Proceedings of Heap Leach Solutions, 2015
September 14-16, 2015, Reno, Nevada, USA
Published by InfoMine, © 2015 InfoMine, ISBN: 978-0-9917905-8-6

Leach pad monitoring and control through instrumentation

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Abstract

The success of a copper heap leach is dependent, in part, on the ability to deliver the right amount of raffinate solution to the right places. This concept is especially critical at Freeport-McMoRan's Safford Mine, where the acid-consuming nature of the ore requires a high level of precision regarding where the raffinate flows are delivered. This is to ensure the right amount of acid per tonne of ore is delivered over the leach cycle, which is the primary driver in achieving targeted copper recovery. Prior to 2013, the irrigation system at Safford was flow-controlled based on a single flow meter for the heap with manual adjustments made on valves at each ~8,000 m^2 module. This basic system did not meet the precision needed for Safford ore, which led to the development of a state-of-the-art control and monitoring system.

Development of this system required overcoming a number of challenges including materials of construction, portability, power requirements, wireless operation, and cost/benefit. Taking these obstacles into consideration resulted in the creation of a portable, self-contained unit consisting of a wireless pressure transducer, a wireless orifice plate flow meter, and a pressure-regulating valve. One unit was installed on each module on the leach pad, for a total of 230 units. These devices allow the individual raffinate flows to be monitored on a real-time basis, with the regulator maintaining a consistent pressure to each module. This system also records the flow and pressure data for each module, providing historical information over the course of the leach cycle. This data has also provided secondary benefits such as monitoring flushing efficiency, monitoring real-time drip emitter plugging rates, and instantly alerting operators of any piping failures. This new system has been very successful in improving the monitoring and control of raffinate flows to the Safford leach pad.

Introduction

Freeport-McMoRan Safford is a mine-for-leach operation that started production in 2007. Ore from the mine is crushed and agglomerated, then placed on the leach pad using a portable conveyor stacking system. Placement of ore began on the first phase of the leach pad (Phase I) in 2007, with the expansion to the directly-adjacent second phase (Phase II) in 2012. Each phase is approximately 2,300 m (7,500 ft) in total width. The ore is then leached with a weak sulfuric acid solution, generating pregnant leach solution (PLS) that is processed through the SX/EW circuit. Electrowon copper cathodes are the final product of the operation.

The ore body at Safford is predominantly oxide, with chrysocolla making up the primary copper mineralization of the deposit. The ore is also characterized by the large amount of acid-consuming gangue materials that exist within the deposit. These two factors are the drivers for the high acid consumption. Sulfuric acid is introduced into the process in two locations. The first location is during the agglomeration process, where 35-45% of the total required acid is introduced immediately to the ore. The second location is through acid contained in the raffinate, where the remaining 55-65% of the required acid is delivered over the full leach cycle. Because of the relatively high percentage of total acid delivered via raffinate, correct flow distribution across the leach pad is critical to ensure the correct amount of acid is being delivered to the ore.

Process description

The ore is retreat stacked in cells that are nominally 125 m (420 ft) in width, and are currently 400 m (1,300 ft) in length on Phase I and 500 m (1,700 ft) in length on Phase II. The irrigation system is designed to follow the stacking pattern, and has a primary feed line on each cell that feeds from the opposite end of the stacking equipment. The area on the top surface of the ore is broken up into modules that are 65 m (210 ft) in length and 125 m (420 ft) in width, and are fed from the primary feed line on the cell. Raffinate is pumped to the feed lines through a pumping system consisting of a raffinate tank located at the SX circuit with an in-line booster station. Each module is irrigated using drip irrigation at application rates ranging from 4.9–6.1 L/h/m^2 (0.002–0.0025 gpm/ft^2), with sulfuric acid concentrations ranging from 9–14 gpl. Raffinate flows are determined for each module through a pressure targeting process. Drip irrigation lines have a pressure/flow relationship that is defined by the manufacturer. This creates a simple correlation using the module surface area to convert from application rate to pressure. To reach the desired application rates, pressures for each module are targeted to 100, 135, or 170 kPa (15, 20, or 25 psi), with application rates varying based on ore characteristics within the module.

