Reconciling mineral reserves at the well-to-well in-situ copper leaching operation at San Manuel mine, Arizona, USA

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ABSTRACT At the San Manuel mine (Arizona, USA), in-situ copper leaching of a copper porphyry deposit was carried out from 1986 to 1999 during underground and open-pit mining. In 1993–1994, well-field testing of the supergene zone, composed primarily of chrysocolla and copper-rich clay minerals, led to estimates that 52% of the acid-soluble copper (ASCu) could be recovered during in-situ leaching; however, the actual recovery from zone 6, which had the longest leach history, was approximately 42%. Comparing drillcore assay data from holes drilled before and after leaching also indicated an approximate recovery of 42%. The discrepancy between the predicted (52%) and actual (42%) recovery is probably related to several factors, including difficulty maintaining fluid saturation, channelling effects, and gypsum precipitation.

KEYWORDS Copper oxides, in-situ leaching, Modelling, Porphyry, Solvent extraction and electrowinning (SXEW), Well-to-well

RÉSUMÉ À la mine San Manuel (Arizona, États-Unis), on a procédé de 1986 à 1999 à la lixiviation in-situ de cuivre d'un gisement porphyre cuprifère pendant l'exploitation minière souterraine et à ciel ouvert. En 1993 et 1994, des essais effectués dans des champs de captage de la zone supergène, composée principalement de chrysocolle et de minéraux argileux cuprifères, ont abouti à des estimations selon lesquelles on peut récupérer 52 % de cuivre soluble dans l'acide (ASCu) pendant la lixiviation in-situ ; toutefois, la récupération réelle dans la zone 6, qui affiche l'histoire la plus ancienne en matière de lixiviation, était d'environ 42 %. La comparaison des données d'analyses de forage obtenues à partir de trous forés avant et après la lixiviation indiquait également une récupération approximative de 42 %. La différence entre la récupération prévue (52 %) et réelle (42 %) réside probablement dans plusieurs facteurs, notamment la difficulté à maintenir la saturation des fluides, les effets de canalisation et la précipitation du gypse.

MOTS CLÉS d'un puits à l'autre, extraction par solvant et extraction électrolytique (SXEW), lixiviation in-situ, modélisation, oxydes de cuivre, porphyre

INTRODUCTION

in-situ copper leaching at the San Manuel mine, Arizona, USA (Figure 1), began in 1986. It was recognized that some of the copper oxide resource was not economically recoverable by conventional open-pit and heap leach methods using solvent extraction and electrowinning (SXEW) and a high stripping ratio would be required to access part of the resource. At the time, in-situ leaching was becoming popular in the uranium industry, but the approach was virtually unknown in the copper industry, especially at a large scale.

From 1986 to 1989, the San Manuel mine underwent considerable technical changes related to the design, development, and implementation of in-situ well construction methods, including the formulation of suitable well pattern arrays and the development of extensive hydrogeological and geochemical knowledge of the mineral deposit (Wiley, Ramey, & Rex, 1994). Surface access was limited due to the active open-pit operation; therefore, in-situ leaching was applied in the areas that were available. Initially, this resulted in injection wells developed to build up solution in the dewatered area of the open-pit operation envelope. Pregnant leach solution (PLS) was collected via gravity flow from an abandoned portion of the block cave underground mine.

In 1989, the first well-to-well pattern was drilled to test the feasibility of extracting the PLS from the surface. Some of the upper benches of the open-pit operation were selected because the system could operate for up to a year before open-pit stripping had to remove some of these wells. By 1994, an increased number of benches had been deemed available for use, allowing the expansion of the in-situ leaching operation, which was transformed into a combination of well-to-well recovery from surface and collection from the underground workings.

In January 1995, the last load was hauled from the open-pit operation to the heap leach pad. This permitted a rapid expansion of the in-situ operation, focused primarily on increasing the well-to-well extraction method. During the next four years, more than 1,000 wells were put into operation. At that point, the injected raffinate had an average pH of 1.3 and contained 0.05 g/L copper in solution. The composition of the PLS produced by the extraction wells varied considerably, with a pH of 1.5 to 3.5 and a copper content of 0.20 g/L to 3.0 g/L. Although extraction from the underground workings continued as some solution migrated downwards, more than two-thirds of the copper was extracted from pump wells on the surface.

The final phase of development was the west side expansion, which put wells on the west side of the deposit for the first time. The PLS was expected to be recovered equally from the underground workings and from well-to-well pumping. Construction of the expansion began in late 1998 and well spacing was increased from 12.1 to 15.2 m for the first time. Low copper prices forced the closure of the San Manuel mine operations, including the underground block caving operations, in 1999. The in-situ operation closed at the same time, even though it was producing close to 18,000 t (40 million lb) of copper annually and had an operating cost of only US$0.18/kg ($0.40/lb). The in-situ operation had the potential to continue as a standalone operation due to its low operating cost.

STUDY

The topic of this study is the reconciliation of mineral reserves—comparing the expected copper recovery to the actual amount recovered. Both measurements have associated levels of accuracy due to error margins in their determination. Numerous examples of standard mining reconciliations exist; however, this study discusses some of the basic parameters for determining mineral reserves for an in-situ operation. The San Manuel production data were examined to demonstrate how accurate the estimates of those mineral reserves were to the actual amount of copper recovered.

