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Overcoming high temperature water ingress in deep shaft mining

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Abstract

Resolution Copper Mining LLC, along with mining contractor Cementation USA, Inc., are in the process of developing what is planned to become the largest copper-producing mine in North America. A project of this magnitude does not come without challenges, and No. 10 Shaft, the first of six record-breaking shafts, has presented many. An impressive feat of engineering, the project will eventually use block caving methods to mine approximately 1.7 b t of porphyry copper ore at rates of up to 120,000 t per day. It will rely on the six 2,130 m deep shafts for ore extraction, ventilation, man access, and utilities.

This paper will discuss the unique challenges faced during the sinking of No. 10 Shaft and the innovative thinking and engineering required to overcome them. These challenges include unexpected water ingress more than 1,950 m below surface. Within a 50 m section of shaft advance, water inflows increased from negligible amounts to totals in excess of 1,700 L per minute at temperatures exceeding 80°C. Attempts to reduce water ingress by pressure grouting were unsuccessful due to the highly fractured nature of the rock at this depth. In order for shaft sinking to continue, the water had to be efficiently handled and removed from the shaft using inventive and relatively unproven methods.

Accompanying this water ingress was another unforeseen obstacle, a considerable heat load. Upon intersecting this high temperature water, shaft air temperatures and humidity levels immediately began to rise and continued to increase until worker safety became a concern. The shaft was generating a heat load of 6.61 MW, easily overwhelming a cooling system designed to handle less than half that amount. A complete overhaul of the shaft cooling and ventilation systems was required with just over 90 m of advance remaining to reach shaft bottom. This overhaul included the retrofitting of 610 of 2 m diameter vent duct in the shaft as well as the installation of six massive cooling coil units underground, weighing nearly 5,900 kg each.

Together, the water and heat forced the project to drastically modify the shaft sinking process. Pump box-outs, hanging sumps, concrete-embedded dewatering lines, and dewatering buckets are a few items that have become irreplaceable parts of the sinking process at The Resolution Copper Project. While the remaining shafts will have the benefit of being better prepared to handle these obstacles, sinking with these exceptionally hot water inflows will never be considered routine. Numerous challenges remain for the project, challenges that will only be overcome by innovative thinking, adaptable operations, and 'brute force engineering'.

1 Introduction

Located approximately 96.5 km (60 miles) east of Phoenix, Arizona in The United States of America, the Resolution Copper Project is an underground copper mine currently under development. This project is a joint venture between Rio Tinto Group (55%) and BHP Billiton Ltd. (45%), with the intention of eventually mining one of the largest porphyry copper deposits ever discovered. It is operated by a subsidiary of Rio Tinto, Resolution Copper Mining (RCM), and is currently being developed by Cementation USA, Inc. This deep-seated orebody is located below the historic Magma Mine, which ceased operation in 1995, and contains a relatively high concentration of copper at approximately 1.52%. The orebody contains over 1.7 b inferred t of copper ore, and RCM plans to mine this ore using block caving methods at a rate of up to

120,000 t per day during full production. To accomplish this, six large diameter shafts reaching over 2,100 m in depth will be required to serve as production, service, and ventilation shafts. The existing Magma Mine No. 9 Shaft, which currently sits at approximately 1,490 m in depth, will require deepening to 2,134 m to become one of the six shafts. The first new shaft for the project is No. 10 Shaft (Figure 1), an 8.5 m finished diameter shaft that was started in 2007 with full sinking beginning in 2009. The shaft progressed as planned initially, even better at times, to a depth of 1,969 m at rates up to 3 m per day. Until this depth, shaft groundwater inflows were minimal and hardly played a role in the sinking cycle.

Figure 1 Resolution No. 10 Shaft Headframe, located near Superior, Arizona, USA

Based on analysis of core samples from the shaft pilot hole, a geotechnical consulting firm recommended that water probe holes be drilled ahead of all shaft advance. For every 15 m of shaft advance, four 67 mm diameter, 25 m deep water probe holes are drilled from the shaft bottom, ensuring 9 m of overlap. As shown in Figure 2, these holes are drilled through grouted standpipes with high pressure shut-off valves to ensure that if significant water was encountered, it could be contained. Prior to 1,770 m in depth, these holes were typically dry with the exception being a hole producing 1-2 L per minute (L/min). Small pockets of water inflows were experienced between depths of 1,770 and 1,969 m, but cumulative inflows never exceeded 250 L/min at the shaft bottom. Cementitious pressure grouting was used to slow these inflows, and while they were never sealed off completely they were typically reduced to some degree.

Figure 2 A cementation miner using a pneumatic jumbo rock drill to drill a 25 m probe hole on the 1,969 m bench

On the night of 5 January 2013, probe holes were drilled on the 1,969 m bench according to plan. A hole in the southwest quadrant of the shaft encountered approximately 140 L/min of 80°C water at 13 m depth.

This water was under pressure at the time it was encountered, causing the water to flow from the standpipe with notable velocity. The other three holes encountered less water initially at varying depths, but within hours had established connectivity to the water source, bringing the inflow total up to nearly 500 L/min at the shaft bottom. The standpipe shut-off valves proved to be ineffective due to the highly fractured nature of the ground at this depth. When the valves were shut, the water began flowing into the shaft through existing fractures, primarily through pyrite veins which easily washed out and became conducive to water flow. This caused the measurable back pressure of the groundwater to decrease significantly, as there was no effective method of containing the water and allowing pressure to build.

