Understanding the leaching efficiency of the Hydro-Jex® technology

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Abstract

Hyper-Leach experiments were conducted on oxide ore and flotation tailing samples to determine the effect of pressure at room temperature to simulate the in situ leach reaction during Hydro-Jex® stimulation. Some experiments show double the gold extraction in 30% of leaching time at room conditions. Hydro-Jex technology is in situ leaching of a heap and Hyper-Leach is the name of the new technology used for high pressure leaching found during Hydro-Jex operation.

Precious metals leaching extraction was higher than anticipated during the short time span of stimulation in the interior of a heap using Hydro-Jex. Normal heap leach kinetics involves days to months, so having a high gold recovery during the pumping simulation for a few hours is above expectation.

The concept of previously leached precious metals inventory due to capillary solution migration being held in place without a solution flow to sweep the values to recovery can explain some of the solution grade response to the Hydro-Jex stimulation. But test work on drill samples reveal only a small quantity of precious metal values fit this sweep affect.

Operational experience with the technology does show a remarkable increase in dissolved oxygen in the leaching solution pumped deep into the heap via Hydro-Jex. Dissolved oxygen is essential in the leach reaction and may be deficient in the interior of a mature heap. But this alone may not explain the rapid kinetics of leaching in a few hours during stimulation.

Is there another phenomenon responsible? Theorizing high oxygen solubility, adequate leaching lixiviants and high pressure may be the answer. The results are named high pressure leaching or Hyper-Leach™.

Introduction

Nearly 30% of the world's gold production is from heap leaching operations − 236 metric tons gold/yr (Marsden, 2006). Thus, heap leaching is an important hydrometallurgical process for the mining industry. Mature heap leach pads may retain 6-8 % of the recoverable metal values even after the final rinse operation. A heap is defined as mature herein when the ore is no longer being placed on the pad. This is usually due to achievement of the permitted maximum height, or the mine discontinuing ore mining. The stacked ore has a variety of local void spaces and volumes of material that are compacted. The heap may also contain zones where the chemistry may affect the quality of the drain-down solution as meteoric water passes through the pad. Hydro-Jex is a 3-D leach technology invented to recover the stranded metal inventory from the pad while reducing the heap rinse time and changing the chemistry of targeted zones. This technology is used widely in the United States and is available to aid operators worldwide during leaching and rinsing before heap leach closure.

Operations that use the Hydro-Jex technology experience higher precious metal recovery to the pregnant solution than predicted from the short time span of stimulation in the interior of the heap. Normal heap leaching is measured in weeks and months. Hydro-Jex stimulation induces barren solution and additional reagents for a short duration of hours per zone targeted to re-channel the pad and reduce dilution while adding reagents for enhanced leaching during a later rinsing phase.

After working many years as a metallurgical manager for several large heap leach operations and now utilizing that experience to teach the art of heap leaching in a university setting, the authors has the opportunity to develop operational hypotheses on observations made during a variety of field operations, experiments and tests. Thanks to the support of the mining companies operating in Nevada, the authors have been able to test a hypothesis of determining the effect of in situ leaching at elevated pressures in a laboratory setting to explain the improved metal recovery from the Hydro-Jex technology.

Hydro-Jex Technology Development and Operational Review

A brief overview of the Hydro-Jex technology is presented as a basis for the hypothesis of improved precious metal dissolution with elevated pressure.

As the ore is stacked higher and a heap grows taller, the ore weight settles and the voids at the lower lifts compresses with a resultant lower permeability. Figure 1 shows the change in permeability for a typical Carlin-type heap to a permitted height of 91 m (300 ft).

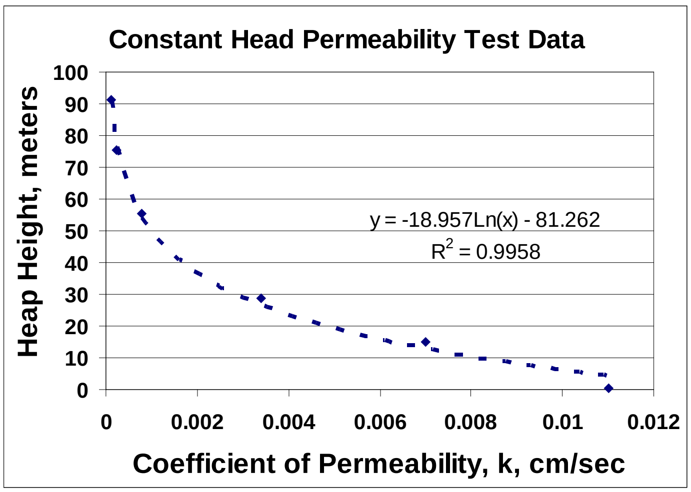


Figure 1: Laboratory testing Carlin-type ore, coefficient of permeability per depth in a heap, of (Seal, 2004)

Besides heap settlement, zones in the heap's interior display reduced permeability due to truck and equipment compaction, inadequate ripping of lifts after ore placement, lack of adequate agglomeration, migration of fines, clay zones, and chemical precipitation. Heap leach operational experience and laboratory experiments show that the application rate should not exceed the percolation rate, or the solution will flow horizontal and channel downward (Bartlett, 1998). Thus in the interior of a heap there may be zones of low permeability where the surface application of lixiviants will channel around the material containing the un-leached or under-leached metal recovery. These compacted zones become mostly unavailable to standard surface solution management leaching and rinsing techniques. Thus the un-recovered metal values recognized as inventory in a heap are found in these un-leached or under-leached zones in the heaps interior (Seal, 2007).

A Carlin Trend heap leach pad is shown in Figure 3 being re-sloped at 2.5 (H) : 1 (V) in preparation for closure and to allow uniform solution application for a side slope leaching program (Seal, 2005). These side slopes had been extensively leached for years prior to the re-sloping, Figure 2.

Figures 2 and 3: Side slope leaching then re-sloping a Carlin-type ore heap.

The re-sloping was conducted in the early spring of 2002. The effect of the re-sloping on the gold recovery is displayed in Figure 4 (Seal, 2003). Thus rearranging the material in a heap will enhance gold recovery upon releach.