Deposit geology and geotechnical description

The San Manuel ore deposit has been cited as one of the classic copper porphyry systems (Lowell & Guilbert, 1970; Guilbert & Park, 1986). Copper porphyry systems have a few key characteristics that make them viable candidates for in-situ leaching, including closely spaced fractures and copper mineralization on the fracture surfaces. Copper leaching is typically restricted to copper oxide minerals, which are commonly best developed in the supergene zone of a copper porphyry deposit, if the deposit has been altered and the oxidation products preserved.

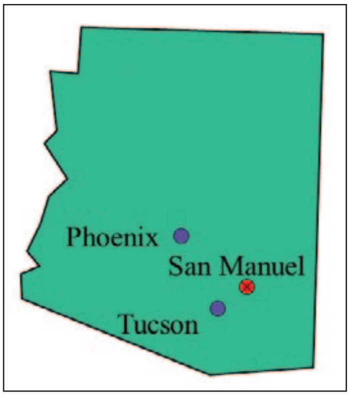

Figure 1. Location of the San Manuel mine in southeastern Arizona, USA

The hostrocks at San Manuel are a Precambrian quartz monzonite and a granodiorite porphyry formed during the Laramide orogeny. Both rock types are fractured and faulted by basin and range tectonics, weathered and altered by leaching, and mineralized by supergene precipitation. The in-situ leaching operation at San Manuel focused on this supergene zone. The readily leachable mineralogical suite consisted largely of chrysocolla acting as a filled fracture and as a coating accompanying clays on altered feldspars (Wiley et al., 1994).

Because the amount of fracturing impacts the ability of fluids to migrate through the rock mass and subsequently leach the copper, a well-fractured rock mass is important for any successful in-situ leaching operation. Diamond drill core logging within the supergene zone of San Manuel had a rock quality designation (RQD) averaging below 10%. In fact, an intact core was the exception rather than the rule at San Manuel, with many core boxes containing only a few pieces of core greater than 10 cm (4 in.) in length.

Systematic measurement of the longest piece of core can be used to indicate the density of fracturing and, therefore, the degree of fluid flow through the rock mass. In more than 10,000 core intervals logged during the open-pit study at San Manuel, 95% of the intact core was less than 30 cm (12 in.) in length. This estimate should be qualified because it is from the entire drilling campaign and includes substantial waste intervals. An example of typical core quality is drillhole A-17, which encountered approximately 122 m of oxide ore with typical San Manual characteristics; data from 30 m of the interval are presented in Table 1. Another measurement that relates to the amount of fracturing present is the average size of the core fragments. As seen in Table 1, the typical average size of fragments is less than 2.5 cm (1 in.) in length.

Copper porphyry deposits tend to be composed of highly fractured rock due to the manner of orebody emplacement. At San Manuel this was enhanced by fracturing due to the underground block cave mining method used beneath and adjacent to the open pit. This block caving had three major impacts: additional fault surfaces were created with displacements on the order of metres to tens of metres; existing faults that already had brecciated zones up to 1 m thick experienced additional displacement; and the rock mass near the under-

Table 1. Core data from an interval of drillhole A-17 with typical San Manuel deposit characteristics; RQD (rock quality designation)

From (m)	To (m)	Mean fragment size (cm)	Maximum fragment size (cm)	RQD (%)
121.92	123.44	1.3	16.5	0
123.44	124.66	1.3	10.2	0
124.66	126.19	1.3	7.6	0
126.19	127.71	1.3	8.9	0
127.71	129.24	1.3	10.2	0
129.24	130.76	2.0	12.7	8
130.76	132.28	2.5	12.7	0
132.28	133.50	1.3	8.9	0
133.50	134.72	1.3	8.9	0
134.72	136.09	1.3	8.9	0
136.09	137.62	0.5	7.6	0
137.62	139.14	1.3	6.4	0
139.14	140.67	1.3	6.4	0
140.67	142.19	0.5	7.6	0
142.19	142.95	0.5	5.1	0
142.95	144.48	0.8	9.5	0
144.48	145.39	1.0	5.7	0
145.39	146.91	1.3	25.4	12
146.91	148.44	2.5	22.9	8
148.44	149.96	2.5	12.1	0
149.96	151.49	5.1	10.2	0
151.49	152.40	5.1	12.7	0

ground operation was fragmented into "cave breccia," a term used to describe an unconsolidated breccia material. The impacts of block caving on the rock mass likely make San Manuel unique to most other existing or potential operations considering the in-situ leach extraction technique; this should be kept in mind during the remaining discussion.

Mineral reserves

The San Manuel ore reserves published in 1999 (BHP Technical Oxide Planning and Projects Group, 1999) followed the Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (JORC code, which can be found at http://www.jorc.org/) because the mine was owned by an Australian company. It included a comprehensive ore reserve report for San Manuel for the years 1996 to 1999. Due to the uniqueness of in-situ leaching, there was very little previously published material that could be used for comparison.