Raffinate flow controls were very basic prior to 2013. The pumping system had a single control loop located at the in-line booster station that consisted of a single flow meter and a variable frequency drive (VFD) placed on the motor of one of the four pumps. The VFD was set up to control the flow out of the in-line booster station, which was also the full raffinate flow to the leach pad. A control system was also established for flows at the module level, but was completely manually operated. Each module consisted of a 10 cm (4 in) butterfly valve and a manual pressure gauge at the connection with the feed line, which would be manually adjusted based on the targeted pressure for the module. The leach pad would have to be walked 2 to 3 times per day with modules being adjusted each time to maintain their targeted pressure values. Manual data was collected for each module once per week providing a snapshot of how the full system looked at that time. Process engineers would walk the entire system and record manual readings from the pressure gauges. All of this information was compiled and a report was generated based on what was seen at the time of the walk-through.

Because of the sensitivity of the ore being stacked, this monitoring method raised questions about whether the precision of the system could meet the optimal acid application needs of the ore. The aggressive acid-consuming nature of the ore makes it very sensitive to changes in acid delivered, even over a short duration. In addition, the kinetics of the copper leach recovery are not linear. Areas that have been below their flow target cannot be caught up by simply raising flows to average out the application rate. The probability of variance across the system was high with an irrigation system that, prior to 2013, could only automatically control the full system flow of 4,100 m^3/hr (18,000 gpm) relying solely on manual adjustments at each of the 102 operating modules. Since that time, the system has expanded to 8,200 m^3/hr over 220 operating modules. These concerns led to the bigger issue of not knowing what was happening at the module level. Total flow to the leach pad was tracked in real time, however data at each module was only tracked once per week. Even when total flow was at target, there was no way of knowing what was happening at each of the individual 230 modules over the 7-day span between data points. It also raised the concern that there would not be a way to see increases in precision if they were implemented in the system.

Development and implementation

To address the concerns with the existing system, a process needed to be established that would improve the precision of the raffinate flows to each module on the leach pad while providing feedback to indicate the level of precision being achieved. The first step in this process was to identify the basic principles that would need to be incorporated into the existing system to meet this objective. There were two necessary categories identified. The first category was automatic flow control that would react to any changes in the system. The second category was remote flow and pressure monitoring to provide immediate feedback on what was taking place. Ideally, these would be located at the module level where manual adjustments and monitoring were already taking place. The module level is a preferred control point on the system since it is the closest point to the ore possible and would provide feedback that is realistic to the conditions being fed to the ore.

Incorporating these two categories into the existing system ultimately led to the development of a portable self-contained unit known as an “instrumentation skid,” or simply a skid. One skid is installed at each module, and consists of a wireless orifice plate flow meter, a pressure regulating valve, and a wireless pressure transmitter connected in series with standard piping and enclosed within a protective frame. There are currently 230 modules over 33 cells between the two phases of the leach pad, with 220 modules in operation at a given time. Implementing such a system on this large of a scale required overcoming a whole different set of challenges, which included materials of construction, portability, power requirements, wireless operation, and cost/benefit considerations.

