

Grouting of the Residual Uranium Waste in Fernald Silos

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ABSTRACT

At the Fernald site in Cincinnati, Ohio, huge concrete silos containing K-65 spent uranium ore were to be decommissioned and demolished as part of the decommissioning and restoration of the site. The K-65 waste in the silos was to be removed by sluicing with a low pressure water jet and placed in a new tank for the solidification processing. However the process was expected to leave at least a few inches of hard residual heel of waste on the floor and perhaps the walls of each silo. The contaminated concrete of the silos along with this waste heel represented a huge volume of material that would pose a hazard to workers, air quality, and groundwater during demolition. The heel material contained significant lead and radium as well as depleted uranium. The waste emitted a large amount of radon gas that was normally captured by a silo off-gas treatment system.

Project plans called for the heel material to be mixed in place with a large volume of cement/flyash grout. This would chemically bind up the contaminants reducing the leaching potential of the material. The hardened grout would reduce the release of radon and dilute the concentration of radioactive contaminants allowing the grout to be disposed along with the contaminated concrete. The challenge was to develop an efficient method to mix the waste heel material with the grout without sending workers into the silo.

INTRODUCTION

Fernald Inc., acting under its prime contract with the U.S. Department of Energy (DOE) at the Fernald Closure Project (FCP), planned to remove K-65 radioactive waste from the concrete storage Silo 1 and 2 and demolish the silos by mid 2005. The K-65 waste is essentially residual separated material from uranium ore that still contained substantial radioactive components and emitted radon gas. The larger objective was to completely dismantle the entire Fernald facility and return the site to green field condition surrounding a central landfill containing all the non-radioactive debris from the demolished facilities. The bulk of the K-65 waste was removed from the silos by a sluicing system but it was anticipated that a small residual heel of K-65 waste could not be removed by this method. The material had a consistency similar to clay with some residual areas very hard and difficult to mobilize. Plans called for this material to be

“grouted”, that is, mixed with a low strength cement/flyash grout, and disposed offsite along with the concrete of the silo itself.

This paper is the story of the grouting of silo 1 and 2 that was successfully completed in March of 2005. The process successfully entrained and blended the K-65 residual material in each silo with up to 190 cubic meters, (250 cubic yards) of a flyash cement grout. The grout also reduced radon levels to facilitate demolition work. After the grouting work was complete, the soil embankments surrounding the silos were removed to expose the exterior of the concrete silos. The silo and the solidified residual were then demolished with heavy equipment and the broken pieces of grout and concrete were placed in rail cars for off-site disposal.

Background

The “silos” were 20 centimeter, (8-inches) thick wall concrete tanks built to contain spent uranium ore known as K-65 waste. There were two silos side by side approximately 24.3 meters, (80 feet) in diameter with domed tops about 11.5 meters, (38 feet) high above grade. The silo floors were at grade but soil was stacked against the sides of each silo so that only the domed top was visible. The vertical portion of the silo walls was about 8.5 meters, (28 feet) high and the interior floor of the tank sloped slightly to a central sump. There were two large 90 centimeter, (35-inch) diameter flanges on both sides of each dome and one 127 centimeter, (50 inch) diameter flange opening in the center of each dome. The domes were well past their design life and were too weak to support equipment and were further stressed by a negative pressure radon control system that was required to continuously circulate and filter radon from the air inside the tank. An elaborate steel bridge structure was placed above the top of the domes to provide access to the dome openings without placing any weight on the dome of the aging concrete silos. Three containment modules mounted on the bridge structure accessed the three flanges. A large sump pump was lowered through the central opening while a remote controlled sluicing water nozzle could be lowered through each of the smaller side openings. Video cameras were also inserted through the dome at three points to monitor the position of the sluicing nozzles.

The water sluicing system had been developed and installed on the steel bridge over the silos to remove the waste and transfer it to a new process tank for solidification prior to shipment to a permanent disposal facility. The sluicing system consisted of the two elaborate remote control water cannons (sluicers) that could be remotely lowered into the silo from the two containment modules. A large electric pump was lowered down into the silo from the central opening to collect the water along with the suspended waste material and pump it to the new treatment facility. The waste laden water was allowed to settle in a new process tank and the water was re-circulated back to the silo sluicing system. The sluicers operated at an average pressure of about 689 kilopascals, (100 pounds per square inch). It was anticipated that a “heel” of residual material up to 5 centimeters (2 inches) thick would remain in each silo after removal operations. This heel was the material to be grouted.