During the 1990s, the proportion of copper extracted at San Manuel via the in-situ method increased. Plans to ramp up in-situ production following the closure of the open pit in 1995 required a better understanding of the potential copper recovery using the in-situ method. In 1993 and 1994, wellfields were tested to more accurately determine the amount of recoverable copper. Ramey, Wiley, and Rex (1993) and the BHP Technical Oxide Planning and Projects Group (1999) determined that the fluid would reach 70% of the leachable copper minerals (sometimes referred to as the sweep factor or sweep efficiency) and that 75% of the leachable copper minerals would be recovered. This suggested an overall expected recovery of 70% × 75% = 52% of the acid-soluble copper (ASCu) within the supergene zone, which was composed primarily of chrysocolla and copper-rich clay minerals. From 1995 to 1999, the reserve estimates of the in-situ leaching operation are based on this recovery formula.

Fluid saturation

The operating conditions of an in-situ leaching operation will affect the amount of saturation and the likely sweep efficiency to be used to determine recovery. Heap leaching, which is the mainstay of copper oxide extraction, operates only in partially saturated conditions (Rucker et al., 2015). in-situ leaching may need to operate in saturated or unsaturated conditions depending on the local situation. San Manuel operated within the dewatered area of the open-pit and underground workings. Early attempts at using in-situ leaching at San Manuel resulted in little barren leach solution being returned after injection into the ground. It was concluded that the solution had to build up in the rock mass, thereby producing somewhat saturated conditions, before fluid would be available for collection. This was confirmed as San Manuel operations progressed and a nearly saturated zone built up under leach. Newly created wells adjacent to the existing wellfields encountered some level of saturation, indicating that the solution was migrating beyond the active wellfield; however, there were difficulties maintaining fluid levels near the surface. Even though the orebody was exposed at the surface, in some parts of the open pit it was not feasible to maintain fluid levels all the way, or even close, to the surface because slope failure due to seepage out of the pit walls was a concern. In addition, the lack of automated injection wells caused fluid levels to rise and fall daily, resulting in unsaturated conditions near the surface.

Figure 2 shows the cross section of a controlled-source audio-frequency magnetotelluric (CSAMT) survey performed within the San Manuel open pit (Carlson, Zonge, Ring, & Rex, 2000), which was used to track the fluid saturation of the wellfields. The vertical axis topography shows the open pit outline and the 20 ohm-m contour was considered the limit of fluid saturation. The survey indicated that a substantial portion of the wellfield was saturated, but a few areas were only partially saturated—near the open-pit surface, the upper pit benches, and the base of the pit slope. Note that the extended saturation zone (areas greater than 20 ohm-m) from the base of the pit to the 1,200 ft. level matches the old underground workings, where much of the solution migrated.

Well spacing

Well spacing can lead to differences in recovery rates. Determining optimum well spacing is a complex endeavour that ultimately must be deposit specific; factors like capital costs, fluid flow, fracture intensity, grades, and copper recovery must be considered. During the 1990s, attempts were made to maintain a 12.1 m corner-to-corner well spacing at San Manuel. Open-pit benches at San Manuel were typically 18.3 m in height and approximately 19.8 m from toe to crest with some variability. The availability of pit benches and the necessity of keeping a set distance between the wells and the toe and crest locations typically resulted in a double row of wells on each bench with the rows spaced approximately 6.1 to 12.1 m apart. The distance to the adjacent row on the next bench was approximately 12.1 to 18.3 m. This spacing was determined early in the operation through trial and error. In the last year of operations, the spacing was increased to 15.2 m to reduce capital costs and because the particular zone that was being developed was anticipated to have a large underground collection component. Underground collection normally resulted in higher grades due to the longer flow paths of more than 100 m through the rock mass. It was expected that the expanded well spacing would not impact production rates but would result in a significant reduction in the capital cost.

Given the limitations at San Manuel, including the pit bench limitations and complex faulting, it was necessary to keep well spacing at or below 15.2 m. Projects such as Taseko Mines Ltd.'s Florence (Florence, Arizona) and Excelsior Mining's Gunnison (105 km east of Tucson, Arizona) proposed 21.6 m corner-to-corner well spacing, which might be functional if these projects encounter less complex environments and require substantially lower capital costs in order to be more economic while still maintaining high sweep efficiency.