Multiple rounds of pressure grouting were attempted to seal off the water inflows and establish a grout curtain in the rock outside the shaft diameter. As shown in Figure 3, extremely hot water along with fractured rock made grouting extremely difficult. Grouting continued for three months before the decision was made to resume sinking and attempt to handle the water inflows. Resuming sinking from the 1,969 m bench was a slow and deliberate process. As the shaft advanced, water inflows continued to increase rapidly, exceeding 1,700 L/min by the time the 2,019 m bench was reached. Innovative methods were required to pump these high volumes of hot water from such extreme depths up to surface, especially with an installed shaft dewatering system designed to handle a maximum of 750 L/min.

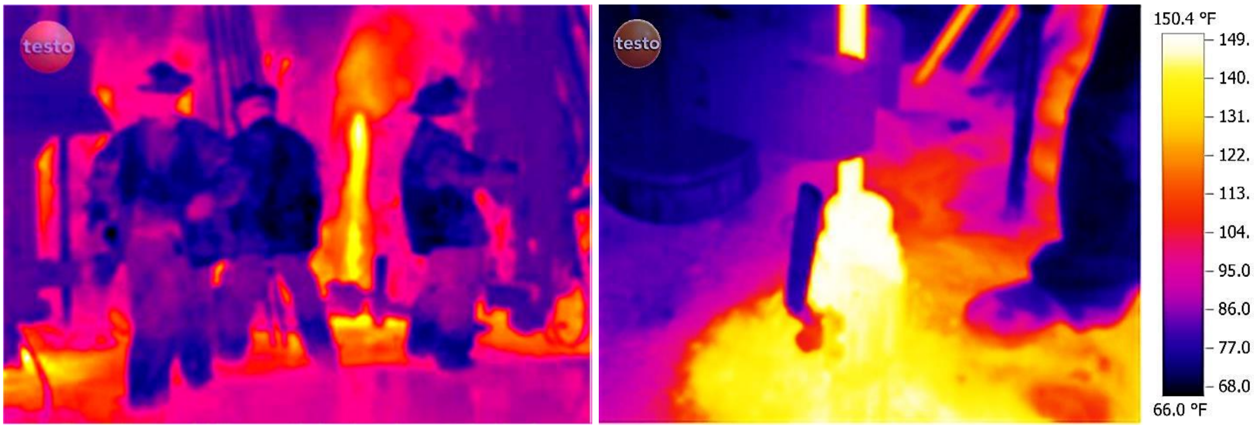

Figure 3 Thermal imaging of miners drilling grouting holes on the 1,969 m bench

After intersecting the water, temperatures at shaft bottom increased from approximately 25°C with minimal humidity levels to temperatures exceeding 40°C with humidity levels of 90-100%. While rock temperatures were in the range of 55-60°C, nearly the entire heat load was generated by the 80°C water inflows and the resulting steam. Water leaving the rock would cool 10-15°C within seconds as it discharged heat energy into the surrounding air. The water would further cool to around 50°C by the time it left the shaft, discharging additional heat into the shaft while travelling up the shaft through the pump system and piping. The ultimate shaft heat load was calculated at 6.61 MW, double the 3.30 MW capacity of the existing shaft cooling and ventilation system. Sinking was put on hold in September of 2013 to engineer solutions to improve working conditions and ensure the safety of the crews working in the shaft.

2 Methodology

According to the shaft geotechnical report, RCM No. 10 Shaft was expected to experience minimal water inflows throughout its sinking, with nearly all water inflows anticipated to be above 1,200 m depth. Based on this report, the designed and installed shaft dewatering system had a capacity of only 750 L/min. It should be noted that this report was based upon a single core hole, and all hydrology assumptions were based on this limited data. After all, it was accepted that No. 10 Shaft was an exploration project, a large diameter shaft to be sunk to depths far beyond what had ever been accomplished in the region.

The heat load for the entire shaft was anticipated to top out below 3.30 MW, a cumulative total for the heat generated by the rock temperatures and all mechanical and electrical equipment in the shaft. Because significant water inflows were not expected, this additional heat source was not a part of the original calculations. To overcome these unforeseen obstacles, modifications to both the dewatering and cooling systems were required.

2.1 Initial groundwater contact

Upon encountering the initial inflows, limited pumping infrastructure existed in the shaft and dewatering of the shaft bottom was reliant upon pumping water into the sinking buckets. The shaft crew would fill these 7,200 L buckets using pumps on the shaft bottom, after which they would be hoisted to an existing level 335 m below surface and siphoned into the level sump. The double-drum hoisting setup in No. 10 Shaft allowed for dewatering rates of up to 1,300 L/min with this method. However, this rate could not be maintained consistently as the hoist was also required for man travel and delivery of supplies throughout the day. This method's reliance on the hoist also slowed all other shaft activities, delaying shaft progress. The areas of water ingress that were intersected between 1,770 and 1,969 m did not generate high enough volumes to completely halt sinking operations, but they did significantly reduce advance rates for this reason. Pressure grouting was somewhat effective in slowing the inflows, but upon advancing the water would begin to report through the matchers in the concrete liner between sets and run down to the shaft bottom below. To counter this, steel water rings were installed in the liner when an inflow of approximately 100 L/min was accumulated. These water rings (Figures 4 and 5), have an inside diameter matching that of the shaft and collect all water flowing down the liner before it can reach shaft bottom.

Figure 4 Sections of a water ring on surface before installation

Figure 5 The installation of a water ring during a shaft liner pour

Initially, the water ring would drain to a temporary hanging sump that would be suspended from the shaft forms using properly-rated rigging and house a submersible pump as shown in Figure 6. This engineered sump was fabricated onsite using a 3 m long, 300 mm diameter pipe with an integrated pump shroud and centring brackets. Located in the shroud, the pump would be hosed to a pipe embedded in the concrete liner that connected to the existing recovery pump system above. This was required until an installed pump box-out was exposed from behind the forms of the next concrete set. Once exposed, water would drain to the sump in the pump box-out, shown in Figure 7, which would also house a submersible pump and handle the water similarly to the pump in the hanging sump. This style of submersible pump, traditionally used in groundwater wells, was chosen for its high-head capabilities and portability.