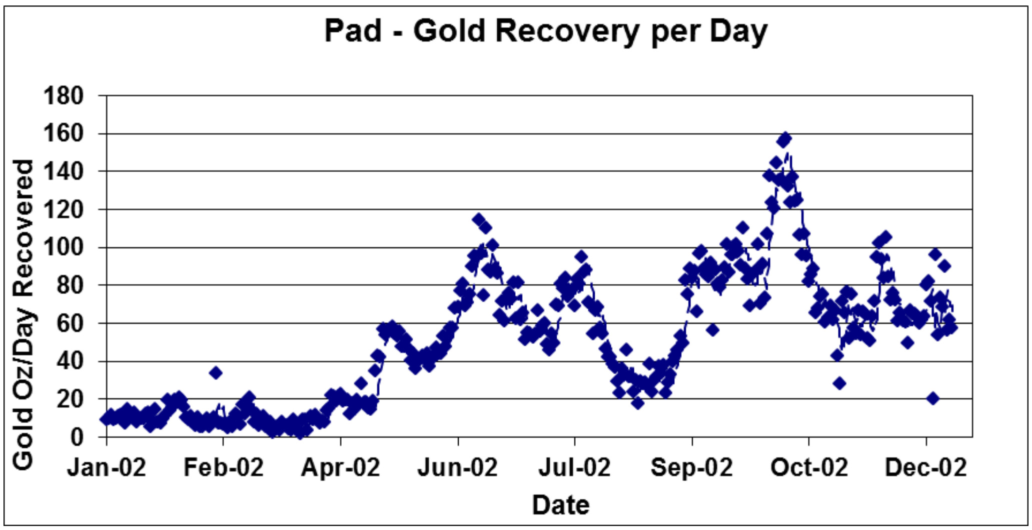
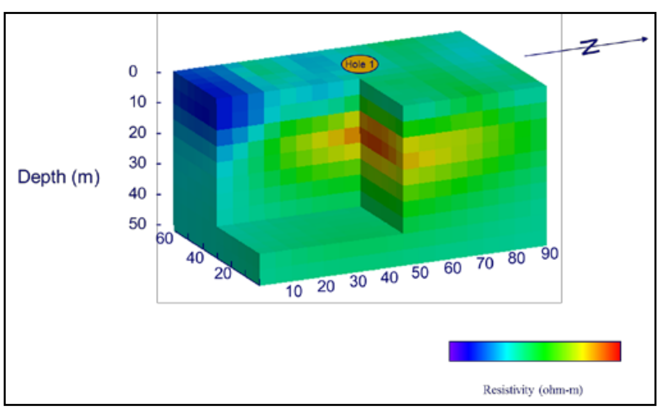
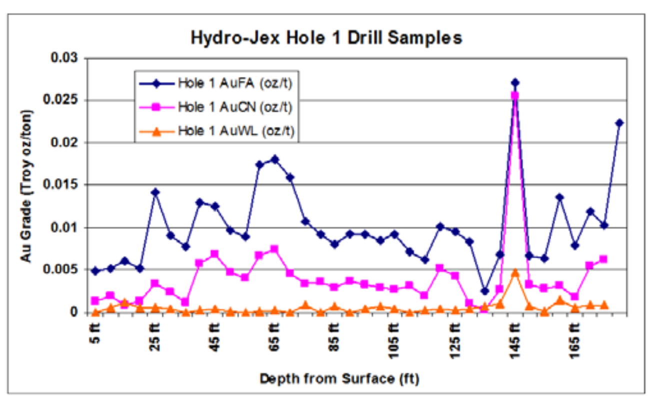


Figure 4: Enhanced gold recovery from re-leaching a re-sloped Carlin-type ore heap.

Figure 5 shows a geophysical resistivity survey of the location of a dry zone with a sampled drill hole in the cut away. The assays of that drill hole are displayed in Figure 6.





Figures 5 and 6: Heap resistivity survey with a dry zone and drilled well with and assay data.

The assay data in Figure 6: AuFA is gold by fire assay, AuCN is cyanide soluble gold determined by a cyanide shake test and AuWL is a new test for determining the amount of gold dissolved and leached or rinsed with water or water leach (WL), and all units are troy ounces per dry short ton. Thus the dry zone in Figure 5 shows the location of un-leached or under-leached metal and the shadow or umbrella effect of a low permeably zone channeling the leach solution away from leachable inventory below. The key to recovering this metal inventory is to transport the lixiviants to the unleached or under-leached zones to leach the metal values and rinse the pregnant solution from the individual rock surfaces and micropores.

Acknowledging the concept of moving material during the re-sloping and the resulting enhanced gold recovery, a technology was utilized to mobilize the material in situ by injecting high pressure barren solution and is called Hydro-Jex for water chemistry hydro-lixiviant solution injection and metal extraction (Seal, 2004). The technology basically involves drilling and sampling a heap leach pad and installing a well with zone perforations. The zones are isolated using standard drill tools, and high-pressure solution is pumped in, to open solution pathways and channels, achieving 3-D leaching. In addition, any pumpable solution or slurry can be metered into a specific location in the interior of the heap. Due to the encasement of all the solutions delivered into the heap's interior, strong reagents can be used without environmental concerns. The reagents are mixed and diluted with other fluids that make up the pregnant solution flowing from the heap. The horizontal component of the solution profile ranges from a 30 to 48 m (98-157 ft) radius, Figure 7, depending on the depth of the targeted zone and the size distribution of the rock in the heap (Seal, et al. 2011). Geotechnical studies show a static factor of safety against slope instability of greater than 1.5 during the pumping and the follow-up rinse process (Seal, 2008).