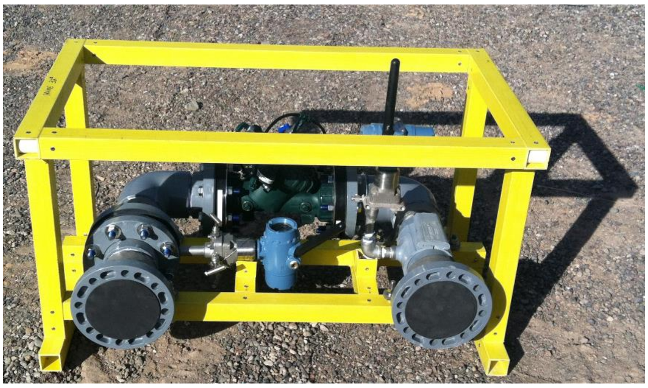

Figure 1: Instrumentation skid

Instrument selection

To begin development of the device, the instruments needed to be selected in order to measure the flow and pressure. The main objective of these instruments was the ability to remotely communicate the data back to the central network for real-time feedback and tracking. Many of the instruments in use at Safford at the time connected to the network using a hard-wired fiber optic connection. This option would have required fiber optic lines to be installed; none existed on the top surface of the leach pad. This option was deemed to not be feasible for several reasons. Any lines that were installed would have to be removed prior to placing a new lift, and then need to be reinstalled once the ore was stacked. Also, fiber optic lines would have to be run along every single cell to capture each installed skid. Instead, the more feasible option was to utilize a wireless communication system. This type of system required antennas as part of each instrument to transmit a signal out that would be received by a central data collection point, known as a gateway. The gateway would be connected to the network by a hard-wired connection that would allow the data to be transmitted back to the network. When fully implemented the system would consist of 460 individual instruments spread out over 1,300,000 m^2 (14,000,000 ft^2), which required a detailed network design to ensure reliability of the wireless connections. Gateways were strategically placed around the perimeter of the leach pad at the base where fiber optic lines were available. The gateways were located lower than the top surface of the leach pad, which required signal repeaters along the crest of the top surface to communicate the signals from the surface down to the gateways below. The individual instruments would be placed at the ground level, which required additional signal repeaters along each cell to help transmit the signal to the repeaters along the crest.

Once the communication system was determined, the next challenge was determining how to provide power to the instrumentation. For the best results, the instruments need to operate for the full leach cycle. Prior to 2013, the cycle time was 120 days. This has since expanded to 280 days. Line power was not an option due to the same concerns as providing fiber optic lines for communication, leaving solar power and battery power as the two remaining options. In previous applications on the leach pad, neither option had proven reliable. This was typically due to the power draw required for items operating on the pad, depleting the batteries in a short amount of time. This placed another selection criteria on the instruments to have the lowest power draw possible while continuing to be an effective tool. The first consideration was the level of accuracy that was needed for these measurements. Reliable feedback is critically important to meet the precision goals, however the margin of error of flow measured by differential pressure was acceptable compared to the precision of a magnetic flow meter. There was only one style of pressure transmitter available which met the requirements. The second consideration was frequency of data collection. Other instruments measuring in "real-time" would communicate a data point every 2–3 seconds. For this application, the conditions at each module would not change enough to warrant data collection that frequently. Instead, collecting one data point per minute would still allow enough feedback to accurately see what was happening on the module over the full cycle. This would allow the instruments to power down in between data collection points, and only draw power when taking a measurement and communicating the data back to the network. Both of these considerations allowed the instruments to operate using a lithium battery that would provide 3-5 years of battery life.

Multiple styles of differential pressure flow meters were available for use. The primary differences between the meter styles were the pressure drop across the meter and the straight lengths of pipe required on both sides of the meter. The selection criteria for this meter was to minimize the size of the skid while not creating any hydraulic operation issues. The orifice plate flow meter was selected for the skid as it provided the smallest piping configuration around the meter. The trade-off was a higher pressure drop across the meter, however this did not create a concern because of the available feed pressure to the skid.

The final selection criteria for the instruments was material of construction. This consideration was needed for both components that would be in contact with the raffinate as well as components exposed to the environment. Having instruments placed at the module level requires them to be on the top surface of the leach pad above ore that is under irrigation. The drip irrigation system creates wet, acidic conditions under normal operation. In most cases the only source of raffinate within a module comes from the drip emitters, which passes into the ore without creating ponds or surface channels. In this standard case, the ore will maintain a moisture content that has the ability to corrode any materials that are in contact with the ore. It is also a common occurrence for small leaks and sprays to develop within the irrigation system. Even though these are fixed quickly, there is still the potential for the instruments to be sprayed with raffinate. Most of the components of the instruments that could come in contact with raffinate are metal. To ensure the instruments will be protected from corrosion, all of the metal parts were specified for 316 L stainless steel construction.