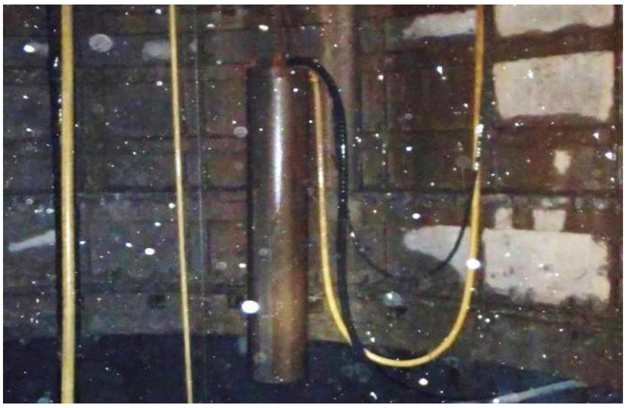

Figure 6 The hanging sump in operation

Figure 7 A typical steel pump box-out setup installed in the shaft liner

2.2 Additional groundwater inflows

Upon encountering the significant inflows on the 1,969 m bench, the sinking buckets were no longer effective dewatering the shaft bottom. Pressure grouting was being attempted but saw little success due to repeated flooding of the bench. Aside from dewatering, the hoist was required for shift changes and to re-supply the crews with grout and supplies throughout their shifts. These gaps in dewatering allowed water to build up on the bottom to depths of 1 m or more, forcing crews to retreat to the work stage above. Significantly more time was spent dewatering the shaft during the first month of grouting than was spent actually pumping grout into the rock.

To counter this, an entirely new series of pumps was installed. This system handled the water up the shaft in stages terminating into an existing pumping system used to maintain water levels in No. 9 Shaft. Using similar but much larger versions of the multi-stage centrifugal pumps used with the water rings, the system was comprised of three stages. Consisting of one pump positioned horizontally on the shaft bottom and two additional pumps located in polyethylene tanks at shaft stations above, this system combined to lift the water a total head distance of 573 m. Water was pumped though pipelines embedded in the shaft concrete liner between stages up to the Pump Level located at a depth of 1,396 m. At this level, the water was drained through an existing drift connecting No. 10 Shaft to No. 9 Shaft. It was run along the drift floor to settle out solids before it reached No. 9 Shaft and its dewatering system designed for relatively clear water.

This system, located at 1,481 m depth in No. 10 Shaft, was used to dewater No. 9 Shaft through boreholes drilled up into the bottom of the No. 9 Shaft Sump Level. No. 9 Shaft has historically generated groundwater inflows ranging from 500-800 L/min dependent on the season. This water, independent of the water intersected in No. 10 Shaft, generates from connections to the groundwater table throughout the old Magma Mine workings that drain into the shaft. Despite this, these pumps had plenty of additional capacity to handle the extra water and pumped it out of the shaft along with the existing No. 9 Shaft inflows.

2.3 Grouting campaign at 1,969 m bench

With the water better handled, a true pressure grouting campaign on the 1,969 m bench began in late January of 2013. High-pressure standpipes were installed around the perimeter of the shaft bottom in a circular pattern, as shown in Figure 8. This was in an effort to once again create a grout curtain just beyond the shaft walls and seal off inflows below. The 67 mm holes were drilled out and grouted in 3 m intervals, with time being allowed for the injected grout to cure in the rock before the valves were opened and the holes redrilled. While some temporary success was experienced, water inflows generally increased as the depth of the grout holes increased. This was further complicated by the fact that the inflows could not be stopped by closing the valves on the standpipes. Once the water-conducting rock was tapped, the water would not only flow from the standpipe but would propagate through pyrite-rich fractures in the rock and enter the shaft from multiple points. Grout injected into the rock at varying pressures behaved similarly, with much of it returning to the shaft through these fractures.

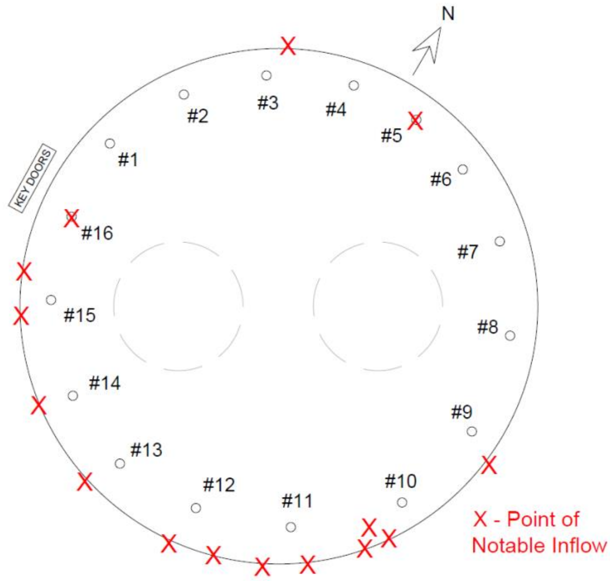

Figure 8 Plan view of the original sixteen standpipes installed on the 1,969 m bench with points of notable inflow identified

Throughout the campaign, experts from within Cementation as well as external consultants were brought in to provide insight on methods to slow the water inflows. However, the fractured nature of the rock and the high pyrite content created conditions that became referred to as 'ungroutable'. After nearly three months of unsuccessful grouting and the pumping of over 200 t of cementitious grout, a meeting was held. Top members of both RCM and Cementation along with grouting and shaft sinking experts were present for decision-making and to provide their input. Based on these opinions, the grouting results, and a thorough assessment of the risks, it was decided that the best path forward was to resume the sinking of the shaft and handle the water rather than try to grout it off.

