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Simulation of integrated underground mining-processing

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The paper examines the design issues associated with the integration of mineral processing within underground mining systems. It demonstrates conceptual integrated system design options appropriate to a range of geological scenarios. Particular reference is then given to a case study of stoping in narrow base metal veins.

The performance of such integrated systems in terms of productivity, economic and environmental criteria is demonstrated by means of simulation. Particular attention is given to the potential benefits to mine waste management. Processing technologies appear to offer genuine potential benefit, whilst underground mining methods may need to evolve further to facilitate full integration. This paper is based on industry supported research aimed at developing selective and clean underground mining systems.

Introduction

The traditional metal production life cycle is from mineral exploration, to development and mining the orebody, transporting ore to a plant for mineral processing and sending the mineral concentrate to a smelter. Coarse waste is sent to dumps and fine waste to tailings ponds. Pressures to improve the sustainability of mining have led to the development of technologies that have created more integrated metal producing systems. For example, advances in hydrometallurgical technologies have eliminated the need for smelters and the associated environmental impact. Heap leaching has enabled the recovery of metals from lower grade deposits and thereby improved resource utilization. Paste technology has allowed greater storage of waste underground reducing the surface footprint and the associated environmental risks. Backfill also created underground support enabling greater recovery of reserves (Lloyd, 1990). Each of these technologies involves integration of the traditional metal production components and the consequence has been incremental improvement in mine sustainability by promoting selective and clean systems (Moss, 1999; Scoble, 1994; Parsons and Hume, 1997).

These examples demonstrate how technology can lead to significant improvements to mining sustainability. Despite such improvements, however, there are ongoing pressures to reduce the mining footprint. One way to accomplish this is by the further integration of underground mining and mineral processing. The paper presents a discussion of the various underground scenarios that might be envisioned. A specific scenario is presented based on a case study example of underground pre-concentration in a hard rock nickel mine and its evaluation using simulation.

Underground mining and processing design scenarios

System-wide, the integration of mining and mineral processing underground is considered from the perspective of conventional mineral processing technology. Mineral processing has been applied sparingly underground, although numerous underground crushing and screening facilities exist. A few more complete integration examples exist, such as:

- The McArthur River uranium mine, Saskatchewan, that uses underground semi-autogenous grinding with hydraulic transport to a surface processing facility (Dyck, 2001)
- The Andina copper mine, Chile, has a complete underground grinding and flotation plant treating 32,000 tpd (Brewis, 1995).

Several constraints must be addressed for successful implementation of mineral processing underground, including (Lloyd, 1978; Klein *et al.* 2002):

- The physical volume of the processing facility should be as small as possible to minimize costs. Also, geotechnical issues may limit the size of excavation to house a processing facility
- The process should be robust with respect to being capable of treating ore at a range of feed rates and grades while maintaining high metal recoveries
- Processes that can separate at coarse particle sizes, requiring minimum comminution, are preferred over fine particle processing technologies
- The process should require a minimum amount of infrastructure. In general, dry processes are preferred over wet ones
- The waste should be suitable for backfill with regards to its physical properties and volume. Returning waste to mined voids limits the amount of rock that can be rejected (assuming a swell factor of 1.3) to about 85% of the feed. At a higher rejection, waste will need to be transported to surface for storage.

There are two main design options involving underground mineral processing:

- *Pre-concentration*—This would require crushing, screening and coarse particle separation to reject waste rock. These systems may be mobile and modular to facilitate relocating to different areas as mining fronts

progress laterally and with depth

- *Full scale mineral processing*—This would involve crushing, grinding, mineral separation and de-watering. Integration of full-scale circuits into underground excavations would likely be preceded by success in pre-concentration efforts.