Pressure regulation

The other primary objective for this device is to improve the precision of raffinate flows to each module, ideally through an automatic flow control valve. Controlling flow was initially selected due to the direct connection back to application rate, however such a device would not be feasible in this application due to the typical power draw one would require. The same power supply constraints apply to the regulator as the instruments, which would not be reliable under battery power for the full leach cycle. Instead, the option for using pressure regulation was visited. Pressure targeting was already a practice used on the leach pad, and because of the correlation back to flow and application rate it would still be an acceptable practice. Having the ability to monitor the flow rate to the module would provide a level of redundancy to ensure the desired flow to the module was being reached with the pressure set point. A pressure regulating valve also provided a major benefit over flow control by operating using the pressure of the incoming raffinate. The valve regulates using the differential pressure between the inlet and the discharge pressures of the valve to physically adjust the diaphragm within the valve body, and does not require any other power sources to operate.

Manual adjustments would still be required on these valves, similar to the manual adjustments made with the existing system. Unlike the existing system where a butterfly valve was manually adjusted, the pressure regulating valve will react automatically to changing feed conditions. The only adjustments that would be necessary on the pressure regulating valve would be an adjusting nut that allows the discharge pressure to be fine-tuned. The automatic regulation without any fine tuning provides a significant improvement to the precision of flow control to the module.

Structure and deployment

Once all of the instrumentation components were selected, they all had to come together to form one functioning unit. From the component standpoint, only the orifice plate flow meter had a specification on installation. The two requirements were for the straight lengths of pipe required, and also installation with the instrument facing parallel to the ground. The only other consideration was for ease of installation that was compatible with the piping system on the module itself. This led to a horseshoe shape in the piping. The flow meter was placed first, with the required straight lengths of pipe on either side, followed by the pressure regulator, then finally the pressure transmitter. The horseshoe shape allowed for the module piping to remain in its original location, and allowed for simple installation of the skid.

A critical piece for success of the project was to create a unit that was easily portable. Each skid would remain in one location for an entire leach cycle, but then would need to be removed from the module for placement of the next lift of ore. The skid would then need to be re-deployed on the new module on top of the newly stacked ore. An additional concern with moving the units was providing protection to the components on the skid to prevent damage. Many of the components contained small and fragile parts that would render the component non-functional if they were damaged. To achieve both goals, a rectangular frame was developed that enclosed the components and the piping. The frame provided structure on the base to mount and support the weight of the components. The sides and the top of the frame provided added protection by enclosing everything except for the connection points within the framework. The top also created a stable lifting point either by hand or with forks on a piece of equipment.

Data collection

With the system implemented and properly functioning, the next major hurdle came from managing the data that was now available. The skid on each module communicates four different raw measurements back to the network: static pressure from the pressure transmitter, differential pressure from the orifice plate flow meter, and battery voltage measurements for each of the two instruments. Under typical operation, 220 of the total modules are under irrigation at a given time, generating four data points each minute for a total of 1,267,200 individual data points each day. For the new system to be successful, data management would be a critical step. This required the data to be organized into a format that seamlessly fit into the existing operational structure in a user-friendly manner.