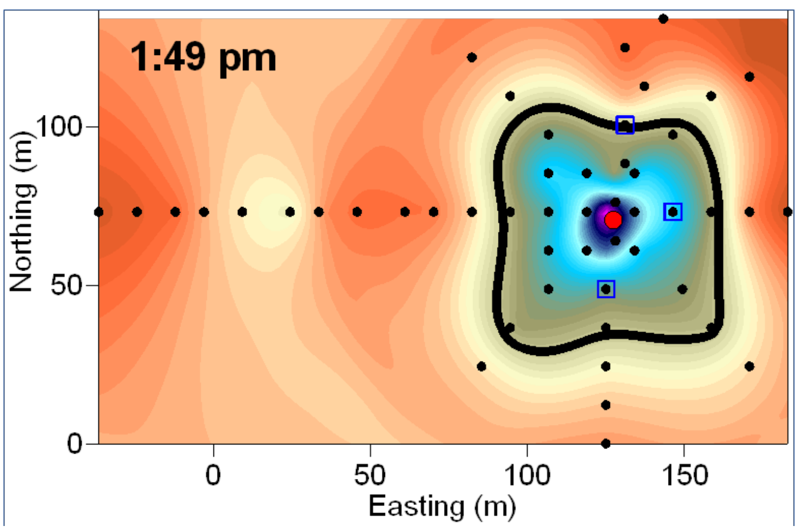


Figure 7: Resistivity survey monitoring of a Hydro-Jex stimulation in a heap leach operation.

Hydro-Jex wells are designed with casings driven down holes drilled in the heap and perforated at target depths as shown in Figure 8, corresponding to locations identified as having high concentrations of residual gold and/or adverse chemistry (Seal, 2007). Assays on cuttings obtained during the drilling can be used to refine understanding of subsurface conditions; but Rucker (2010) showed that assaying alone may not be adequate for describing the spatial distribution of hydrological and metallurgical parameters and that these parameters can be better described by coupling traditional assays with electrical resistivity characterization.

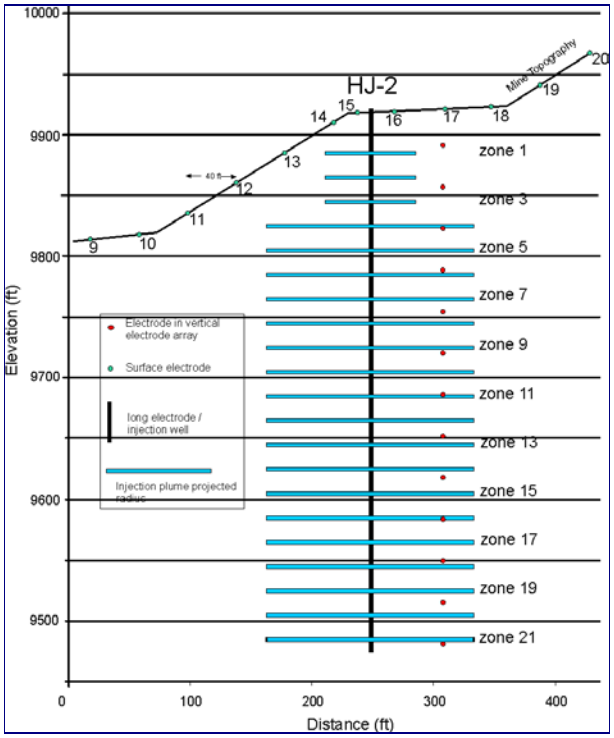
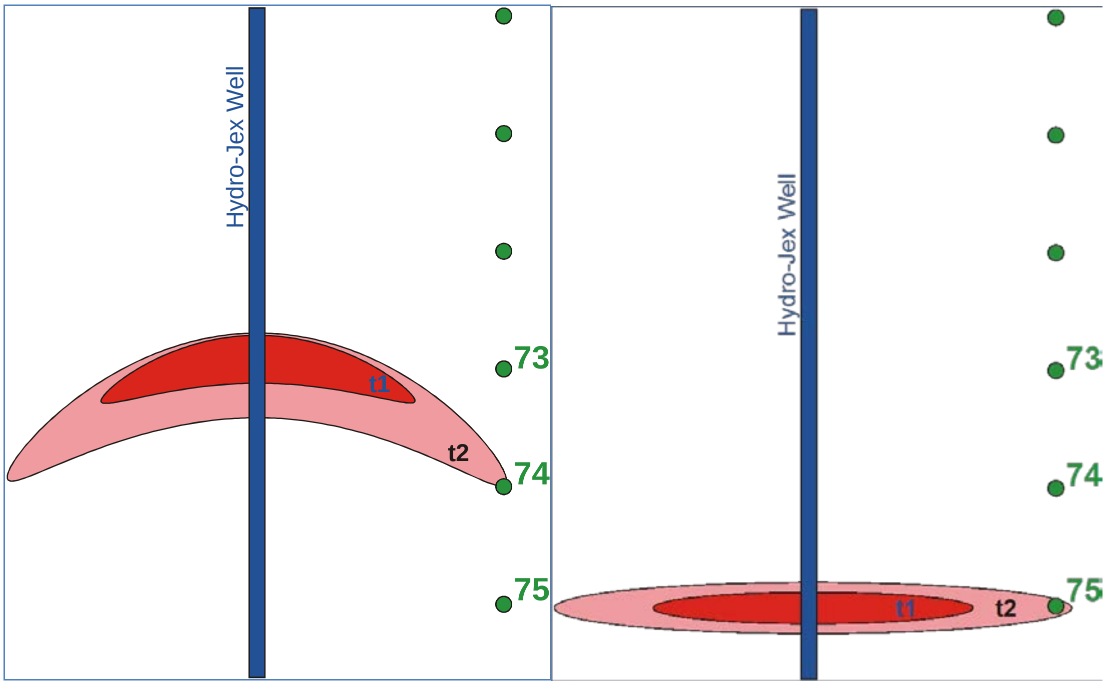


Figure 8: Typical Hydro-Jex well above HDPE liner with zones identified for treatment.

Through a welded wellhead attached to the casing, a high-pressure pump is used to force solution down into the interior of the heap creating new solution paths while adding reagents to targeted zones of under-leached ore, Figure 9. A downhole isolation mechanism isolates each zone and controls the depth at which solution enters the heap allowing specific areas to be targeted. Multiple depths can be targeted and treated by repositioning the isolation system. The injection solution initially flows horizontal with very little vertical component, until in-heap solution friction allows gravity to slope the pumped solution profile as shown in Figures 10 and 11, where resistivity sensors were placed adjacent to the Hydro-Jex well (Seal, et al. 2011). With low internal pH in the heap, milk-of-lime slurries can be added to the injection operation to change the pH in the zone and alter the pregnant solution pH. In a normal gold heap, the void space has sufficient oxygen to dissolve into the fluid film encompassing the rock particles. As heaps reach greater depths, the void volume decreases and if organic carbon and/or sulfides are present in the heap, the oxygen concentration in the void space decreases or is non-existent. Leaching gold and silver requires dissolved oxygen and if oxygen is depleted, then leaching kinetics are reduced. The Hydro-Jex technology mixes sparged air into the injection fluid to reach 11−13 ppm dissolved oxygen, as determined in bench scale tests (Seal, 2004).