Pre-concentration involves the rejection of waste, thereby reducing the amount of material that needs to be transported and processed downstream. The merits of pre-concentration at coarse particle sizes are well known (Feasby, 1995; Klein *et al.* 2002; Peters *et al.* 1999; Schena *et al.* 1990). Benefits include:

- The possibility of increasing mining rate without increasing the size of the fine particle processing facilities
- Reduced grinding and fine particle processing costs
- Increased metal production
- Reduction in the quantity of fine waste and
- Separation of non-reactive waste from reactive wastes for disposal.

There are several site-specific motivations to consider underground pre-concentration. One motivation relates to mine depth and grade (Lloyd, 1978; Peters *et al.* 1999). As mines become deeper, then underground pre-concentration represents an opportunity to reduce transportation cost for handling waste material, both out of the mine and in some cases subsequent replacement back underground. The reduction of these costs would affect cut-off grades and therefore resource utilization.

The mineralogy of the ore determines the potential for pre-concentration and the suitability of a processing technology. Several coarse particle processing technologies exist. Dense media separation has been used at several lead-zinc mines (Collins, 1995). The dense media separation process is capable of efficiently separating minerals with small density difference (<1 specific gravity) at coarse particles sizes (0.5 mm to 20 cm). Modular plants are compact and may be well suited for underground operations. To date, dense media has not been used in an underground environment.

Electronic sorting has been used at some copper base metal operations (Sivamohan, and Forssberg, 1991). Electronic sorters separate particles based on optical properties, luminescent properties and conductivity. Other coarse particle (>1 mm) process technologies that may be suitable include magnetic separation and electrostatic separation. These are dry processes that may have advantages with respect to space and infrastructure requirements in an underground environment.

Integrated mine architecture

Figure 1 shows a conceptual view of an underground metal mining layout that integrates a central processing facility. The facility may be accommodated in a custom-excavated opening or within an early stope void. The Figure is intended to demonstrate the concepts of the overall underground architecture of what might be an early generation integrated mine-mill system. It shows a simplified underground hardrock mine, operating in a steeply dipping orebody using some form of open stoping with delayed backfill. The metals are assumed to occur in sulphide veins that vary in thickness.

Figure 1 demonstrates the manner in which an underground mineral processing plant (4) might be integrated into the mining architecture, either as a pre-concentration or full mill operation. The design attempts to ensure that three stopes are routinely operational to meet production targets (2), with three old stope voids available for back-filling (6). The stopes below the level of the plant (levels 4 and 5) feed fragmented ore to it via drifts and ramp access. Stopes at or above the level of the plant (levels 1,2,3) can take advantage of gravity and feed ore via drifts and ore passes (3). The main means of handling the concentrate from milling is via a drift and vertical shaft (7). An alternate means is via the second means of egress to surface, the ramp system (8). The ramp also provides backup to the mill for taking waste reject from the processing to surface in the event that adequate stope void space is not available or other factors impede waste disposal. Gravity affects the management of waste reject as with the ore feed to the mill plant. Options are drifts, raises and ramps (5) to transport and place the waste as backfill. Such systems are dependent upon the reliability of the backfilling process. The alternate ability to transport waste out to surface would be important in order to maintain the continuity of production. The system is waste management bound. The swell of rock on fragmentation will mean that not entirely all waste reject will be capable of disposal underground in this rather conventional looking systems architecture.

Figure 2 is a conceptual flowsheet for an underground processing facility consisting of two main components: feed preparation and mineral separation. Ore passes offer surge storage capacity to ensure a constant feed supply to processing. The objectives of crushing are to liberate waste and prepare material with correct feed size for processing while avoiding the production of excessive fines that bypass the process. Following screening, coarse fractions are processed to reject waste rock and depending on their grade, the fines can be combined with either concentrate or waste. In the case of sulphide ores, the friable sulphides may enrich the fine fraction to increase its grade, which would support combining it with the concentrate. The quantities of concentrate and waste will change with feed grade, which must be accommodated by sufficient storage capacity so that it can be handled by the material transport system.

Underground mining-processing integration issues

Work to date has identified the following as potential critical issues in the design of integrated underground mining-processing systems (Schindler, 2002).