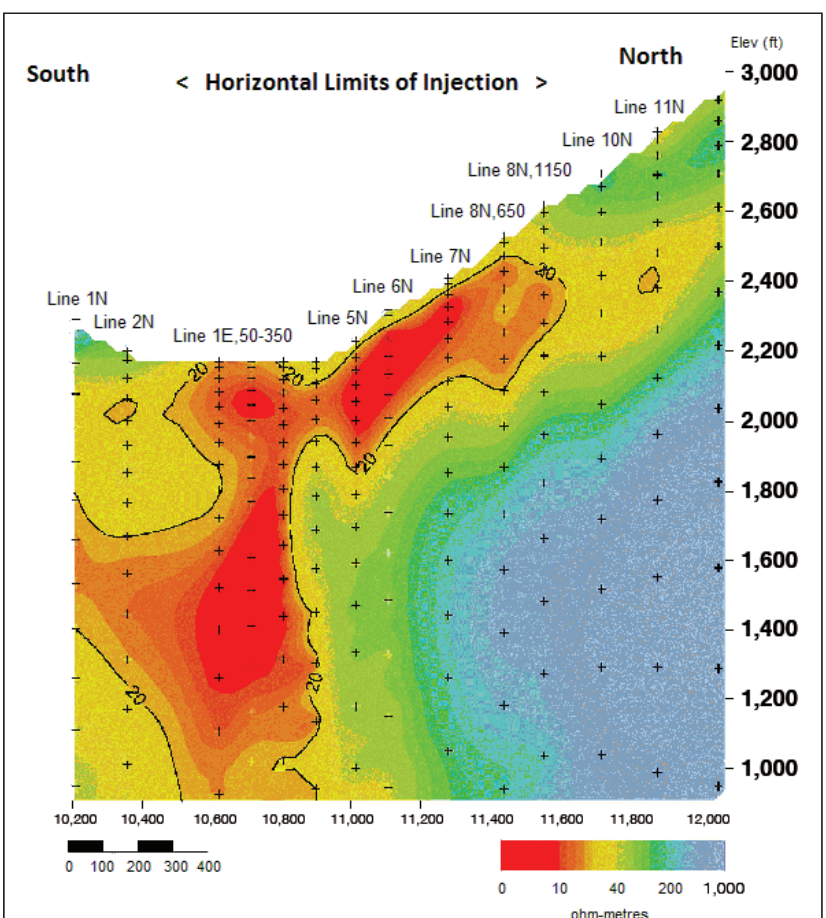

Figure 2. Cross section of a controlled source audio-frequency magnetotelluric survey performed within the San Manuel open pit (from Carlson et al., 2000)

Channelling effects

One of the concerns with in-situ leaching is the possibility of fluid becoming channelized and either not reaching or insufficiently reaching all available fracture surfaces. This problem is also faced by heap leach pads. In the in-situ case, however, it is difficult to determine the scale of channelling unless the leached rock mass can be examined. Fortunately, in the case of San Manuel, a handful of diamond drill holes cored within the leached rock mass could be analyzed.

Diamond drill hole SMO9607 (drilled May 6, 1996, in zone 6, on bench 2460) is representative of the effects of leaching after the area had been under leach for approximately 3 years. It is possible that the leach solution had been in the area or the adjacent area for several years prior;

this was corroborated by other drillcore that exhibited similar characteristics. It is estimated that by the time drillhole SMO9607 was drilled, the in-situ leaching operation had recovered approximately 35% of the ASCu; however, it should be noted that underground collection was allocated to zones based on operational experience and precisely which bench and zone it came from was not known.

Figure 3 shows the ratio of acid soluble copper grade to total copper grade (ASCu/TCu), which gives a good representation at a macro scale of the effects of leaching on the rock mass. As previously noted, the orebody is a copper porphyry, which has a relatively high level of homogeneity with regard to rock type and copper grade. Figure 3 shows the effects within the supergene zone, where the copper ore consists primarily of chrysocolla with some copper-rich clays. No sulfide minerals were observed in this interval. The typical ASCu/TCu ratio of unleached materials was 75–80% in the supergene zone of the deposit. It can thus be inferred that copper has been leached wherever the ratio falls significantly below 70% within the supergene zone. Additionally, physical characteristics noted in the core log identifies the areas with low ASCu/TCu ratios as portions that show the effects of leaching, whereas the high ratio areas do not show leaching effects. Leaching effects show on the core as gypsum precipitates and powdery white residue. The following two paragraphs relay specific measurements and comments from two sections of core.

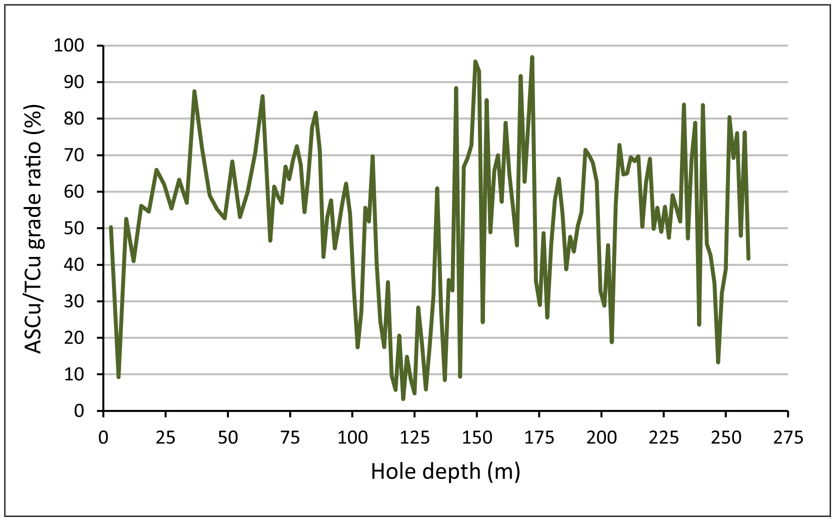

Figure 3. Grade ratio of acid soluble copper (ASCu) to total copper (TCu) in drillhole SMO9607 at the San Manuel mine

The interval from 86.9 to 140.2 m shows strong leaching effects. The average grade is 0.45% TCu and 0.13% ASCu, which is a 32.2% ASCu/TCu ratio. The entire interval has been logged, with the rock type being a monzonite porphyry displaying fairly typical copper porphyry characteristics and not containing any significant fault material. Common core descriptions include strong leaching effects and moderate quantities of gypsum. This interval has fairly typical copper porphyry characteristics and does not contain any significant fault material.