Figure 1: Exposed dome of silo 1 with bridge mounted blue containment modules

The K-65 waste contains depleted uranium ore and radium that emits a short half-life radon gas. The amount of this material estimated to remain in the bottom of the silos after removal efforts were complete was up to 4 curies, primarily of radium. This material generates radon gas that could pose a hazard to demolition workers or persons nearby. The silos have a ventilation system that pulls air through the silo to a radon treatment system. This system was designed to operate with a very small negative pressure to minimize stress on the aging silo structure. The waste material was expected to be of a clay-like consistency but could contain numerous debris items such as bottles, buckets, gloves, plastic sheeting, PPE, and small tools. Silo 2 also contained some larger debris that was partially removed with a “grab” style excavator clamshell.

PROJECT OBJECTIVES

The grouting objective was to mix the residual heel material of the silo with a large amount of grout to chemically and mechanically stabilize it so that it could be broken up with minimal dust and radon release and disposed of along with the concrete of the silo itself. Previous studies had already shown that the K-65 waste could be stabilized to meet regulatory requirements by blending it with an approximately 4 parts of class F flyash to 1 part of Portland cement. The waste contained high concentrations of lead. The flyash component is believed to improve leaching resistance by using up the free lime

released by cement hydration which prevents excessively high pH that can increase leaching of certain heavy metals such as lead.

Uniform mixing of the waste residual and debris around the 24.3 meters, (80 foot) diameter of the silo was initially considered a daunting task. The disposal options available dictated that the residual be mixed with a substantial amount of grout so that the waste/grout mixture would be the same waste class as the concrete wall of the silo. It was believed that the sluicing nozzles, which operated at a pressure of only 689 kilopascals, (100 pounds per square inch), would have insufficient power to stir up the waste and debris to suspend it in the grout. No one could know just how hard and tenacious the residual material might be or how hard it would be to mix it in place with the grout until the sluicing was finished. If the material was as hard as dry clay or as sticky as wet clay, mixing could require substantial energy. Due to the tight schedule it was not feasible to simply wait and see what the condition of the waste would be before preparing a plan.

DEVELOPING THE GROUTING PLAN

Many possible methods were considered and rejected. One method involved introducing a remote controlled dozer-like machine into the silo to push the grout around and scrape the bottom of the silo. Carter Technologies Co was subcontracted as a grouting consultant to conceive and develop workable plans to grout the waste heel and develop the grout for the work. The Fernald Closure Project team desired a range of options that did not require workers to enter the silo. The grouting consultant was directed to propose multiple conceptual plans to accomplish the work without the need for workers to enter the silo.

Several different approaches were considered and described in some detail. Most plans involved either high-pressure jet grouting pumps or concrete pumping pumps. Due to the very large size of the silo getting the jet energy to the cover the entire floor of the silo was a challenge. One industrial tank cleaning company offered a remotely controlled nozzle with a built in video camera, but its range and power were too limited. One patented approach considered at length involved placing a large number of non-moving jet nozzles on the floor of the silo to create enough turbulent mixing to stir up the waste. This brute force method had been demonstrated on smaller tanks but would require many high-pressure grout pumps working together along with many grout plants to make the slurry at the required rate making it the highest cost option. Another interesting method involved opening a window in the side of the silo and extending a telescoping or articulated boom of a concrete pumping truck into the silo to direct a grout nozzle around the floor of the structure.

The initially selected option (Option1) was to replace the low pressure sluicing nozzles with high-pressure high-volume grout cannons capable of delivering 757 liter per minute (200 gallons per minute) of grout at 351 kilograms per square centimeter, (5,000 pounds per square inch). This was considered certain to have sufficient power and was within the range of commercial jet grouting pump equipment. Flow straitening technology used

in the cannon nozzle would keep the stream together in a tight pattern allowing it to mobilize large objects from a distance. It was considered likely that there could be a lot of large debris on the floor of the silo. This jet of grout would have sufficient kinetic energy to push debris around and disturb partially cemented waste while mixing it with the grout. The jet of grout would be remotely manipulated to direct the jet of grout at all points of the floor of the silo to perform kinetic mixing of the tank heel material. The three existing video cameras in the silo would be used to guide the remote operation. One variation on this plan called for the grout cannon to sweep an automated pattern instead of using manual control.