During this stimulation phase, any combination of reagents can be added to the solution pumped down the well to accelerate gold dissolution or remediate any adverse chemical conditions. The final stage of the process consists of periodically irrigating each well with leaching solution to rinse the dissolved gold to the liner and to further enhance chemical changes.

Figure 9: Typical Hydro-Jex apparatus hooked to barren line on a heap near a heap crest (Seal, 2013).



Figures 10 and 11: Hydro-Jex solution pathway depending on ore properties and stacking direction.

Typical Hydro-Jex® stimulation lasts for about 3 hours per zone and achieves pressures in situ up to 2,070 kilopascals (300 psig).

Gold recovery from two heaps that underwent Hydro-Jex treatment are presented in Figures 12 and 13. Gold recovery at Cripple Creek and Victor (CC&V) was about 4,300 troy oz or over 8 ounces/stimulation hour.

Hypothesis

Typical heap leaching occurs over periods of weeks and months. A 3 ft cyanide column test on a crushed oxide ore is presented in Figure 14.

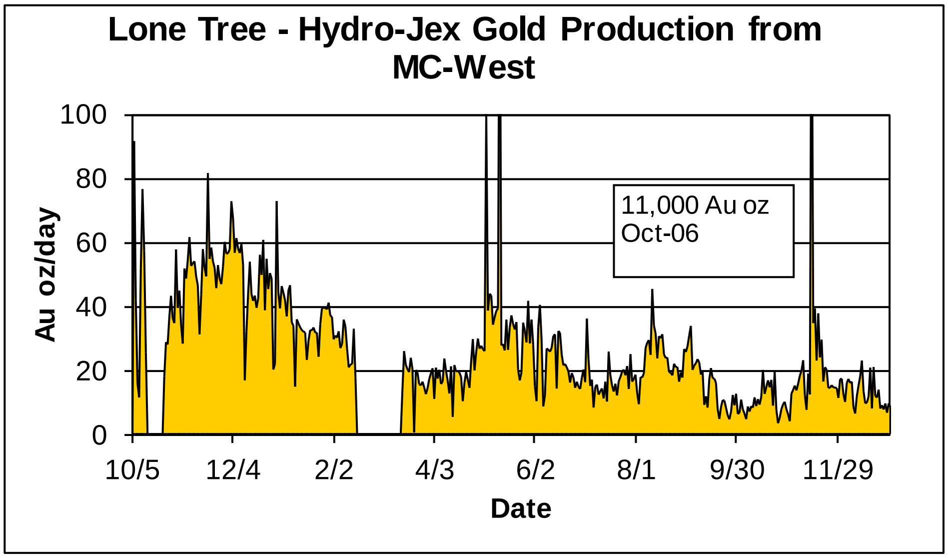


Figure 12: Increase in gold production from 10 t oz per week by Hydro-Jex stimulation on a pad (Seal, 2008)

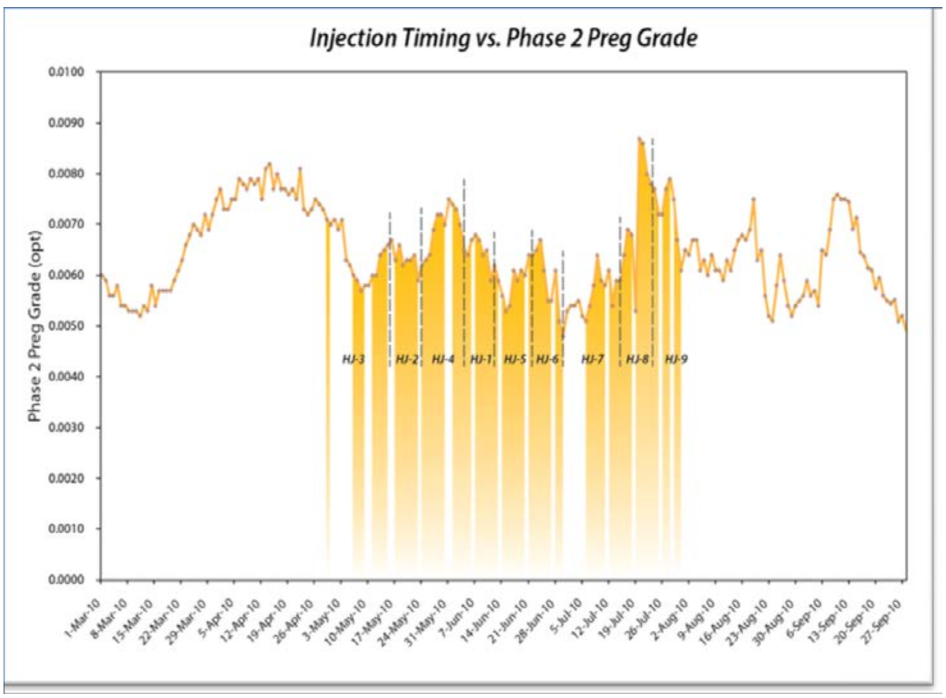


Figure 13. Pregnant solution grade vs. time at CC&V. Shaded areas for active injections. (Seal, et al. 2011)

The breakthrough grade was 0.0009 Au oz/ton solution after about 48 hours post-solution application. Only 5.5% of the extractable gold (AuCN) was recovered in about 72 hours with a solution grade of 0.04 Au oz/ton solution. What would be the extraction in just 3 hours, using pressure cyanide solution injection, like during Hydro-Jex stimulation? There must be a different a mechanism that promotes a faster recovery.