The interval from 140.2 to 172.2 m shows only limited leaching effects. The average grade is 0.59% TCu and 0.35% ASCu, which is a 67.6% ASCu/TCu ratio. For the entire interval, the rock type is a monzonite porphyry. Common core descriptions include little to no leaching effects and little to no gypsum present. One of the bigger differences from the previous interval is that the presence of gouge and breccia is recorded several times. The phrase “gouge and breccia” was commonly used at San Manuel when the rock mass had been considerably brecciated by faulting and block caving. The elevated amount of fine-grained material in the breccia may have been a barrier to fluid flow. This was a potential cause of channelling in the operation.

If leaching is occurring only in select areas where solution has been flowing through the rock mass for extended periods of up to several years, as Figure 3 suggests, then the cause of the channelling needs to be considered. Although this paper does not comprehensively address the exact cause of channelling, a number of observations are shared here. As demonstrated by the CSAMT survey, the entire rock mass was not saturated. There were numerous fault surfaces in the orebody that could have acted as conduits or barriers to fluid flow. The faults are commonly up to 1 m thick and composed of brecciated material with clay. The wellfields are delineated by zones that are defined by fault boundaries. As was described in the core interval from 140.2 to 172.2 m, there was a considerable amount of fine-grained material present, which could have inhibited fluid flow. It is also possible that activating pump wells too early would not give the injection wells enough time to saturate the rock mass. Once preferred flow paths are established it may be difficult to correct the situation.

Original grades in the supergene zone of the San Manuel deposit were on the order of 0.50–0.80% ASCu, based on the grade of unleached rock and the expectation that the original grade would have been similar in the leached areas. Figure 4 shows the ASCu grade for drillhole SMO9607 as an illustration of the subsequent reduction after leaching. In areas of strong leaching, the ASCu is nearly depleted (approximately 0.03%).

The amount of copper that appears to have been recovered in some of the areas that have been well leached should be determined. A good example is the interval of drillhole SMO9607 from 109.7 to 112.8 m. Samples and assays were taken at 1.5 m increments; therefore, this example represents two separate assays that essentially produced the same results. Both samples included the presence of gypsum in the

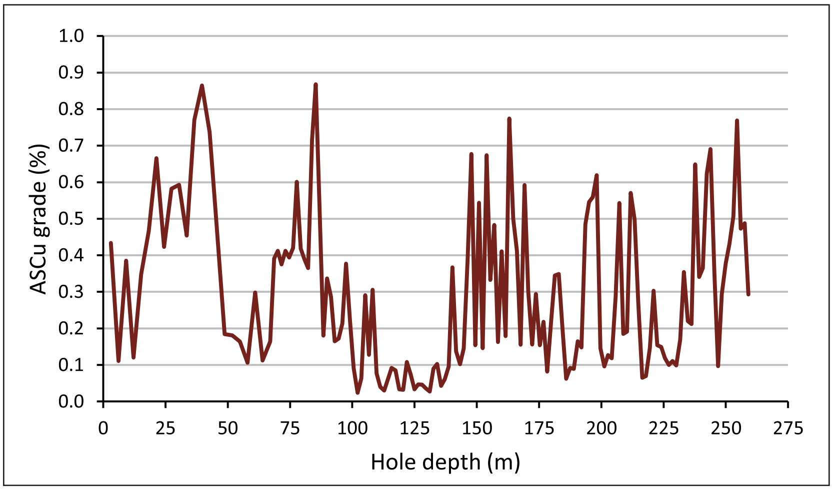

Figure 4. Acid soluble copper (ASCu) grade of core from drillhole SMO9607 at the San Manuel mine

highly fractured rock, which has almost the consistency of gravel. The interval was composed of the monzonite porphyry, which hosted the mineralization, and strong leaching effects were seen. The total copper (TCu) grade based on assays of the interval (Figure 5) was 0.168% and the ASCu grade (Figure 4) was 0.035%. It should be noted that this interval was entirely within the supergene zone and no copper sulfide minerals were present. This zone showed extensive leaching and may have had leach solution flowing through it for three or more years; however, the ASCu grade was not 0% here or in other results from this hole, nor in numerous other holes. If the residual ASCu grade of 0.035% is close to the ultimate limit of depletion and typical starting grades in the orebody are 0.40% and higher, then a recovery of 90% of the ASCu can be presumed if the leach solution reaches the rock mass in an area. It should be noted that this presumption is based only on small-scale observations because this degree of leaching was not found over complete core intervals and instead only in a small number of core holes drilled in the deposit after the initiation of leaching.