All of the data that is collected from the modules has no meaning without context. Each of the instruments allows added information to be mapped that provides details as to what the instrument is actually measuring. In most cases the information mapped would be very basic, such as "Booster Station Raffinate Flow" that is used for the flow meter at the in-line booster station. In this case the naming system cannot be that straight forward, as each of the 230 skids would be taking the same four measurements. To make this system effective, each instrument needed to be mapped based on its physical location on the leach pad. This required creating a numbering system that would create a unique identity for each skid based on its corresponding module location. Based on the way the leach pad is stacked, each module has a quick reference to the cell and the phase in which it is located. The only addition necessary was to add a module reference within the cell itself. The naming convention used for the stacked cells consisted of numbers, so to avoid confusion the module references were created as letters. The "A" module of each cell would always be the first ore stacked within the cell. This allowed for a numbering system to be based on phase, cell, and module and align as a grid. For example, a module on Phase II Cell 4 that was three modules in from the start has a name of 2-04-C. Each instrument was mapped with this naming convention upon deployment, which provided data back into the system organized by its physical location.

A second major benefit for creating this naming system was to ensure correct placement of the skids on the leach pad. Once the instruments are mapped and placed on the skid, it is assumed that the data within the network corresponds to that location. Since the skids were designed to be portable units, there was the possibility that a skid could be placed in a different location, especially when re-installing on top of a newly stacked lift. It is not possible to see the mapped location on the instrument itself without connecting a special device, so a large metal label was created for each of the skids with the new module name stamped into it. The label was riveted to the exterior framework, and is very easy to see. It is also very robust so that it does not fall off or deteriorate over time, which could lead to confusion as to what location the skid should be placed.

Setting up the instruments based on location upon deployment allowed the data points to be transmitted back in an organized fashion. The grouped data could then be transferred into the site's existing data collection and management system, which allowed the information to be sorted and displayed on a computer screen. The static pressure measurement and both voltage measurements were transferred directly over, while the orifice plate flow meter measurement was converted from its raw format of differential pressure into an actual flow reading in gallons per minute. This was to avoid confusion of having two separate pressure measurements coming across for a single module and potentially mixing them up, and also for the ease of the end-user to provide the data they are expecting.

Providing immediate feedback and monitoring to the operators using this system required displaying the actual data points in real time. When operators would be making pressure set point adjustments to conform to the daily pressure targets, they would be able to see the pressure measurements of the full system in real-time to check the progress of adjustments, and to identify areas that needed extra attention. It would also provide identification of any areas that were missed or remained off target. Using the grid concept applied when the naming convention was developed was the most visually effective method to display this information. A grid was set up with cells across the horizontal axis and modules on the vertical axis, with the individual pressure data points displayed in their corresponding location on the grid. As additional feedback, the data management software also allowed for conditional formatting around each of the data boxes. Any time a module was more than 7 kPa (1 psi) away from 100, 135, or 170 kPa (15, 20, or 25 psi), the data box would automatically turn yellow. This would indicate that a module was far enough off of a target value that it needed to be corrected.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
H	15.4	15.9	16.9	14.8	15.5	15.7	14.8	15.1							15.5	15.3	15.6	
G	16.1	16.0	15.5	15.9	15.6	14.4	15.9	15.0					0.0		16.1	15.6	15.2	
F	14.6	16.1	14.9	16.0	15.8	17.9	15.0	15.6				16.5	15.9	15.4	15.7	15.1	15.7	25.3
E	15.4	15.4	15.3	15.9	15.0	15.3	15.3	15.4				15.4	15.6	16.2	16.7	15.7	15.2	15.1
D	15.3	16.4	15.0	14.8	15.1	15.5	15.3	16.4	10.8			15.2	25.6	26.2	16.0	15.7	16.0	15.7
C	14.9	15.4	15.9	15.5	15.1	15.2	15.4	15.4	10.7			16.3	25.5	25.5	15.7	15.8	15.7	25.4
B	16.8	15.6	15.4	15.7	14.9	15.2	15.0	15.3	11.0			15.9	25.8	24.9	16.2	15.7	15.5	15.1
A	14.9	15.8	14.5	15.5	16.1	15.6	14.6	15.6	15.5			15.6	25.8	25.1	25.8	15.8	16.7	15.6
HD	36.0	36.9	28.5	28.9	29.1	31.8	32.4	23.8	36.7	-0.6	-0.3	39.3	39.6	36.3	31.0	31.0	27.9	0.0