One possible hypothesis is that during the Hydro-Jex stimulation the injected fluids rinse away leached metal values that are contained in the rock micropores after normal surface solution application for a long period of time when barren solution migrates horizontally through a low permeability zone via capillary action, but these metal values are not swept away under surface applications. This hypothesis may contribute to the recovery, but examining Figure 6, the values of precious metals available for rinsing is relatively low. Another possibility to explain the higher than enhanced recovery is the presence of sparged and dissolved oxygen in the stimulation fluid.

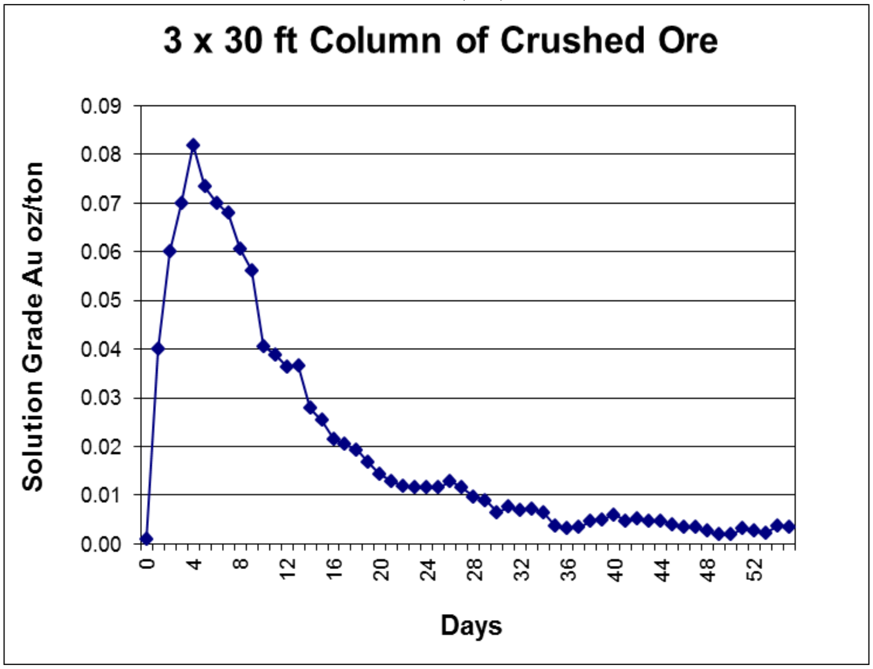


Figure 14. Pregnant solution grade vs. time with a 3 ft cyanide column test on crushed ore

Often, in situ dissolved oxygen is at a minimum within a mature heap if any sulfides, bacteria or organic compounds are present to utilize the available oxygen, thus there is not enough dissolved oxygen for the gold leach reaction. Calculations show that oxygen solubility in water at 25^{o}C increases from 8.3 mg/l at 101 kilopascals (14.7) psi to 51.8 mg/l at 621 kilopascals (90 psi) (Duru, 2014). But the observed leaching kinetics from a well aerated column leach test viewed in Figure 14, still lack the kinetics observed during the pressurized stimulation treatment.

While the above contribution to gold recovery by enhanced oxygen solubility and sweep efficiency may be significant, the key may be in the pressurized solution itself.

Effects of Pressure

When a viscous fluid is injected within unconsolidated and non-cohesive particulate matter, the flow regime will depend on the ratio of inertial to viscous forces as described by the Reynolds number. At low Reynolds numbers, less than ten, the flow can be described by Darcy's Law with the hydraulic gradient (***i***) proportional to the seepage velocity (q):

$$i = -Rq \qquad (1)$$

Where ***R*** is the hydraulic resistivity (reciprocal of hydraulic conductivity). Fluid pressures within the host media in this regime are sufficiently low that the overburden principle effective stress that holds the media rigid is not exceeded and the fluid simply flows away from the injection source as leak off. When pressures are increased and inertial forces greatly exceed viscous forces, the flow is considered non-Darcian and the gradient is proportional to a nonlinear seepage velocity (Basak, 1977):

$$i = -aq^{m} \qquad (2)$$

Where ***m*** is a fitting parameter that relates, empirically, the relationship between gradient and velocity, and ***a*** is the hydraulic resistance. At low Reynolds numbers the value of ***a*** approaches the value of ***R*** in Equation 1, but at progressively higher Reynolds numbers, the turbulence itself adds a head loss due to friction (Bordier and Zimmer, 2000), causing the value of ***a*** to diverge from ***R***. At this stage, the mechanical drag forces imposed by the higher velocity are still too low to move particles away from the wellbore and the pressure is still lower than the overburden principle effective stress caused by the weight of the overlying heap. (Wu,2006) refers to this as a fixed bed flow.

As injection pressures are increased further, the internal fluid pressures eventually exceed the overburden pressures and the flow regime changes dramatically. (Wu,2006) explained that for these pressures and fluid velocities, cavities can form near the injection point, and three stages of cavity evolution can be explained as: (1) cavity initiation in the vicinity of the injection point when the velocity of fluid reaches a certain critical value (a schematic of the cavity formation near the wellbore is shown in Figure 15 A; (2) stable cavity development and fracture initiation in response to each increment of velocity increase (Figure 15 B); and (3) unstable cavity propagation after the injection velocity reaches a second critical value. Furthermore, (Wu,2006) explains that these stages can be explained by considering the drag forces applied to the particles by the fluid continuously seeping through the particle assembly. The drag forces cause particles to move away from the injection point, thus the particulate material is unloaded which causes a tensile volumetric strain in its vicinity. Once this strain reaches a critical value, corresponding to the loss of contact between the particles in all directions, a cavity forms. This critical strain value corresponds to the “fluidization” of the particle-fluid mixture (Wu 2006). When the injection velocity increases, the cavity or fracture begins propagating until it reaches a stable state.

Figure 16 shows the surface pressure imparted to the formation via Hydro-Jex treatment where pressure is measured in time. Note the fracture initiation and formation breakdown in the curve, the two drops in pressure sections.

Thus, the hypothesis for testing in the laboratory is to determine the effect of pressure on cyanide leaching of a typical gold ore as compared to room pressure.