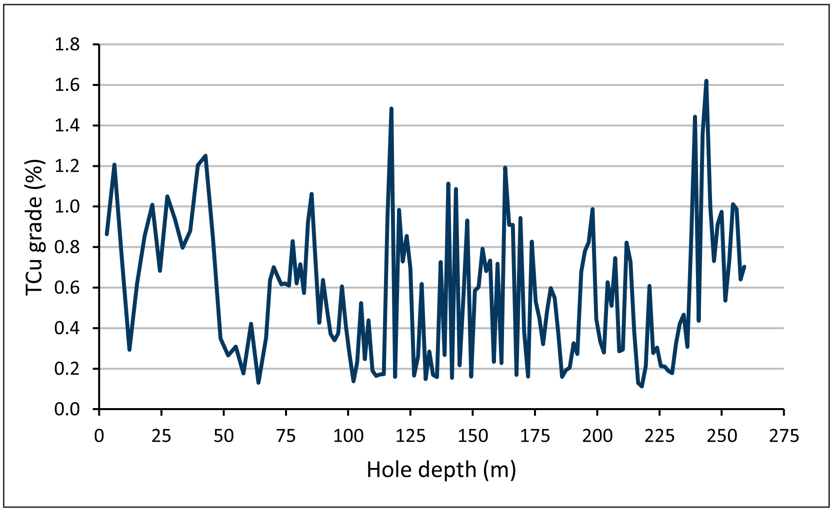

Figure 5. Total copper (TCu) grade of core from drillhole SMO9607 at the San Manuel mine

Effect of gypsum precipitation (selenite crystals)

The presence of gypsum in the form of selenite crystals was prevalent in rock chip samples from well drilling. Because well drilling was normally done immediately adjacent to existing wellfields, leach solution was commonly present in the areas being developed for new wells. Also, during the 1997 core drilling campaign, several holes were drilled in active leaching areas. After drying the core from these holes overnight, the surface of the core was sometimes coated with selenite crystals the next day.

The exact effect of selenite on production from the in-situ operation was not clear. Were the crystals present and, if so, were they the observed size prior to drilling, or did crystal growth occur after rock chips and core were removed from the ground? It seemed that both scenarios occurred. Rock chips from well drilling showed the presence of selenite crystals as soon as they were recovered. Because only a few minutes of time had passed, not enough time for significant crystal growth, these crystals developed underground. In the case of core drilling, crystals grew on the cores overnight when exposed to the air.

As leaching occurs, material is dissolved and removed from the rock mass, opening up pathways for the solution to travel; gypsum may have partially filled these new open spaces. Records illustrate, however, that many wellfields experienced decreasing flow rates. This may have been caused by gypsum plugging up the rock mass, although no scientific study has been done on this issue. Several other factors may have caused decreased flow rates, such as ground subsidence shearing wells off, pit bench failures, and seepage from pit walls. The presence of gypsum in drillcore and the geochemical modelling completed on the Florence project showed that the saturation concentration of gypsum was reached in most leach tests (Sinclair, 2015). This issue should be considered for future in-situ leaching operations because it might have a significant impact on the sweep efficiency used in reserve calculations.

Other factors

A number of other factors should be considered with respect to production reconciliation. The factors that had perhaps the largest potential effect on reconciliation at San Manuel were the ASCu assaying, the challenge of attributing production to the correct wellfields, and the use of the block modelling method.

The ASCu analysis method used by the San Manuel laboratory would not meet today's best practice standards. The San Manuel method consisted of measuring a specific quantity of pulverized sample, placing it in a sulfuric acid bath for a set period of time, rinsing, and performing atomic absorption analysis. To the best of the author's knowledge, all assays were completed by the internal San Manuel laboratory. A small number of assays were sent to external labs for comparison, where "check samples" or duplicate samples were assayed to validate and verify. During an internal 1997 core drilling campaign, check samples, duplicate samples, and third-party lab assays were implemented and it was found that there were some discrepancies in the results from the San Manuel lab. Furthermore, during the Gunnison project prefeasibility study, M3 Engineering (2014) noted that the San Manuel laboratory was a non-independent lab and that because they were not reproduced during re-assaying done in 2014, the original results were not used in their study. The Florence project prefeasibility study (M3 Engineering, 2013) includes a detailed explanation of the "San Manuel" method for ASCu assays. During the 1990s, there were several ASCu assaying methods used in Arizona. Although all were relatively similar, each did have its idiosyncrasies. Even though the assay quality would not meet today's standards, the San Manuel laboratory produced consistent internal assays for the mine site and recoveries from the heap leach pad met with those expectations (i.e., 85–87% of ASCu).

Attributing copper production to the correct block model areas was complicated. The challenge with any reconciliation effort is trying to compare what was produced to where it came from. Just as an open-stope mining operation will be in production in multiple zones with differing geology and grades at the same time, in-situ leaching draws from areas with differing geology and grades, which leads to the challenge of determining the correct location from which the copper is leached. At San Manuel, there were a couple of factors to consider. First, a portion of the copper production came from collecting PLS from the old underground workings. Because the distance from the bottom of each well to the workings was more than 100 m, partially saturated conditions were encountered, and fluid migration could be controlled by unknown fault surfaces, it was never known precisely from where production had originated. Operationally, increases in flow rate when new zones were put online gave some indication of the source, but not with a high degree of accuracy. The second issue was that there was a gradient. The orebody was inclined, and solution migrated toward the bottom of the pit. Because of this, it was expected that the solution being pumped probably originated from the adjacent injection wells and, in part, from the injection wells in the bench above. The amount of solution coming from each location could not be determined exactly.