Pressures - psi

Figure 2: Pressure data feedback grid used by the operators

Interpretation and results

Once the organized data set was established and being effectively transmitted back, the next steps were to compile and interpret the data to determine if the levels of precision desired with this new system were being achieved. Since module pressures were the targeted values and also monitored each day by operations, the pressure data set was also used for monitoring flow precision. For each module, the 24-hour average pressure was calculated from the data set and displayed in the same grid format as the monitoring display. The next step was to determine a reasonable variance from the pressure targets that the actual data could be measured against. Previously, an absolute variance of 7 kPa (1 psi) from target was considered good, 7-35 kPa (1-5 psi) from target was considered acceptable, and greater than 35 kPa (5 psi) unacceptable. The same metric was used for the new system, but with more of a focus to keep the system in the “good” category instead of merely “acceptable.” This provided a solid metric for measuring the performance of each individual module in the system; however, with 220 modules in operation there was a need to take a step further to also determine a metric for how the system performed as a whole. To achieve this, a quality scoring system was created. This utilized the same pressure information but took an additional step beyond by comparing the variance between the actual pressure and the target pressure.

A quality score of 100% would indicate that the pressure for the individual module was exactly on target. For scaling the quality score based on pressure variance from target, a linear scale was established where every 0.35 kPa (0.05 psi) variance from target would reduce the quality score by 1%. This scale translates an absolute variance of 7 kPa (1 psi) to an 80% quality score, and a 35 kPa (5 psi) absolute variance to a 0% quality score. This new metric is used in two ways to display the precision over a 24-hour span. The grid still displays the 24-hour average pressure, but has conditional formatting built in based on its quality score. This provides a quick visual indication for each module if the variance falls into the good (green), acceptable (blue or yellow), or unacceptable (purple or red) category. In addition, the quality score for each module is averaged and displayed as a metric of the whole system. This value is also measured against the same color-coded categories. Both the full system and the individual module quality scores are reviewed on a daily basis to ensure that the desired precision is being reached in all locations on the leach pad. Since the implementation of the system in 2013, quality scores have routinely been above 80%. This indicates that precision is regularly within 7 kPa (1 psi) of the targeted value over a 24-hour span. This met the level of precision that was desired when this project began.

Module		Pressure (psi)																	
	H	15	14						15	15	16	15	15	19	14	14	16	16	
	G	15	14						16	24	26	25	25	25	15	16	15	15	
	F	15	17	17				12	16	24	15	24	15	19	15	16	16	16	24
	E	16	16	16	11			12	15	15	15	24	15	19	15	16	16	15	15
	D	15	16	16	10			12	16	24	26	24	14	19	13	15	16	16	15
	C	15	15	15	10			12	15	25	16	25	14	25	15	16	16	16	24
	B	11	16	15	10			12	16	24	16	15	15	25	15	16	15	16	15
	A	16	16	15	10			13	16	25	15	16	15	19	15	16	16	16	16
Header		41	28	36	68	0	0	49	45	30	48	22	34	28	31	26	27	25	
Cell		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18

Figure 3: Example of consolidated data visualization for the Phase II leach pad for a 24-hour span

Additional benefits

As the new system continued to develop into the standard operation of the leach pad, additional monitoring parameters using the collected data became evident. Part of monitoring the precision of raffinate flow to each module included monitoring data trends over different time periods. When anomalies in the data trends were observed, investigation in the field would be performed. At first, the thought was that an issue had taken place either with the pressure adjustments, physical construction, or assumptions built into the targeting strategy. In a handful of cases this was true, however many anomalies continued to be seen across the whole system. As these were investigated, additional monitoring techniques were developed using the data.