Since the jet grouting pumps, high-speed slurry mix systems, and high-pressure operations are specialty work, the grouting consultant determined that the work would require a jet-grouting contractor. The grouting consultant was directed to prepare detailed plans and a technical package to send out for bids. The grouting consultant cautioned that the level of technical sophistication required to quickly assemble an automated jetting cannon for nuclear service and develop a grout with the required characteristics was beyond the resources of most jet-grouting contractors. Asking too much of the contractors could have resulted in too few or perhaps no bids at all. To help address this concern, the grouting consultant was directed to reduce the burden of potential bidders by procuring these items separately. The consultant located a vendor that was marketing a remote control water cannon that had most of the required characteristics and could deliver the grout cannon within a month. The Fernald site workers would perform the installation since they were already certified to work on the silos. The grouting consultant also developed and provided a recipe for the low viscosity grout formulation with the required characteristics. The jet-grouting contractor would only have to handle making the grout and pumping it.

RETHINKING THE GROUTING PLAN

After the sluicing began in the first silo, it became clear that the high-energy systems planned might not be needed to stir up the waste. The degree of uniformity required was also re-evaluated and it was determined that precise mixing while desirable, was not a critical requirement but that keeping on schedule was a critical requirement. Fortunately, the request for proposal had not been sent out and an alternate low-energy, shorter-schedule plan, (Option 2) was already available due to the foresight of the project managers in asking for development of multiple options.

In view of this new guidance, the grouting consultant recommended the (option 2) plan using the existing sluicing nozzle system, but powering the existing sluicing nozzles with commercial concrete pumps. Powering the nozzles this way would increase the mixing energy significantly but could also exceed the design pressure of the system. Using the commercial concrete pumps decreased complexity and increased the operational reliability of the system compared to custom engineered systems. In order to facilitate this approach, a very special grout would be designed that could be made and delivered by ordinary concrete mixer trucks. The grout would have to have the ability to keep waste and debris suspended in the grout. It would also need to have very low line

friction, be resistance to nozzle plugging, and closely match the chemistry of grout mixes already developed to stabilize the K-65 waste.

This plan was a highly cost efficient blend between self-performance and clever use of ordinary construction vendors. The grouting consultant, working for the Fernald Closure Project, provided the technical bridge know-how to combine commercial concrete pumping equipment, commercial concrete mixing equipment with the unusual highly specialized grout requirements of a nuclear waste treatment process.

ENGINEERING THE GROUT

A special low friction grout was developed using oil field drilling fluids technology. This grout could be reliably pumped through small orifices but still possessed the same stabilization chemistry as the mix being used to solidify the waste removed from the silos. The grout also possessed the critical thixotropic properties that would keep the disturbed waste residual suspended in the grout. Samples of the grout were taken to the Fernald Lab and mixed with samples of radioactive residual retrieved from the silo. These samples solidified in a few days as per the design with no indication of any chemical interference from the waste. It was noted in these lab tests that grout mixed in a laboratory cup quickly became viscous enough to allow the stirring stick to stand up in the viscous grout. However, when stirred the grout would flow readily through a small 3 millimeter (.125 inch) funnel. When being pumped at large scale, the grout gave the appearance of a low viscosity material and produced minimal pressure drop in the lines but developed enough gel strength in 3 minutes to prevent settling out of coarse sand. These thixotropic properties were achieved using a pre-hydrated slurry of MI brand "Supreme" premium Wyoming bentonite, with MI Spersene CF viscosity modifier.

The grout mix design had the same 1 part cement to 4 parts flyash ratio proposed for the waste stabilization. This mix took up to 4 days to harden and could tolerate only a limited volume of excess water in the waste. As the grouting day approached, it became apparent that the grout would need to tolerate a significant amount of residual water in the silos. The grouting consultant developed an alternate mix design using 2 parts flyash to 1 part cement. This mix would be able to tolerate more excess water and would harden in less than 24 hours. Both mixes produced the desired final properties resulting in a cured grout with strength comparable to chalkboard chalk. The final strength of the grout was required to be low to facilitate breaking up the grout during demolition. The higher cement content mix was selected to move forward.