2.4 Sinking through peak inflows

Sinking after the grouting campaign progressed at an arduously slow pace. Sinking rates had reduced from around 2 m per day after initial water contact to less than 0.5 m per day. Water inflows continued to increase with depth, with nearly all of it reporting directly to the shaft bottom through the exposed rock. Significant issues came to light with the new heat and water problems that existed. Out of necessity, sinking progressed in 1.5 m increments rather than the typical 3 m, as the water inflows required that only half of a bench be taken per round. This benching method allowed for a low side that would act as a sump for the water, while work took place on the dry higher ground. Vertical concrete liner pours were reduced from 6-3 m in length due to poor ground conditions and to better contain the heat produced by the water flowing from the exposed rock. Often times these pours would be flooded out and delayed for hours due to difficulties with pumping water concurrently. Installation of shaft services above the work stage required moving the stage away from shaft bottom, temporarily eliminating all pumping capabilities. As a result, hours of dewatering would be required upon completion before sinking could resume. All combined, cycle times for sinking were increased dramatically, and they were further hampered by the increasing heat.

Shaft bottom temperatures were rising into the 35 to 40°C range, and humidity levels were between 90 and 100%. Temperatures at some of the shaft stations above were even higher due to the existing ventilation setup which delivered cool air to the bottom and exhausted the hot air up the shaft barrel. Additional fans were added to the exhaust system in an effort to better exhaust the shaft and increase the velocity of the air traveling up the barrel. These measures were not successful however, as the exhaust system began to draw more cool air from above rather than the hot, humid air from below. Heavy, saturated air became trapped beneath cool air from above, further limiting the exhaust rate of the shaft.

Based on Rio Tinto and Cementation standards, a written permit was required for any work that took place when the wet-bulb temperature was in excess of 31°C. Per the permit, breaks in cool rest areas were required at certain time intervals dependent on the temperature in order to maintain a safe body temperature and prevent heat exhaustion. To make this possible, cool rooms were established at the stations and in the vent duct on the Galloway. These rooms were typically pop-up work tents with a small air conditioning unit that kept the temperature around 25°C. Miners would work for a period of time before taking a break in the cool room, lowering their body temperature and rehydrating. Research was done in conjunction with a local university to track the body temperatures of the miners throughout their shifts using ingested 'pill sensors' to ensure that overheating was not taking place.

Additional difficulties were experienced with the water and heat and the effect that they had on the explosives used on the shaft bottom. The detonators used with the explosives were rated for a maximum temperature of 79.4°C, which presented challenges with water temperatures exceeding 80°C. A 3 m long probe was used to measure the temperature at the bottom of each water-producing hole before loading. Any hole with a temperature exceeding 79.4°C was not loaded, although this typically did not exceed 3-5 holes per round. As a backup, Resolution Copper and Cementation worked with explosives supplier Orica to certify a different, existing type of detonator up to 85°C. Although far more time consuming to use, these detonators were kept on site to be used in the event that too many holes exceeded the 79.4°C limit to effectively load and blast. Additionally, the water eliminated the use of bulk emulsion explosive, which had been key to faster cycle times to this point in shaft development. The emulsion would often wash out or not detonate properly due to dilution in the water. In its place, the full round was required to be loaded with stick powder, resulting in increased loading times. Orica was consulted regarding the proper types and quantities of stick powder to be used in order to maintain ground integrity and minimise overbreak.

As sinking progressed, continuous improvement of the dewatering system was required due to increasing inflows as well as increasing head pressure requirements on the pumps. The staged centrifugal pump system to the Pump Level was doubled in capacity by the addition of a second pump at each stage. These pumps later required upgrades to a larger version with the increased head pressure requirements as the shaft advanced. The largest pump model used was handling approximately 570 L/min with head pressure in excess of 2,700 kPa. Although these pumps assisted greatly in reducing dewatering times when clean water was built up on shaft bottom, they struggled with the handling of suspended solids found in the water during most sinking activities. Solids content of the water was at times approaching 10%, especially during the mucking cycle. The lifespan of pumps in the system was reduced to days at times, with each failure resulting in a flooded bench, increased dewatering costs, and further delays to the sinking cycle. Multiple pump experts were consulted in an effort to find a pump better suited for the conditions, but no pump was found that could provide the flows and pressures required while remaining portable and fully submersible. The installation of a pump system mounted on the sinking Galloway was considered, but weight, space, and electrical limitations made this impossible given the head pressure requirement. As sinking continued to slow and water ingress increased, it became apparent that a new approach to water handling was going to be required.

It was decided to install an unplanned pump station at Set 326 (1,987 m below surface) to allow for more efficient water handling. Due to poor ground conditions, the station was not excavated beyond a 3 m ring around the shaft, making a tight fit for the pumps and equipment. Given the high solids content of the water being pumped from shaft bottom, it was decided to install positive displacement pumps at this station, as shown in Figure 9, rather than centrifugal pumps that were typical throughout the shaft. Two pumps were installed with a capacity of 1,150 L/min each, designed to run in an alternating setup in order to provide sufficient downtime for each. The feed tanks for these pumps were fed by submersible pumps on the shaft bottom through 150 mm steel pipe embedded in the shaft liner. There were some issues with the system and maintenance plan initially, primarily due to inexperience with these types of pumps. The heavy pyrite content of the rock, which is extremely abrasive to pump parts, caused additional problems with premature wear of the pump parts. Over time, an intensive maintenance plan was established, significantly increasing the uptime of the pumps and reducing associated delays to sinking.