- Stoping method, with respect to continuity of production; control over fragmentation; level of dilution and recovery; stope geometry and mining rate; equipment requirements; and ground control.
- Mining sequence and number of stopes in governing the reliability and flexibility in matching not only the mill design characteristics but also the waste management system design characteristics.
- Access development (drifts, raises etc.) rates and sequencing, in order to facilitate the required stope production capacities and support the waste management system.
- Materials handling equipment selection, productivity and reliability. Design and technologies for continuous handling systems (e.g. horizontal/vertical conveyors) would be sought to ensure a consistent flow rate of ore to the mill from stopes, concentrate to surface, waste rock (from development and milling reject). Design

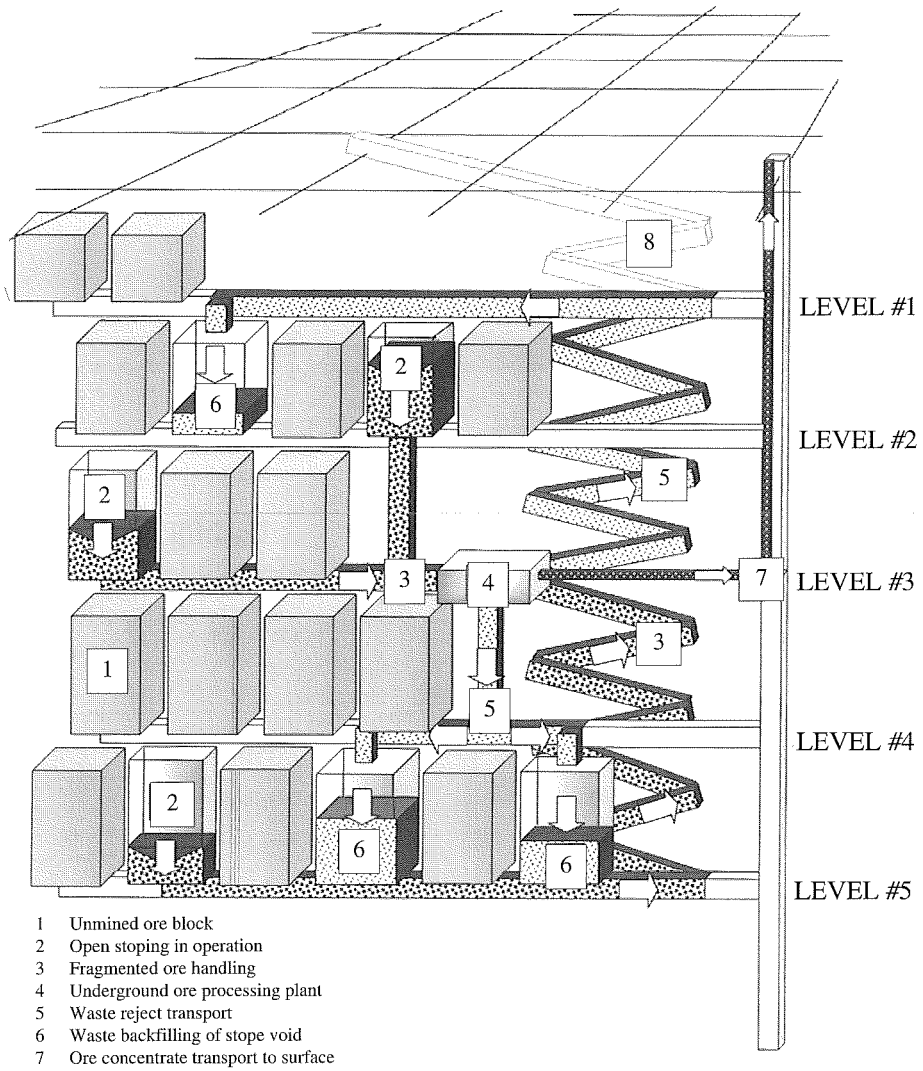

Figure 1. Conceptual mine layout with underground processing plant

needs to account for the conventionally cyclic nature of the excavation and backfilling processes. Flexibility needs to be considered by adopting alternate system components and providing temporary buffer stockpiles where possible. This is a challenge compared to the open environment of the surface mine.