Developing the 3D block model for the resource was more challenging than typical block models. In 1995, the first resource block model was created specifically for the in-situ operation. Prior to that, the model had been designed for open pit operations. An immediate challenge in creating the 1995 block model was that leaching had already taken place and creating a 3D block model that was representative of the current conditions was not possible; therefore, the 1995 model relied on drilling data that were collected prior to any in-situ leaching in the area or, where possible, more recent drilling data if the area had not been affected by the in-situ leaching. Additionally, ground subsidence had occurred since the original drilling campaigns, causing the ground level to drop. Drillhole collars had to be manually adjusted to reflect the new ground level but ground subsidence had not been entirely vertical, resulting in a less than ideal drillhole dataset.

Copper production from zone 6

Of the 16 named zones at San Manuel, zone 6 is the best one to use to compare production history with the reserves for reconciliation because it was in production for the longest period of time and was near its economic limit at the time of mine closure. Based on the mine economics, a resultant PLS grade of 0.20 g/L copper was determined as the cut-off grade for economic processing. Keeping in mind that it was difficult to attribute production to exact wellfields, looking at an entire zone does give a good indication of the potential total recovery. Zone 6 was, however, below the average grade for the deposit, so it might not be representative of recoveries everywhere in the deposit. Recovery might be tied to starting grade for this type of operation, with higher starting grades resulting in higher recovery rates. This has not yet been studied in sufficient detail to be conclusive. For reconciliation purposes, wellfield production was reported by the zone and open-pit bench where the leaching operation was located. Production statistics for zone 6, including the starting ASCu grade from the block model, the available ASCu (in kg), the copper production attributed to each bench, and the calculated recovery of ASCu are listed in Table 2. Note that this zone was still in production at the time of mine closure and would likely have approached 50% recovery by the time economic limits were reached.

Reconciliation

Reconciling the copper recovered from an in-situ leach operation is complex and there are many uncertainties. Even with good operational data, it is difficult to exactly determine the origin of the dissolved copper. Looking at a larger scale is a better approach because solutions can migrate along unknown paths and dissolved copper can come from anywhere along that flow path. Because there have been few in-situ copper leaching operations in the world and even fewer that have used the well-to-well recovery method, there is insufficient information available

Table 2. Production data from zone 6 at San Manuel mine; ASCu (acid soluble copper)

Bench	Block model ASCu grade (%)	Available ASCu (kg)	Cu production (kg)	ASCu recovery (%)
2340	0.423	15,182,041	7,121,400	46.9
2400	0.469	12,283,126	5,216,308	42.5
2460	0.480	11,633,005	4,082,328	35.1
2520	0.479	14,580,695	6,486,366	44.5
2580	0.398	11,199,172	4,762,716	42.5
2640	0.375	11,094,283	5,669,900	51.1
2700	0.341	18,892,391	7,779,103	41.2
2760	0.347	9,487,860	3,764,814	39.7
2820	0.342	7,440,730	2,449,397	32.9
2880	0.336	2,538,315	430,912	17.0
2940	0.312	571,011	165,561	29.0
Total	–	114,902,618	47,928,799	–
Average	0.406	–	–	41.7

in the literature regarding what kind of recovery could be expected. Most research has relied on laboratory testing to infer potential recovery rates. San Manuel was one of the largest scale well-to-well in-situ copper leaching operations in the world; even so, it only partially leached the orebody and mining approached economic limits only in a limited area. As discussed above, zone 6 had the longest operational history of any zone brought online at the operation. The operational data suggest that approximately 42% of the ASCu was recovered and that 50% recovery could have been reached if mining had continued. The grade at zone 6 was slightly lower than the average grade of the deposit, so it may not reflect the recovery for the entire operation. With respect to reconciliation, the reserves were based on 52% recovery of the ASCu and production came close to supporting that figure; therefore, on a macro scale, it seems that production would have eventually matched the expected recovery. The two main components that were used to determine the expected 52% recovery rate were a sweep factor of 70% and an ASCu recovery of 75%. The post-leaching core hole data suggest that the ASCu recovery was closer to 90% based on short core intervals; this results in a calculated sweep factor of closer to 55%.

A second way to test the reconciliation would be to drill core holes in the same location before and after leaching. This would seem impractical for the entire deposit because it would require twice the number of holes drilled; however, at San Manuel there was one instance of a second hole (SMO9607) being collared in the leach area 18.3 m away from an original hole (ARM158) collared prior to leaching. The distance apart makes them a less-than-perfect example; however, being a copper porphyry deposit the grades did not tend to change that much over these distances. For comparison, the typical range value found in the variography was 76.2 m. This method of comparison is even less accurate than the well production method. Nevertheless, since few data exist regarding the reconciliation of reserves at a well-to-well in-situ leach operation, the comparison is worth mentioning.