Figure 9 One of two positive displacement pumps installed at the Set 326 Pump Station

Figure 10 on the following page contains the dewatering system layout during the final phase of sinking between the Set 326 Station and the shaft bottom. This setup relies primarily on the centrifugal pump at the Set 284 Station fed by water rings and the positive displacement pumps at the Set 326 Station fed by submersible centrifugal pumps on shaft bottom and water rings. The existing staged pumping system became the contingency system. All dewatering lines terminate into the REDA pump system at the Transition Pump Station (TPS), either directly into the tanks or through No. 9 Shaft via the boreholes.

With the Set 326 Pump Station construction complete and the pump system commissioned, the shaft advanced an additional 32 m. Water was being better handled by a reliable pump system with redundancy through a back-up system. However, within this short stretch of advance, water inflows in the shaft had increased to over 1,700 L/min and the heat produced was creating unworkable conditions. Temperatures on shaft bottom were regularly above 40°C with humidity levels remaining between 90 and 100% due to the intense steam generated by the groundwater. Progress slowed even further as miners were required to spend more than half of their shifts in the cool rooms. In September of 2013, with the shaft bottom at a depth of 2,019 m, it was decided by RCM with support from Cementation USA that sinking would be put on hold and a complete overhaul of the cooling and ventilation system would take place.

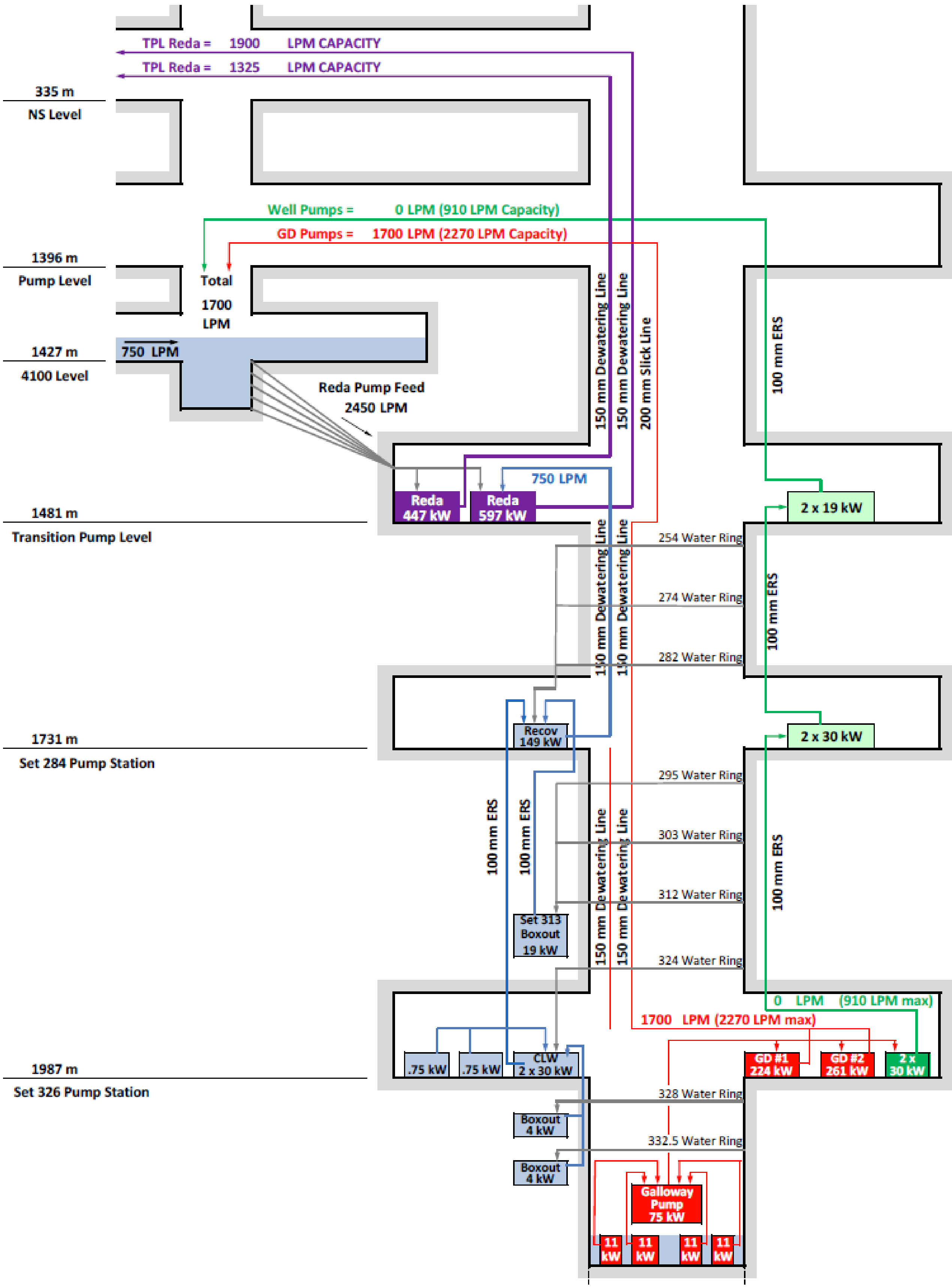

Figure 10 No. 10 Shaft Dewatering System Layout during the final phase of sinking between the Set 326 Station and the shaft bottom