Plugging rates

The pressure targeting system for each module used the defined pressure/flow relationship provided by the drip line manufacturer, which when coupled with the area of the module would provide an estimated flow to the module at the set pressure. In several cases, the flow rates began to drift downward while operating at the same set pressure. This was seen primarily on modules later in their leach cycles. This led to the concept that flow rates were declining due to drip emitters becoming plugged, especially since plugging rates are typically higher near the end of the leach cycle. This was tested conceptually through manual plugging audits on the drip lines themselves, which showed elevated plugging rates compared to the rest of the system. This confirmed the concept, but only qualitatively. A test was conducted using new, clean drip line to measure the pressure and flow at the start of the cycle. After the baseline was established within a couple of hours, a set number of drip emitters were cut out of the drip lines and spliced back together. This was to simulate the effect of plugging. This test correlated exactly to the manufacturer pressure/flow relationship, indicating that the percentage of flow decrease from the baseline indicated the percent of plugging that exists on a specific module. This information is currently tracked on a weekly basis.

Flushing efficiency

Across the entire system, there would be short periods of time within the day that under relatively constant pressures the flows to the module would increase by 75-100% of their nominal value that day.

The duration would last a few minutes, and then return to its normal operation. Investigation into this phenomenon found that the times of the flow increases lined up with flushing operations. Each time a flushing valve would be opened on a specific module, the flow would always increase. Then within a couple of minutes of the flush valve being closed, the module returned to its operating conditions prior to the flush. By determining an estimated flow increase related to flushing, the flow data for each module was manipulated to generate a data point counter for the number of times a flow measurement exceeded the flow baseline value plus the estimated increase. Since flow measurement data points are taken once per minute, this count resulted in the approximate time that the module was flushed. Operators in the field are assigned a minimum time to flush a module, however up until now there was no way of quantitatively measuring if this was being accomplished. This information was compiled into the same grid as the precision measurements, and provided back to the operators as a tool for how well the system is being flushed.

Leak detection

Other data variances continued to exist within the system that could not be explained by either plugging, flushing, or targeting variances. These changes would typically be minimal flow increases at the same pressure. One concept was that something in the module had come apart or had broken, allowing raffinate to short-circuit out the leak. This concept is consistent with what is expected in larger systems when a large line break takes place. A test was performed to replicate these conditions. In a module, the drip lines are connected to a main header using a plastic connection known as a single. The test disconnected one drip line from the header, allowing raffinate to freely flow out of the single and also the open-ended drip line. The corresponding change to the system was a very similar flow increase to what had been seen in the data previously. Once the drip line was reinstalled into the header, the flow rate returned to its previous level. This allows the system to track even minor leaks, and also indicates that a major failure will be easily seen with a significant flow increase.

Pressure-controlled pumping system

As discussed earlier, prior to 2013 the pumping system to the leach pad was flow controlled based on a single meter. As this project developed, the opportunity arose to change the control loop from the flow meter to the header pressure located at the in-line booster station. One issue that was identified with a flow controlled system was that if flow was reduced in one location on the leach pad, it would be diverted to another location. That location was not necessarily controlled, and would typically cause other modules to drift above target. By modifying the system to control by pressure, the system would only deliver the raffinate flow that was demanded by the pressure on the system. This worked very well with the pressure regulating valves on the skids, as they would only allow the raffinate flow to the module based on the targeted pressure set point. When the pumping system followed the same control logic, the total flow to the system would increase when the pressure regulating valves would open, and decrease when they would close. This shifted the flow control point for the entire system down to the module level, which was one of the primary objectives from the beginning.

Conclusion

The acid-consuming nature of the Safford ore required a higher level of precision in order to be effectively leached. Increased precision was achieved by implementing a portable self-contained unit that provided pressure regulation to improve flow rate precision, along with wireless flow and pressure instruments to quantitatively monitor the level of precision reached. Additional benefits were identified along the way, which allowed plugging rates and flushing efficiencies to be monitored in real-time, as well as detecting leaks in the system. This system has proven very effective at improving the control of raffinate flows to the Safford leach pad.