Hole ARM158, drilled prior to leaching, had an average grade of 0.53% ASCu from 0 to 213.4 m. SMO9607, drilled after approximately 3 years of leaching, had an average grade of 0.31% ASCu from 0 to 213.4 m. The difference in grade is a reduction of 42%. This area continued to be leached for three additional years after hole SMO9607 was drilled, although at a much lower production rate. Production data suggests that approximately 35% of the copper had been removed by the time SMO9607 was drilled and that a further 7% was recovered after the hole was drilled. Although this is not a highly accurate method of comparison, it does indicate an ASCu recovery in the 50% range at the San Manuel mine.

DISCUSSION

Although the reconciliation indicates that San Manuel was on track to recover approximately 50% of the ASCu from one of its zones, one should not conclude that other operations will experience the same results. Operations in higher grade zones at San Manuel appear to have achieved higher recovery rates. Other deposits may not have the amount of faulting that existed at San Manuel and certainly few deposits will have to deal with the effects of ground subsidence from block caving operations. Channelling appears to have been a significant issue at San Manuel, as indicated by the limited data available. This might not be as significant an issue at other operations, particularly if they are working in saturated conditions or refrain from pumping until the injection wells have saturated the rock mass.

The recoverable ASCu was estimated at 75% for the mineral reserves at San Manuel and an expected sweep efficiency of 70% was used in the reserve calculation. The challenges maintaining fluid saturation and the apparent channelling effects meant that 70% sweep efficiency was probably an overestimate. In reality, at least one of the main zones in operation might have been achieving a sweep efficiency of only 55%. It is possible that other operations could achieve sweep efficiencies of 90% or greater, particularly if they did not encounter the complications that occurred at San Manuel. Whereas 90% ASCu recovery was achievable on the small scale—in a 3 m length of core—the main reason that 90% did not seem to be recoverable at the deposit scale was that the fluid flow was not able to reach all of the fracture surfaces where copper mineralization occurred. This issue is related to sweep efficiency, not leachability. The fact that 90% could be leachable on a small scale should indicate that it can be applied to the larger scale.

If mineral reserves were to be reported at San Manuel today, it would probably be more accurate to use a sweep efficiency of 55% and a leachability factor of 90% to produce an overall ASCu recovery of 50%. This would be a positive outcome for future projects planning on using this extraction method because they are unlikely to encounter the extent of issues that San Manuel faced with faulting and the effects of block caving and thus will likely have a much higher sweep efficiency.

Reconciliation will continue to be challenging for future in-situ leaching operations. A number of steps should be taken to better determine the location that the copper is being recovered from: Real-time flow rates should be determined for each recovery and injection well; copper grades in the injected leach solution and PLS grades from each recovery well should be measured at a minimum of daily using an automated system; and hydrogeological models should be created to estimate the fluid flow paths and volume of fluid moving from each injection well to each recovery well. These analyses will result in a more accurate representation of the source of the copper being collected. It is expected that good sampling and assaying techniques and better 3D block modelling practices will also improve understanding and results.

CONCLUSIONS

in-situ leaching operations are not yet common in the copper industry; however, the positive economic results from San Manuel, coupled with the currently anticipated start up of two advanced-stage projects in Arizona, may mark the beginning of the widespread use of this environmentally friendly, low capital cost, feasible extraction method. Being able to accurately reconcile the mineral reserves with copper production is, therefore, of increasing importance.

From 1993 to 1994, wellfields at San Manuel were tested to determine the amount of copper that could be recovered from in-situ leaching of the supergene zone, which was composed primarily of chrysocolla and copper-rich clay minerals. It was determined that the leach fluid could reach 70% of the copper minerals and that 75% could be leached for an ASCu recovery of 52%. For future projects or operations, a pilot test might not be feasible. Studies using flow modelling and fracture analysis have been used to estimate the sweep efficiency, as in the case of the Florence and Gunnison projects.

Determining the amount of recovered copper in a discrete area of rock mass can be done by post-leach core drilling or a combination of flow modelling using daily flow rate collection and solution grades. San Manuel was able to use both methods. The final results of tabulating many years of daily flow rates and grades from the zone 6 wellfield showed that approximately 42% of the ASCu was recovered, indicating that the sweep efficiency was closer to 55%. Comparison of drillcore assay data from two closely situated holes, one drilled before (ARM158) and the other after (SMO9607) leaching, also indicates that approximately 42% of the ASCu was recovered.

The discrepancy between the predicted (52%) and actual (42%) recovery is likely related to a combination of factors, including difficulty maintaining fluid saturation, channelling effects, and gypsum precipitation. These recovery rates do not necessarily indicate what other projects may achieve because each deposit will have its own unique characteristics.

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Gary Sutton was the competent person for declaring reserves at the San Manuel in-situ leaching operation. His work included 3D geological modelling, locating boreholes for the wellfields, and submitting requests for capital expenditures. He now consults on a number of in-situ leaching projects worldwide. **sutton.gary@gmail.com**

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