2.5 Cooling and ventilation system upgrade

Significant modifications were required in order to return shaft temperatures to acceptable working levels. A third-party mine ventilation consulting firm, BBE Consulting of South Africa, was brought in to evaluate the shaft heat load and advise on how to overcome it. BBE was familiar with No. 10 Shaft, as they had been responsible for designing the original shaft cooling system. After re-evaluating the conditions, it was determined that the new heat load including the unexpected water inflows was more than double the capacity of the current cooling system. BBE stated that this heat would only be overcome with 'brute force engineering'; included in their recommendations were the following:

- Early installation and commissioning of the permanent mine cooling plant on surface.
- Retrofitting of 610 m of 2 m diameter exhaust duct between the Pump Level and the Set 326 Pump Station in No. 10 Shaft.
- Installation of cooling coils in the Vent Level Access Drift (on surface) and at the Pump Level (1,396 m below surface) in No. 10 Shaft.
- Upgrades to the fresh air and exhaust fans.

RCM agreed to these recommendations, along with the USD 12,000,000 price tag, and the changeover began immediately.

Construction on the permanent mine cooling plant on surface began in 2012 and was put on hold due to budgetary limitations after the first phase was completed. The original contractor was brought back on to resume construction and complete the second phase necessary to feed the upgraded mine cooling system with a chilled blend of propylene glycol and water. Upon completion, this plant would add 10.6 MW of cooling capacity to the existing 3.30 MW, for a total of 13.90 MW. This capacity was more than double the calculated heat load in the shaft, designed to include contingency in the event that additional heat was encountered.

Cementation began the installation of the 2 m diameter exhaust duct from the Set 326 Station. The new exhaust line was built from the bottom up with 3 m sections slung down from Pump Level by a temporary winch installed at a level 335 m below surface. Figure 11 demonstrates the complexity of this work and the ingenuity required to complete it efficiently and safely. The duct was installed using two work decks with retractable wings, one on each side of the double-drum hoist. Tied off with safety lines, the miners would guide the duct on the winch into place from above, couple it to the duct below, and install a bracket every 6 m securing the duct to the shaft wall. The installation was completed without incident and the duct was successfully tied into the upgraded exhaust fans in the existing Pump Level Vent Service Drift between No. 9 and No. 10 Shafts (Figure 12).

Figure 11 Installation of the 2 m diameter exhaust fans at the Pump Level

Figure 12 Exhaust line tie-in to the exhaust duct mid-shaft

Installation of the cooling coils in the Vent Level Access Drift on surface was completed by the third-party contractor. The six 5,900 kg coils at the Pump Level along with all required infrastructure were installed by Cementation. These coils were placed in structural frames and stacked in two banks of three. High pressure 200 mm piping was run from the shaft to the coils through a large valve bank required to control and isolate the coils. A massive plenum was then attached to the front of the second bank and tied into 1.8 m duct which carried the cold air to the existing shaft duct and down to the shaft bottom (Figure 13).

Figure 13 Upgraded cooling installations at the Pump Level in No. 10 Shaft

The coils on surface are fed glycol from the cooling plant via 600 mm lines and handle approximately 6,800 m^2 per minute of air through them via one 186 kW fan. This cooled air is forced down the shaft barrel to the six cooling coils installed at Pump Level. Glycol is circulated through these coils from the cooling plant on surface via high-pressure 200 mm lines that run down the shaft. Two 186 kW fans take in the cool air fed from surface and force it through the coils and into the shaft duct.

Significant support from Cementation USA Engineering went into the retrofitting of No. 10 Shaft with exhaust duct and the installation of the cooling coils. Installation of the duct required the modification of two existing in-shaft work decks, both of which featured dual-axis cantilever, retractable wings off of a suspended platform. These L-shaped wings were required to reach the shaft liner where the duct wall bracket was installed. Additionally, custom duct slings were designed to allow for simple attachment, detachment, and handling mid-shaft while still meeting all safety requirements. Installation of the cooling coils at the Pump Level was equally as complex due to the sheer size of the coils and their sensitivity to damage during transport. Positioning of the coils into 6 m tall banks and installation of heavy-wall 200 mm piping in a tight underground drift required detailed advance planning and engineering for safe completion.

3 Data

Both water inflows and shaft temperatures were tracked before and during contact with the major water source. This information has been critical to the design of the upgraded dewatering and cooling systems in No. 10 Shaft and will serve a key role in planning future shaft development at the Resolution Copper Project. As shown in Figure 14, water inflows were minimal until the first intersection of water at the 1,780 m bench. Small fluctuations can be seen over the next 90 m during several small grouting campaigns. Water inflows to the shaft bottom decreased around 1,870 m in depth after water rings were installed in the shaft liner to handle the inflows before they reached the bench. The sharp increase at 1,969 m in depth was the first major intersection of water, and the inflows continued to increase rapidly with depth until sinking was halted at 2,019 m. Figure 14 also depicts the correlation between the water inflows and the shaft temperature, which increased significantly upon contact with the high temperature water. Conditions were warm but tolerable up to this point, in the range of 30 to 35°C. During the sinking that took place after the 1,969 m grouting campaign, temperatures quickly increased to beyond 40°C. It was at this point that the decision to halt sinking and upgrade the cooling system was made.

By early July of 2014, portions of the upgraded cooling system were still in the process of being commissioned. However, the underground portion of the system was completed and run in the meantime, utilising the existing temporary chiller plants. With only this half of the full system running, initial results were promising, with temperatures at the shaft bottom reduced by nearly 20°C from their peak to an average of 28°C. Figure 14 below shows the clear and immediate reduction in shaft bottom temperature despite the consistent water inflows once the first phase of the upgraded cooling system came online.