- Short-term storage facilities for ore, concentrate and waste will interface with material handling. Ore storage capacities will relate to peak mining rates. Waste and concentrate storage capacities relate to processing rates and the flexibility and transport rates for material handling systems. The waste storage requirements will also need to take account of the availability of stopes for underground disposal.
- The location of the underground processing plant impacts significantly on the performance and design needs for the development, stoping and backfilling systems. It may be that the design of a modular, mobile plant provides more flexibility than a single comprehensive plant.

Mine design needs to account for the grade distribution in the ore zones. The reliability of grade estimates is important in an underground mine-mill situation because there is less inherent capability to ease grade control and blending through surface stockpiles. The integration necessitates that the system be more agile in responding to variability in flow rates and grade. There may be a need to use underground stope voids for buffer storage and blending.

A similar issue relates to the agility to deal with any localized occurrences of minerals in ore zones that may be deleterious to the mill processing system, e.g. variations in liberation size.

Underground pre-concentration: narrow vein case study

A case study is now considered in order to examine further the potential for underground processing to reduce the mine footprint and minimize waste. This examines the application of pre-concentration for a deep hard rock copper/nickel mine using overhand cut-and-fill mining. Simulation is used as a tool to assess the impact of pre-concentration on production performance. The mineralized veins range in thickness from 2 to 30 ft. Based on the depth and grade, it has been determined that it is uneconomical to recover veins less than 6 feet thick. Since there is a significant amount of ore that falls into this category, underground pre-concentration is being considered.

