*

Following the completion of jetting, a 1.0m<sup>3</sup> capacity clamshell and five tonne motorized hoist was successfully mounted on a monorail, which had been installed in the ore sump during initial construction (*see Figure 13*). Using the clamshell, five 1.5m<sup>3</sup> ore cars were filled with ore recovered from the ore storage sump. The clamshell operated problem free and was completely successful in travelling along the monorail and excavating the jetted material within the sump and discharging the material into the ore cars. As the ore cars were filled, they were transported to surface for storage.

### **Summary**

The overall test mine program and, in particular, the 2000 Industrial Jet Boring Test, were considered highly successful with all initial objectives fulfilled and results meeting expectations.

In the 2000 tests, the complete Jet Bore System with all its subsystems was operated in a production environment including frozen uranium ore and surrounding rock, a 4.25m diameter circular production tunnel, and typical mine services and personnel. The ore was mined and the tunnel diameter proved adequate.

Subsystem interfaces were successfully demonstrated and evaluated. The high pressure pumping system was controlled from the JBS, the cavity survey system communicated via the jet string, and the slurry system transported ore slurry away from the JBS.

The complete jet boring procedures were executed during the mining and backfilling of eight cavities. The cavities were fairly circular and ranged from three to five metres in diameter. A 4.5m average diameter cavity is projected for production.

A jetting parameter “recipe” was followed and no specific attempts were made to alter the cavity shape ore size. Most jetting parameters were varied slightly. However, mining of numerous cavities will be required to determine parameter sensitivity.

Cavity surveys and video inspections indicate that the jet was able to mine around the concrete backfill of adjacent cavities with minimal deterioration of the backfill itself. These results support the initial projections of high ore recovery and low backfill dilution.

All tests proved very successful in keeping personnel radiation exposures to extremely low levels. No significant gamma radiation, radon progeny, long-lived radioactive dust or uranium in urine exposures occurred. There were no significant accidents or incidents reported.

The ore recovery test using the clamshell was completed as planned with no operational or radiation problems, proving the method is feasible. Five ore cars were filled with reclaimed material from the ore sump and sent to surface for storage.

Thirty-six Cigar Lake Project and contracted personnel completed a comprehensive questionnaire on the equipment, procedures, safety, radiation and maintenance. The results were extremely positive and the recommendations provided will assist in future re-engineering.

In the future development and production phases, a tunnelling machine will develop crosscuts below the ore, vertical and sub-horizontal freeze pipes will freeze the ore and surrounding rock, and two JBS’s will mine remote cavities to produce a coarse ore slurry. Following underground processing, the slurry will be pumped to surface (*Figure 10*).

During the first phase of production, the Cigar Lake ore slurry will be trucked to Cogema’s McClean Lake operation for initial processing. The majority of the uranium solution will then be trucked to Cameco’s Rabbit Lake operation for final processing.

The mill tailings will be placed in a tailings management facility at McClean Lake. Cigar Lake waste rock will ultimately be transported to McClean Lake storage facilities.

Conforming to strict federal and provincial regulations, all sites will be operated in a safe, environmentally responsible manner, and undergo suitable decommissioning at the end of their life.

The Cigar Lake Project is now in the detailed engineering, licensing and pre-construction phase.