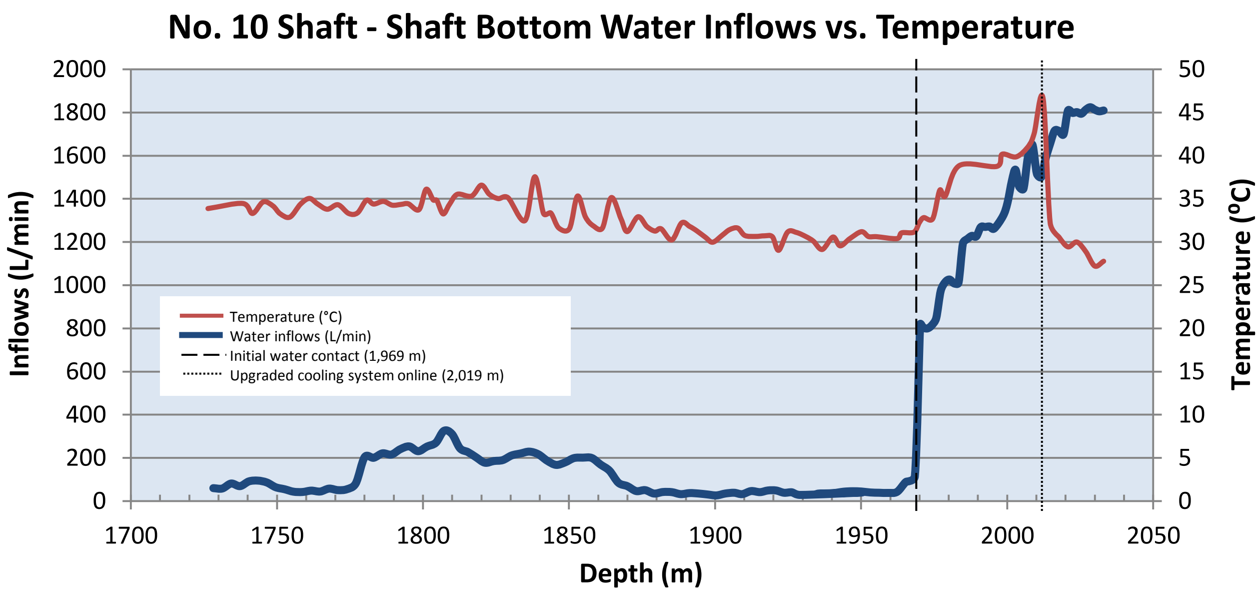

Figure 14 No. 10 Shaft – shaft bottom water inflows versus temperature plotted against shaft depth between 1,730 m and 2,019 m

Figure 15 contains a chart based on calculations completed by BBE Consulting. This plot of the expected heat load used in the original design compared to the actual head load at the time of analysis demonstrates how quickly the heat load increased to surpass the 3.31 MW cooling capacity of the existing system.

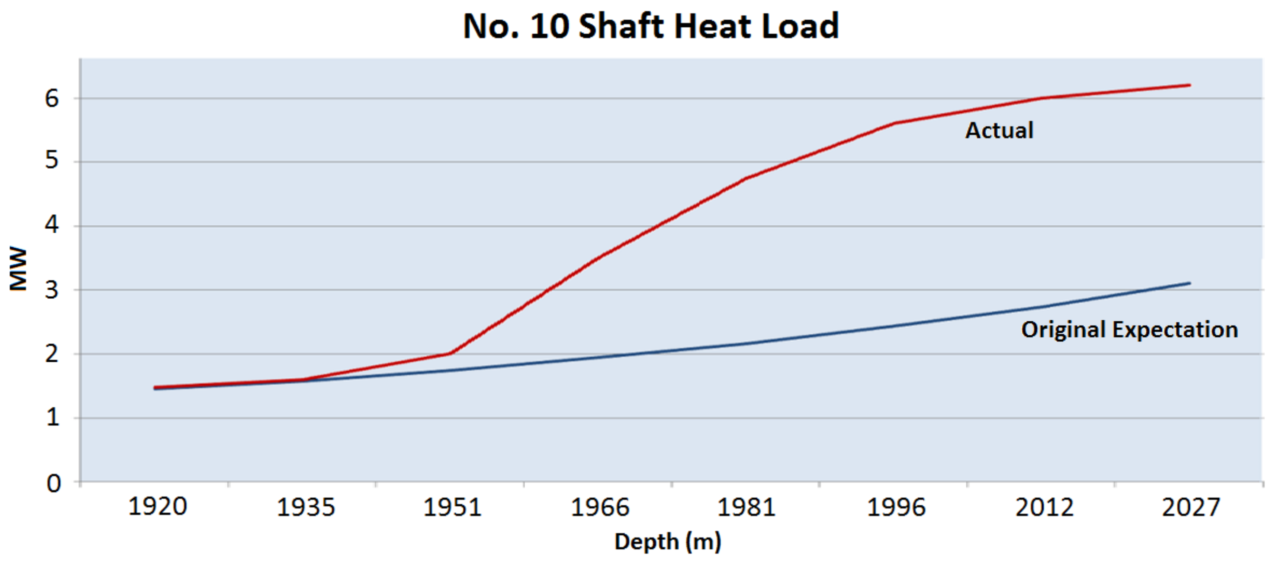

Figure 15 The design heat load as compared to the actual heat load in No. 10 Shaft, plotted against shaft depth