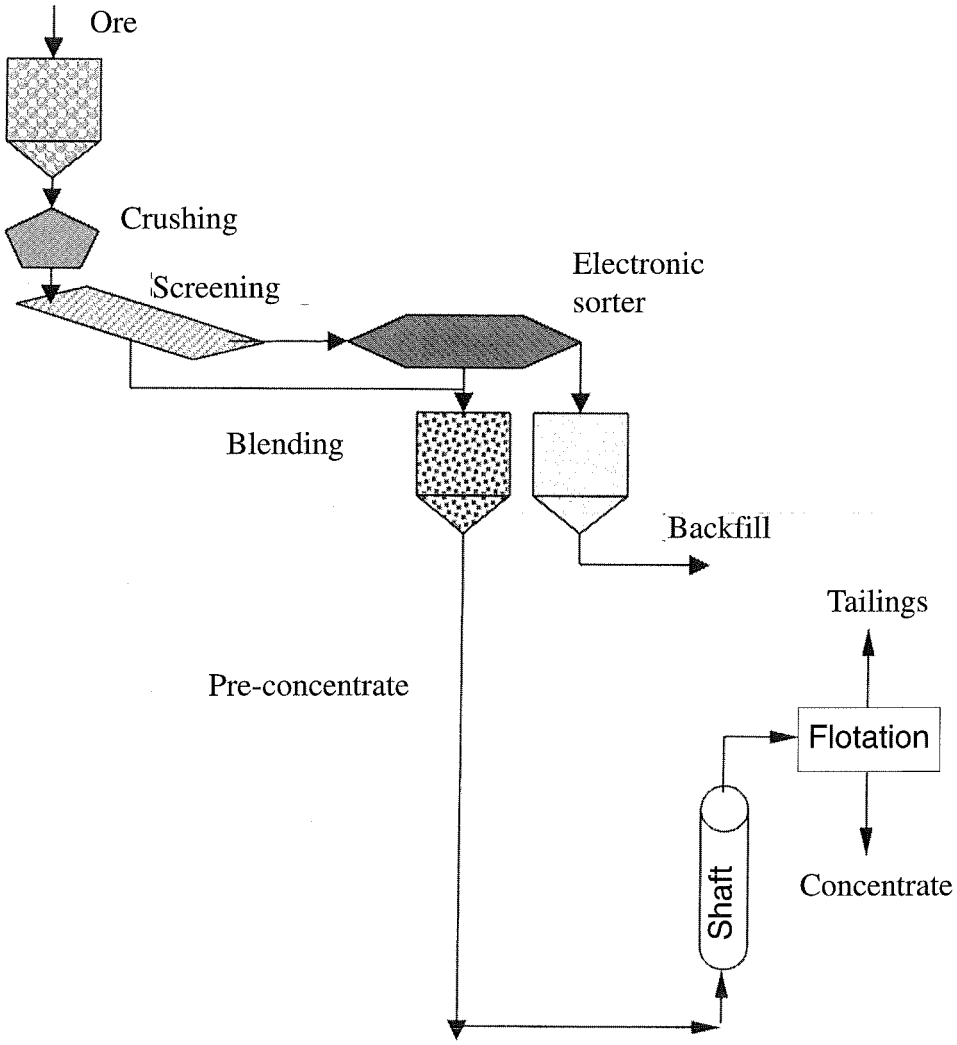

Figure 2. Conceptual flowsheet for an underground pre-concentration system

The primary design integration issues that have to be considered for pre-concentration at this mine fall into four categories pre-concentration technology, materials handling, production rate and fragmentation/comminution.

- *Pre-concentration technology*—For underground pre-concentration, technologies capable of separating particles at coarse sizes and requiring minimum infrastructure and space were considered. While dense media separation is likely capable of good mineral separation, the infrastructure and space requirements associated with the media recovery circuit, were considered prohibitive. Other technologies considered included electronic sorters, magnetic separators and electrostatic separators. Electronic sorters can use three detection technologies including photometric, conductivity and gamma ray scattering.

  Based on pilot testing, optical electronic sorting using photometric combined with conductivity methods gave acceptable metallurgical results. As indicated in Table I, for feed grading 5.7% copper and 0.4% Ni, the separator rejected 54.6% of the rock, while maintaining recoveries of 94.7% and 81.2%, respectively.

  The vein material was composed of coarse grained chalcopyrite, pyrrhotite and pentlandite and the waste contained mostly quartz with disseminated sulphides. Based on the mineralogy, it could be assumed that as feed grade changes, then the grade of waste (0.5% Cu) and concentrate (12% Cu) will remain approximately constant. Consequently, increasing the feed grade will improve recovery and decrease the amount of rejected rock.
- *Material handling*—The primary material handling issue relates to the potential to use the pre-concentration rejects (2-cm—15-cm rock) for backfill. The options include using the rejects directly as backfill, mixing rejects with cemented tailings at surface and returning to voids and mixing rejects with cemented tailings underground and transporting to the voids. Other material handling issues relate to variable mining rates, underground storage for pre-concentrator surge capacity and storing concentrate and waste.

Table I
Results of optical plus magnetic separation on a copper-nickel vein deposit

Product	Weight (%)	Grade (%)		Distribution (%)	
		Cu	Ni	Cu	Ni
Concentrate	45.4	11.8	0.73	94.7	81.2
Tails	54.6	0.55	0.14	5.3	18.8
Feed	100.0	5.67	0.41	100.0	100.0

- *Production rate*—Assuming a fixed processing rate at surface (i.e. fixed rate of transport of concentrate via the shaft to surface), as the vein becomes narrower then the mining rate and pre-concentration processing rate will need to increase. This will also correspond to an increase in the production rate of waste. For mining, the desired production rate and pre-concentrator feed grade will dictate the number of mining faces and the mining sequence.
- *Fragmentation/Comminution*—The objectives of comminution are to liberate waste rock while avoiding the production of excessive amounts of fine particles. Assuming fine particles are combined with concentrate, reducing the amount of fines generated during comminution will increase the amount of waste rejected during pre-concentration. Comminution should be optimized by a combination of controlled blasting and proper design of the crushing/screening facility.