This grout mix was then adapted to be prepared by an off-site concrete batch plant. Mixing this type of grout on site would have required a large footprint of equipment from a specialty grouting subcontractor to produce the grout from dry material at the required rate. Dust control would also have been an issue since all flyash contains a small amount of radioactive constituents. It was desired that the entire 18,900 liters, (50,000 gallons) of grout for each silo be pumped in a continuous operation so that the waste would be uniformly dispersed in the grout. Concrete production facilities can mix material at the required rate but do not work well without gravel in the mix because the tumbling of the

gravel creates most of the mixing action. Simply placing the flyash, cement, bentonite, and water into a rotating concrete mixer truck could result in most of the solid material sticking to the drum in a big lump. The grouting consultant had considerable experience in making nuclear grade grout slurry using concrete batch plants and knew how to make this work.

The grouting work was complicated by extremely cold weather. No one knew what unforeseen delays might occur during the grout pumping operation. Significant delays could cause the grout to freeze in the lines so a hotter grout reduced this risk. The pre-hydrated bentonite slurry was prepared in a heated tank at the batch plant. Due to the ambient temperature of -6.7 degrees Celsius, (20 degrees F), the batch was prepared with hot 60 degree Celsius, (140 degree F) water and allowed to hydrate 24 hours. Additional hot water was placed in each concrete mixer truck along with a water-reducing dispersant admixture. The dry cement and flyash were then weighed into the truck by the batch plant and mixed for 15 minutes. Finally the bentonite slurry was added to the mixer truck as a liquid. After twelve mixer trucks of grout were prepared, the trucks were driven to the site and staged. As each truckload was used, the truck would return to make another batch of grout. Adapting regular commercial concrete equipment to perform the work dramatically simplified the project execution and minimized the on-site equipment.



Figure 2: Bentonite mixing and hydration tanks at the offsite concrete batch plant

Grout Mix Details

The grout manufacture process began by creating about 64,000 liters, (17,000 gallons) of pre-hydrated bentonite slurry. An Excel spreadsheet was used for recipe calculation for the silo work. A large heated Baker tank was filled 4,599 liters, (12,015 gallons) of heated water. Sacks of dry bentonite were fed through an eductor mixer and mixed into this water by a specialty subcontractor experienced in making bentonite slurry and circulated for 24 hours to reach full hydration. This bentonite slurry had an approximate specific gravity of 1.077 and was made from:

- 100 weight parts clean potable water
- 12 weight parts premium natural bentonite, (MI Supreme, from MI drilling fluids)
- 1 weight part Spersene CF, (from MI drilling fluids company)
- 1 weight part generic powdered soda ash, (sodium carbonate)

The final grout slurry had a specific gravity of approximately 1.55 was made with:

- 120 weight parts water
- 150 weight parts Class F flyash
- 100 weight parts Type I Cement
- 0.8 weight parts Spersene CF
- 74 weight parts of the Pre-hydrated bentonite slurry

For this highly fluid grout, the capacity of the mixer trucks batch size was de-rated to 6.88 cubic meters, (9 cubic yards) to prevent spillage. For each batch of grout the concrete plant first added the Spersene, water, cement and flyash to the mixer truck and then mixed the slurry for 5 minutes. Then the mixer truck was repositioned under a discharge nozzle from the bentonite slurry tank and a volume of the pre-hydrated bentonite, measured by a turbine flow meter, was pumped into the truck. This was mixed for another 5 minutes and then sampled and tested for density and flow cone viscosity. Twelve truckloads were prepared and staged prior to the start of pumping. The grouting consultant personally supervised the batching, mixing, and inspection of the first 12 truckloads of grout and then accompanied them to the work site.

Preventing Nozzle And Line Plugs

Plugging of the nozzles during the grouting operation would have been a disaster because there was no easy way to unplug the line on the contaminated end of the nozzle inside the silos. If the grout were allowed to harden in the lines inside the containment module, recovery would have taken many days and the truckloads of grout that were staged and ready would be wasted. More importantly, the grout already placed would then harden and further mixing and dilution of the waste on the floor of the silo would be impossible.

Several measures were taken to prevent plugs from occurring. Before the work, the grouting consultant inspected the facilities at the grout plant and the concrete pumps at

the contractors shop and inspected the hoppers and the vibrators. Instructions were provided on the degree of cleanliness required for this unique work. What the concrete pumping contractor supposed was very clean equipment required significant extra cleaning. The grouting consultant showed the contractor how to make a suitable expanded metal screen that would fit into their existing hopper. The hopper on each truck was carefully cleaned and an expanded metal screen was placed within the hopper to prevent rocks larger than 6 millimeter, (0.25 inches) which could potentially bridge and plug the nozzle, from entering the pump. It was not feasible to clean the concrete mixer trucks sufficiently to avoid introduction of rocks but only to minimize their number so that the screen could handle them.