Methodology

High pressure cyanide leaching experiments were conducted on two different samples, Golden Days oxide ore and flotation tails (CIL Feed). The Golden Days ore total gold (AuFA) and cyanide soluble gold (AuCN) contents were 0.222 and 0.213 troy ounce per ton, respectively, whereas flotation (flot) tailings samples AuFA and AuCN amounts were 0.028 and 0.0124 troy ounce per ton, respectively, which is refractory. Fire assay analyses showed that Golden Days oxide ore has nearly eight times more gold content than the flotation tailings. The cyanide leachable gold content for the Golden Days samples was 96% of the total gold content. The cyanide shake tests showed that 44% of the total gold amount was amenable to cyanide leaching for the flot tails sample (Duru, 2014). This flot tails sample nearly reflects a post heap leach sample in grade and recoverability.

Standard metallurgical laboratory procedures of crushing, splitting, grinding and fresh sample preparation prior to the leaching experiments were utilized, so the test data can be compared. Pressure cyanidation tests were conducted in order to determine the kinetics of the gold extraction with pressures higher than atmospheric conditions at room temperatures. The pressure leaching experiments were carried out in a stainless steel Parr Instrument pressure reactor which could maintain a maximum pressure of under 690 Kilopascal (100 psi). The rotational speed of the impeller inside the pressure vessel was controlled by a variable stirrer motor.

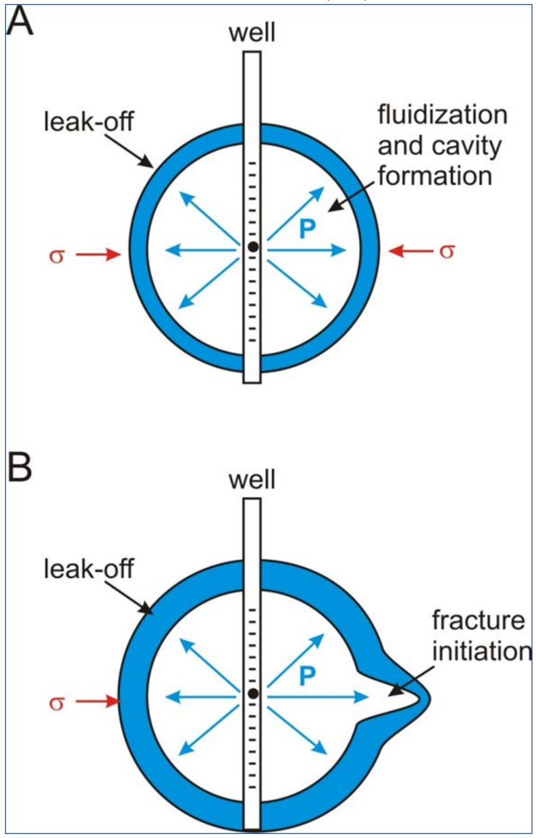


Figure 15. A) Cavity generation and B) fracture initiation during injection. Figure adapted from Chang (2004). P =pressure and σ =effective stress.

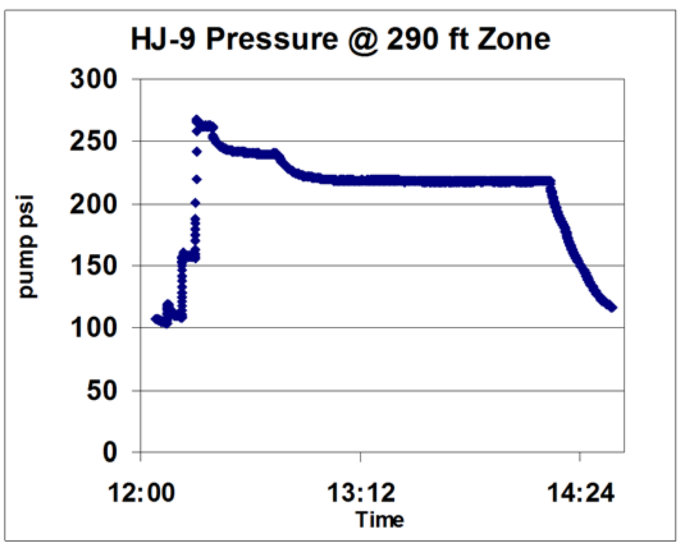


Figure 16. Surface pumping pressure profile at the CC&V mine (Seal, et al. 2011)

All the pressure experiments were compared to an industrial standard cyanide bottle roll test (BRT), with initial rotational speeds for both the BRT (81 rpm) and pressure reactor (400 rpm) adjusted to establish near identical kinetics prior to any high pressure leaching. The pressure for the reactor was supplied from a standard commercial air and nitrogen gas cylinder and desired pressure was maintained by means of a two-stage regulator mounted on the cylinder. Care was taken to leave the head space air in place for the gold leach reaction. Slurry samples were withdrawn from the reactor through a dip tube shared with a gas inlet valve. An illustration of the pressure reactor is displayed in Figure 17.

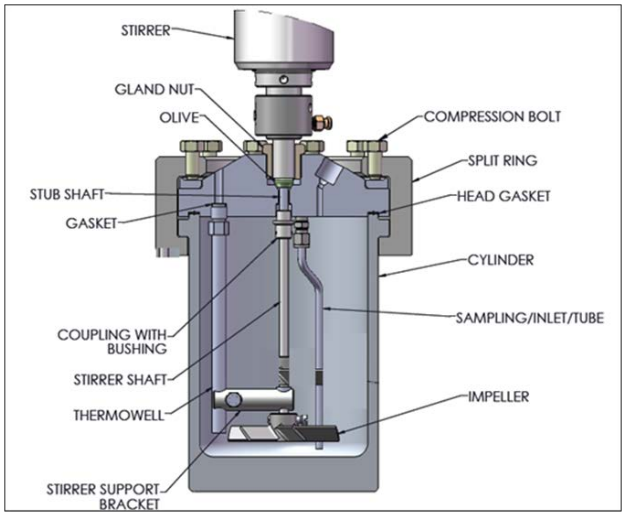


Figure 17. Pressure Reactor (Autoclave) Cross Section

Cyanide bottle roll tests were conducted in order to assess gold recoveries by the standard cyanide leaching technique. Ore was fed to a 1 gallon glass bottle with pre-determined amounts of water, cyanide and base (Duru, 2014). Care was taken to have identical ground ore samples (P_{80}<200 mesh), precent solid pulps and reagent quantities in the leach experiments for comparison of only the effects of pressure. Solid gold analyses were conducted by an outside industrial metallurgical lab. Pulp solutions were centrifuged and freshly analysed using a standard atomic absorption spectrometer (Varian Specta 55B). The average room pressure in Reno, Nevada was 85.5 kilopascals (12.4 psi).