4 Results

From the time water was first intersected, improvements and modifications made to the shaft dewatering system have proven invaluable. Without these upgrades, it would not have been possible to keep the shaft from flooding, let alone advance the shaft to its current depth. Dewatering the shaft by pumping into sinking buckets was effective for water inflow rates below 200 L/min, but above that amount it began to take a noticeable toll on the sinking cycle times. Unsure of the volume of future inflows, the No. 10 Shaft team elected to start with smaller upgrades and continue to increase capacity as was warranted by the water. However, a point was always made to ensure that pump capacity exceeded current inflows plus a contingency for potential short-term increases. The current shaft dewatering capacity, dictated by the REDA pump system at TPS, is approximately 3,225 L/min. At the present rate of ingress, the remaining dewatering capacity for the shaft is around 775 L/min. Estimates by RCM's Hydrology Department have No. 10 Shaft bringing in anywhere from 550 to 1,150 L/min of additional inflows before reaching the final depth of the shaft. For this reason along with understandable uncertainty, a third REDA pump will be added at TPS in the coming months. The third pump, which will add 1,500 L/min capacity, has been procured and engineering is currently underway to integrate it into the existing REDA system.

An important element to the success and reliability of the dewatering system has been and continues to be the proper handling of solids within the system. The solids generated by the sinking cycle are primarily fine particles that become suspended in the water on shaft bottom and enter the system via the submersible centrifugal bench pumps. Due to the high pyrite content of the current ground, these solids are extremely abrasive to pump parts and lead to premature wear. Pyrite is also quite heavy; with a density of about 5,000 kg/m^3, even small percentages suspended in water create noticeable changes in the head pressure, decreasing the flow of the centrifugal pumps. Additionally, the fine particle size of the solids causes them to settle out, collect, and harden in the bottom of tanks and sumps, requiring cleaning to prevent pump feed lines from plugging up. Overcoming these problems will require shaft crews to keep the water entering the dewatering system as clean as possible. Turning off bench pumps for short periods during activities that stir up large amounts of solids assists in keeping the water clearer, as does placing the pumps in a sump surrounded by rock berms during the mucking process. All tanks in the pump system are cleaned out on a regular basis, some multiple times per day, to ensure they do not become overwhelmed with solids. Investing the time in these small steps mitigates the potential for long down times that result from a failure in the dewatering system, with the result being improved sinking cycle times.

Initial results for the partial completion of the ventilation and cooling system upgrade have shown a significant improvement in working conditions throughout the shaft. Cooling the air closer to the shaft bottom at the Pump Level is resulting in the delivery of much cooler air to the work stage. This cool, dry air collects the humidity produced by the steam off of the high temperature water inflows and is immediately picked up by the exhaust duct above the work stage. This constant air movement prevents the air from becoming trapped and heating up, assisting in reducing the overall temperature. These improvements have allowed sinking operations to resume and an additional 15 m of shaft advance since commissioning. At the time of paper submission, the shaft depth was 2,034 m below surface, with shaft bottom temperatures holding steady in the 28°C range.

When the full system comes online, temperatures throughout the shaft should decrease similar to the effects seen at shaft bottom. The air from the surface chillers will travel down the shaft and feed the force fans at the Pump Level, supplying them with cool, dry air and further decreasing temperatures and humidity levels. The full system will also increase glycol flow through the cooling coils, further increasing the temperature reduction over each bank. Once fully commissioned, results to date indicate that the system will meet or exceed expectations based on the design specifications. As long as the water inflows remain within expectations and can continue to be efficiently handled, conditions should allow for the sinking of the remaining 82 m to shaft bottom.

5 Conclusions

Heat and water present challenges in a mine of any design or depth, but these challenges are magnified significantly in deep shaft mining. All water inflows collect at the working face, and pumping can be a challenge due to high head requirements and limited space for pump installations. Ventilation is equally difficult, with both fresh air and exhaust required to travel within the same barrel, requiring extensive ducting and fan installation.

The sinking of No. 10 Shaft was well planned out before any rock was broken, but it was understood that it would be an exploration project. With limited knowledge of the hydrology of the area, there was a risk of intersecting unexpected water inflows. However, because of the fact that water inflows are rare at these extreme depths, and based on the limited core hole data, assumptions that there would be little to no water below 1,000 m in depth were made. While these suppositions are now shown to have been in error, this shaft has certainly fulfilled its role as an exploration shaft, characterising the geological and hydrogeological make-up of the area for future project development. The sinking of the remaining five shafts at the Resolution Copper project will have extensive data from No. 10 Shaft to base their designs upon. Each of the future shafts will be equipped with much larger pumping systems to be used in the event of significant water ingress. These pump systems will be outfitted with the proper equipment to handle the suspended solids generated during sinking. Ventilation and cooling systems will be designed with additional contingency to handle any unexpected heat loads. Future shafts will additionally have the benefit of existing pumping systems in the mine as well as the ability to use existing mine workings and shafts for ventilation. Installations such as pipe embedded in the concrete liner that were unplanned but became invaluable to the shaft will be carried into future designs.

The source of the water intersected in No. 10 Shaft and its capacity are still not known for certain. Based on the pressure, flow, and temperature data that have been gathered, it is believed with reasonable certainty to be coming from a source below the current shaft depth. The water temperature alone, 80°C flowing from 60°C rock is a strong indicator that the water is coming from a depth where the rock temperatures are higher. Multiple analyses of trace elements and pH levels have proven that the water flowing into No. 10 Shaft is not related to the water generated in No. 9 Shaft. The design of future shafts and lateral development has been adjusted to account for increased water inflows. Innovative methods of block caving will be required to handle water on this scale along with the ore. The project faces numerous challenges moving forward, not only through the development phase but into the production phase as well. However, as was proven in No. 10 Shaft, these obstacles can be overcome through innovative thinking, adaptable operations, and 'brute force engineering'.

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