Simulation of preliminary system design

As described, underground pre-concentration must integrate mining, processing and waste management into a system that has an economical advantage over traditional practices. There are, however, constraints on the design that relate to space, infrastructure, materials handling and waste disposal. Simulation was used to identify bottlenecks and evaluate outputs including concentrate, coarse waste, fine tailings and metal production rates.

The conceptual mining and processing systems shown in Figures 1 and 2 were modelled using simulation. The ore is mined in a series of stopes and transported to a screen where coarse and fine (-2 inch) materials are separated. Based on size analysis of mucked rock from the mine it is assumed that the ore mass consists of 40% fine and 60% coarse material. Assuming metallurgical results as shown in Table I, an electronic sorter further separates the coarse material into a concentrate of 12% copper and 0.5% copper waste material to be used for backfill. The fines and coarse concentrate are then blended to form a pre-concentrate that is transported to the shaft. The pre-concentrate passes through a flotation circuit to produce a concentrate of 30% copper and 0.2% copper tailings.

This is a relatively simple model, the following assumptions are made.

- The stopes are assumed to be mining a vein that is becoming thinner so that, as mining progresses, more waste is included in the muck and the feed grade (the 'head grade' for the pre-concentrator) decreases with time. In this case the vein is mined over a ten-month period. The grade is 10% copper in the first month and decreases to 1% copper in the final month.
- It is assumed that as feed grade changes, the grade of waste and pre-concentrate will remain approximately constant.
- The shaft is assumed to have a design capacity of 1000 tpd (30,000 tonnes per month). It is more economic to use the shaft at its capacity.
- Nickel production is assumed to be independent of copper production. Only copper production is used to illustrate the performance of the system.

Simulation results and discussion

Figure 3 shows the trend in the amount of ore that is required to be mined for the conventional approach compared to using pre-concentration. What this graph shows is that immediately upon commencing pre-concentration the amount of ore that must be generated from the stopes increases from 30,000 to 50,000 tonnes per month for a 10 per cent grade and goes to approximately 73,000 tonnes per day if the grade drops to 1 per cent. This highlights one of the previously identified integration issues. Specifically, introducing pre-concentration into an existing mine will require that steps are taken to ensure that the mining process is flexible enough to produce the required tonnages to maintain optimum utilization of the underground pre-concentration plant and the shaft. To achieve this flexibility could require the operation of additional stopes, the addition of lateral ore movement equipment or other approaches. The next step in modelling this aspect of the process would be to expand the simulation to include the mining sequence and stoping cycle. This would allow an assessment of proposed mining solutions for the new tonnage requirements.

In the area of waste management, Figure 4 illustrates how the amount of fines generated by the pre-concentrator goes up as the grade decreases. It also shows that the amount of fine tailings produced is lower when using pre-concentration. Again this highlights a previously mentioned integration issue with respect to handling the material generated by the pre-concentration process. If space does

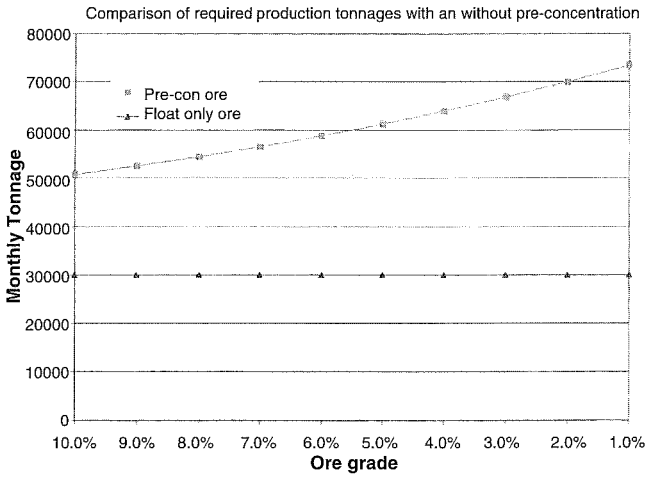

Figure 3. Production requirements for decreasing grade using undergound pre-concentration