Results and Discussion

Heap leach kinetics on large particles for short time intervals of minutes and hours is beyond the ability of the laboratory facilities at the University of Nevada, Reno (UNR). Thus, ground samples were cyanide leached and studied to determine the effect of pressure by comparing the kinetic leach curves from standard BRT tests with those conducted in a pressurized reactor (autoclave). The kinetic leach curve for the higher grade oxide ore is presented in Figure 18.

Gold extraction was 42% higher at 2 and 4 hours at 621 kilopascals (90 psi) when compared to a standard BRT at 85 kilopascals (12.4 psi), room pressure at the same grind size, percept solids, reagent concentration, temperature and near identical stirring speeds. Another way to examine the effects of pressure is the 621 kilopascals (90 psi) test extracted 64% of the gold in 4 hours compared to 66% extraction in 8 hours for nearly a 50% reduction in time. It is important to note that the leach grind size is much smaller than the size of material in a heap leach pad, but merely displays the improved leach kinetics displayed with increasing only the pressure on this oxide ore. To investigate the possibility of oxidation of ore material with compressed air during the cyanide leaching process, a duplicate experiment was run with compressed nitrogen gas instead of air as presented in Figure 19. No discernible differences were observed.

Further cyanide leach experiments were conducted on the lower grade, lower recovery ore material, a flot tail, CIL feed as displayed in Figure 20**.** Gold extraction was 360% higher at 2 and 250% at 4 hours at 621 kilopascals (90 psi) when compared to a standard BRT at 85 kilopascals (12.4 psi), room pressure at the same grind size, percent solids, reagent concentration, temperature and near identical stirring speeds.

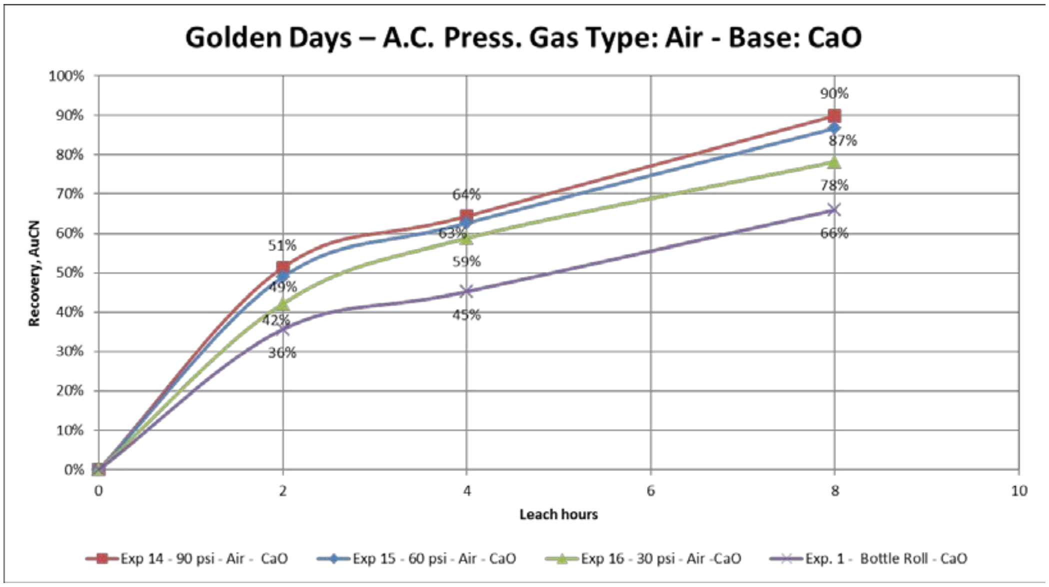


Figure 18. Bottle Roll vs. Pressure Experiments – Air, CaO

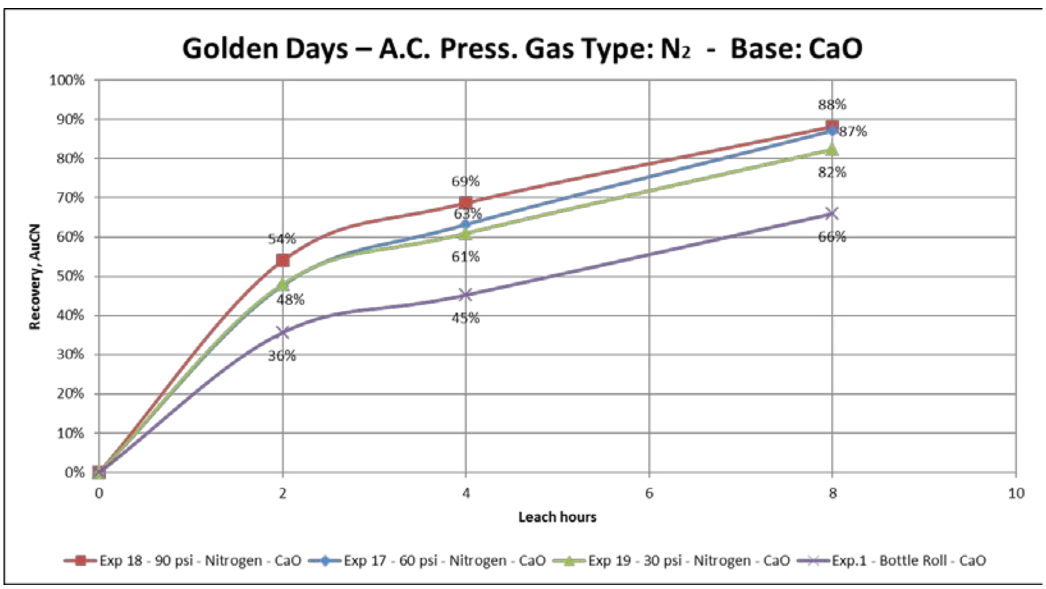


Figure 19. Bottle Roll vs. Pressure Experiments – N_2, CaO

Another way to view these experiments is that at 621 kilopascals (90 psi) and two hours leaching time the gold extraction was 18%, slightly higher than room pressures experiments at 8 hours leaching for a gold extraction of 16%, thus 25% of the normal retention time of normal BRT leaching. Definitely faster leach kinetics! Additional experiments were conducted where the use of nitrogen gas was substituted for compressed air in the pressurized experiment and showed no significant difference from air experiments.