The grout was designed to have a 10-hour working time so that minor delays could be tolerated. The colloidal grout slurry was also designed to be highly resistant to pressure filtration fluid loss as defined by the American Petroleum Institute, (API). The colloidal properties were achieved through the pre-hydrated bentonite slurry so a colloidal mixing of the cement and flyash was not necessary. Excessive pressure filtration fluid loss could allow small particles to concentrate and form a pack that could plug a line or nozzle.

The grout was prepared by first batching the water, dispersant additives, cement, and flyash into the mixer truck. After this, slurry was thoroughly mixed, adding a quantity of pre-hydrated colloidal bentonite slurry containing Spersene and soda ash, additives that reduced the thickening response of the bentonite when cement is added. The dispersed colloidal bentonite in the final slurry reduces friction and helps prevent pressure filtration plugging of the nozzle.

Quality Control

On the morning of the work, the concrete pump trucks were mobilized and connected them to the pre-installed concrete pumping hose. The pump hoppers were re-inspected for cleanliness and the screens and vibrators for function. Final inspection at the batching plant of the pre-hydrated bentonite slurry was completed and they began making the grout slurry. Precise weights of grout were batch blended by the plant (in two batches per truck) and mixed. The pre-hydrated bentonite was then added through a turbine flow meter and a stand that allowed a truck to drive under the discharge spout. After the pre-hydrated bentonite was added, the truck was mixed for 5 minutes and a sample was taken in a wheelbarrow. A standard concrete cylinder mold was filled level with grout and weighed from each batch. A uniform weight for each mold indicated no major batching error and the truck was then released. The mold was then labeled, sealed and allowed to cure. An ASTM flow cone with 12.7 millimeter (½ inch size) opening was performed on finished grout that had aged in the truck for 1 hour. Flow time was typically between 7 and 10 seconds.

SITE PREPARATION AND EQUIPMENT SETUP

The grouting consultant determined that it would be possible to connect the discharge portions of the existing sluicer system to lines fed from commercial concrete pumping

trucks. The existing sluicing nozzles were designed to operate at a relatively low maximum pressure of the central pump, so the line contained components rated at only 1724 kilopascals, (250 psi) and a discharge nozzle of only 6.35 millimeters, (0.75 inches) ID. The concrete pumping units were capable of pumping approximately 984 liters, (260 gallons) per minute. Calculations indicated that at this pump rate, the thixotropic slurry would produce a back pressure of 2585 kilopascals, (375 psi) at the nozzle. The grouting consultant evaluated all the components in the sluicing system such as the swivels, nozzles, hoses, and brass Camlock fittings. The Camlock fitting was determined to be the weak link in the system. An engineering analysis by the grouting consultant indicated it was unlikely to fail catastrophically until it reached over 6895 kilopascals, (1000 psi). This is consistent with the 4 to 1 safety factor typically employed in the design of pressure fittings that are handled under pressure. Since no workers would be allowed inside the module where this component was located, it was acceptable to perform the work with the Camlock fitting contained inside the module. If a fitting failed inside the module, the grout would still gravity drain into the silo. While actual pressures were not measured, there was failure in the system.

76 millimeter, (3-inch) diameter concrete pumping hose was connected directly to each of the 76 millimeter, (3-inch) sluicer lines just inside the containment modules. This kept all the under-rated Camlock fittings contained within the module so that if one failed the grout would still drain into the silo. A reducer located on the silo bridge deck connected this small concrete hose to the standard 127 millimeter, (5 inch) concrete pumping hose from the pump trucks at ground level. Each sluicer line was connected to a separate concrete pumping truck. Contrary to the grouting consultant's advice, the booms on the trucks were not used on the first silo. Instead the concrete pumping contractor preferred to run concrete pumping hose from the truck up the earthen embankments around the silo to minimize the possibility of survey delays in demobilizing the pump trucks. This proved to be troublesome because the pumping contractor had to rely on Fernald site workers to assemble the hoses within the radiologically controlled areas of the earthen embankment. Some of these hoses leaked and sprayed out on the earthen embankment during the work on Silo 1. On silo 2 the grout was pumped through the boom of the truck directly to the deck of the bridge. This was much more efficient and there were no leaks.