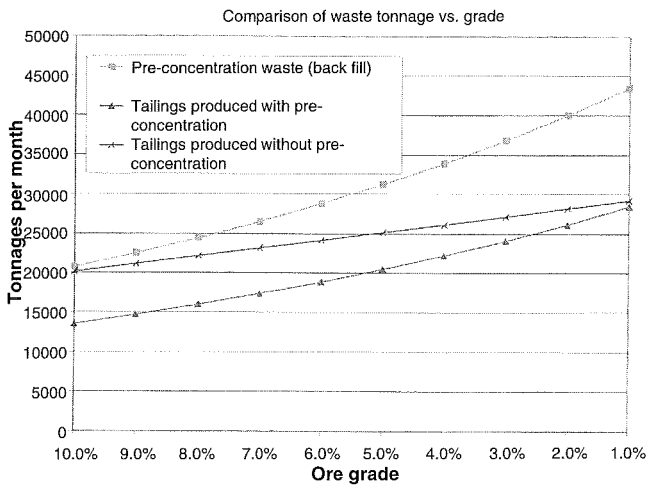

Figure 4. Waste generation for pre-concentration

not exist for the backfill to be placed then it will need to be transported to surface. For mines with only one shaft and no ramp this suggests a reduction in shaft utilization for ore transport. To properly assess the impact of this, the simulation should be expanded to model the backfill process.

Figure 5 shows that the amount of copper delivered to the surface increases with the use of pre-concentration. It also shows that the difference between pre-concentrated copper production and copper production from the conventional process reduces as the *in situ* ore grade decreases. This would suggest that the relationship between grade and copper produced with pre-concentration will indicate whether or not it is worth pursuing.

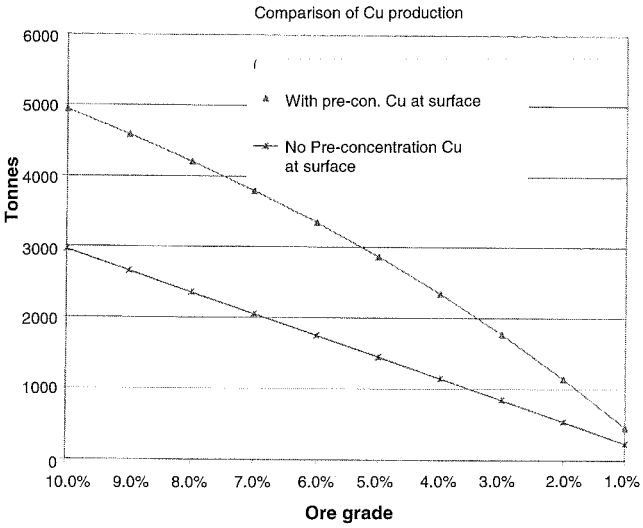

Figure 5. Copper production with pre-concentration

Conclusions and recommendations

This paper has presented the technical concepts associated with underground pre-concentration to reject waste. It has presented a case study where a preliminary analysis of pre-concentration was performed using simulation. The results indicate that pre-concentration would increase the amount of ore delivered to surface. However, the cost associated in doing this is that the mine must be better equipped to both generate raw material for the pre-concentrator and to remove the waste generated by it.

The use of simulation for this case study has provided the baseline model for expansion and performance of trade-off studies. It is envisioned that the next logical step would be to build models of the mining sequence and stoping cycle to assess the required changes to generate the raw material required for the pre-concentrator. Following this, a model of the backfill cycle would be included. Once the complete model is available it could be used to determine the appropriate level of pre-concentration as a function of grade to maximize profit. An economic evaluation would then demonstrate the effects on profitability and resource utilization (Cut off grade).

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