It is clear for the experiments conducted at UNR that pressure cyanide leaching shows substantially improved leach kinetics and recovery when compared to leaching at room pressure and temperature on ground ore. It is theorized that similar enhanced leach kinetics are present during the zonal high pressure stimulation used with the Hydro-Jex technology.

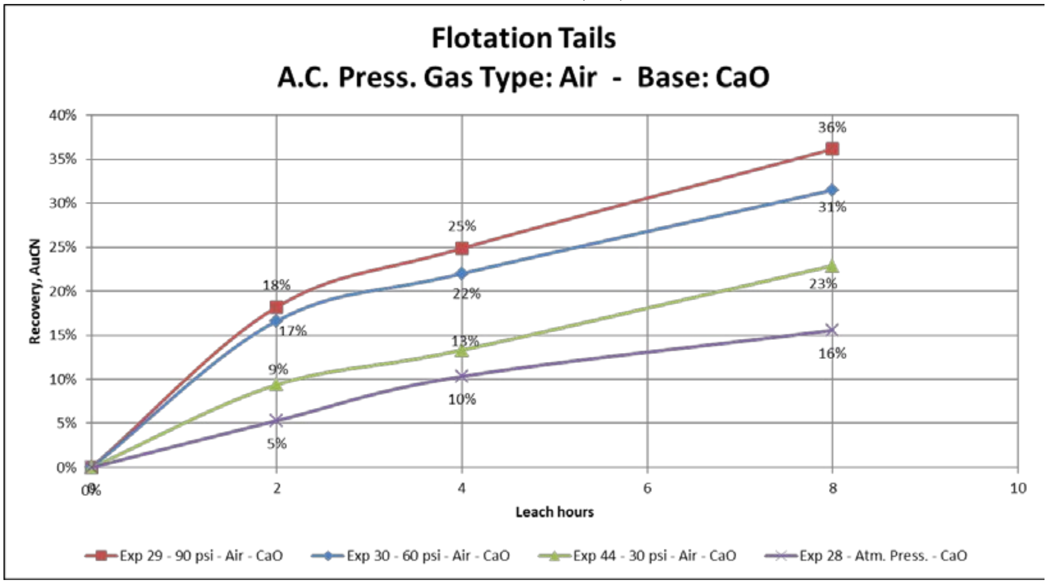


Figure 20. Bottle Roll vs. Pressure Experiments – Air, CaO

This improved recovery experienced with Hydro-Jex is a combination of improved sweep efficiency, enhanced dissolved oxygen solubility for the leach reaction and the impact of in situ pressure to significantly improve the leach kinetics and metal recovery of un-leached and under leached metal as inventory in a mature heap leach pad.

Conclusions and Recommendations.

Further experiments are planned to infuse the pressure in a UNR laboratory setting with solution pumping instead of by an introduced gas. A new larger reactor is being assembled for larger samples and higher pressures. Additional experiments on the kinetics of leaching and oxidation of ore material will be conducted using a host of lixiviants and various ore types beyond just precious metals. This technology is being called Hyper-Leach™. A provisional patent application has been submitted. Financial support for this research at UNR is encouraged.

Several heap leach operations are experimenting with single zone barren solution injection or solution feed systems. It is becoming very clear that these systems can impart a perched water table in the interior of a heap and will significantly dilute the preg grade of the solution flowing to the recovery system if conducted over an extended period of time. In addition, these systems only treat one elevation per well. The key to the efficiency of the patented Hydro-Jex technology is imparting high pressure to a zone to rechannel the heap's material for a short period of time, enhancing oxygen solubility and sweep efficiency plus newly understood and improved leach kinetics due to elevated pressure. The technology can easily move up and down the well and stimulate zones selectively and then rinse the zones equally selectively in the heap material treated, as shown in Figure 21.

During normal heap leaching of ore using unsaturated flows, no additional pressure is added to the leach solution during the leach cycle. In fact, the Hydro-Jex technology supplies sufficient hydraulic energy to mobilize the particles and rechannel the internal heap solution migration profile to allow efficient reagent delivery and expand sweep efficiency, while eliminating any perched solution build up in the heap by providing new channels for solution infiltration and migration. This technology is the answer to heap blinding where the solution migration is horizontal to the pad's exterior, where it can exit as seeps. Thus using Hydro-Jex will reduce heap slope instability and the need for inter-lift liners.

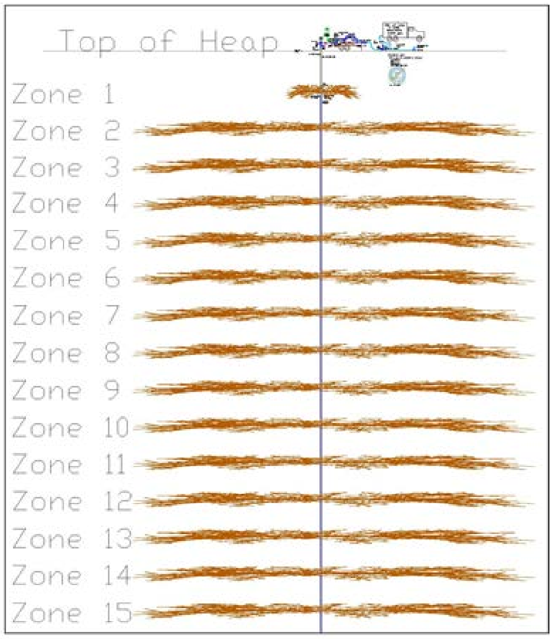


Figure21. Hydro-Jex zonal treatment in a heap leach pad.

Hydro-Jex offers a new solution management tool for operators of heaps by targeting, stimulating and leaching dry zones of under-leached inventory containing recoverable metal values and has the ability to change the internal heap leach chemistry while shortening the rinse and closure cycle. This technology should be used on every mature heap leach operation prior to closure.

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