OPERATIONS

Twelve truck loads were prepared, at 6.88 cubic meters, (9 cubic yards) per truck, and staged before any left the batch plant. In spite of this, the supply was not able to keep up with the pumping rate. Pumping began to the west nozzle of Silo 1 about 1:25 pm and was completed by 5:00 pm. There was no method of accurately measuring pressure at the nozzle so pumping began at a relatively slow rate. Mixer trucks began discharging into the pump hopper at a rate of about 22.9 cubic meters, (30 yards) per hour for the first 2 trucks. Some concrete hose fittings were not sufficiently tight and began to spray grout. Leaks have the potential to aggravate pressure filtration. Pumping was shut down briefly to tighten connections but small leaks persisted. After a brief shutdown, the grouting consultant determined that the leaks of clean grout were only a housekeeping nuisance and did not present a safety hazard so pumping resumed. The second pump on the other side of the silo was then started.



Figure 3: Silo 2 pumping begins at dawn on north side



Figure 4: Silo 2 pumping operations at southeast side

To prevent collapse of the silo dome while preventing emissions, the Radon Control System (RCS) air pressure control system operators were tasked to maintain a very precise air pressure within the silos balancing software controlled exhaust flow to the carbon beds and fresh air inlet. After pumping began, RCS operators had difficulty adapting to the extra volume being rapidly introduced into the silo. Pumping was stopped a few minutes and then resumed at a slower rate for a short time until operators made RCS adjustments. Pump rate was then gradually increased to about 61 cubic meters, (80 cubic yards) per hour on the first nozzle. The flow stream was pulsating in rhythm to the pump stroke at low flow rates but smoothed out significantly as we increased the flow rate to 61 cubic meters, (80 yards) per hour. At this time pumping also began on the east nozzle at the slower 30 cubic meters, (40 cubic yard) per hour rate, to keep RCS pressures within range.

Due to the extreme cold weather on grouting day, -6.7 degree Celsius, (20 degree F), and the potential for unforeseen delays, the grout slurry was made with hot water to produce a delivery temperature of 21.1 degrees Celsius, (70 degrees F) to allow for at least 10 hours of working time in the delivery trucks before the grout began to freeze. This could have been critical if there were delays, however there were no significant delays. The relatively high temperature of the grout caused significant steaming to occur inside the silos and restricted visibility on the remote cameras. This inhibited the operators aiming of the nozzles but caused no other operational problem.

LESSONS LEARNED FOR GROUTING SILO 2

The second silo contained more debris and was of a harder texture than silo 1. Two more months passed before silo 2 was ready for grouting. Several lessons were learned in the first grouting that were applied to the second silo grouting. These lessons included:

- The grout for the second silo was delivered up to the bridge structure deck using the pumping boom as originally recommended. This eliminated the labor of hooking up hoses and minimizes leaks.
- The grout should be delivered at closer to ambient temperature. In the first silo the grout was delivered to site at 21.1 degrees Celsius, (70 degrees F) to help keep it from freezing if the project was delayed. This temperature resulted in production of so much steam in the silo that the nozzle operators could not see clearly on the video monitors. The grout for the second silo was delivered at 10 degrees Celsius, (50 degrees F) to reduce this steaming effect.
- For the first silo pumping was begun at a lower pump rate and gradually ramped up to full pressure when the job was halfway done. By this time the silo had a foot of grout in it and the fog prevented effective aiming of the nozzle. The lower rate allowed the pulsation of the pump to be expressed at the nozzle. In the second silo, pumping began at high rate with both pump trucks so that the residual can be effectively stirred without pulsation in the streams.
- In the first silo pumping had to stop several times to allow the negative air pressure in the silo to stabilize. The RCS system software controls were not prepared for an inflow of 61 cubic meters, (80 yards) per hour into the silo. The

grouting consultant was not aware of this limitation. In the second silo this remained a problem but it was minimized by a pre-job training meeting with the nozzle operators and the RCS operators to plan the work sequence.

- In the second silo the nozzle operators were instructed to concentrate initial blasts on the central low-lying sump area and work their way outward from the low area to maximize entrainment of the sand-like waste.
- A dedicated worker in the control room whose only job to relay comments from the nozzle operators and RCS operators to the grout consultant. Communications were a problem in the first silo due to the multiple tasks and divisions of authority. The grout consultant, the control room observer, the RCS operator, and the observer on the bridge deck needed more reliable radio communication. In the second silo grouting cell phones were used to supplement plant radios.
- In grouting the first silo, the pump ran out of grout several times. For the second silo the batch plant pre-mixed and staged at least 20 mixer trucks of grout before starting work.