Construction of a Concrete Plug in the South Deep's Main Shaft to seal off a major water intersection

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SYNOPSIS

This paper describes the method used to salvage the South Deep's Main Shaft after it was flooded by an inrush of water at about 450 meters below collar on 1 May 1996. The individual techniques employed in the salvage were all proven technology, but the combination in which they were applied was novel and we believe unique and so meriting the recording of the operation. It involved the following activities in order of occurrence:

- The dewatering of the shaft with submersible pumps;
- The placement of a French drain on the shaft bottom muck pile;
- The positioning of large diameter heavy walled draft tubes and smaller tightening up, grout intrusion and reverse flow pipes;
- The casting and curing of a structural concrete plug. The capping of the draft tubes. The intrusion of several thousand tons of cement grout into the aquifer by pressure induced reverse flow;
- The sealing of the aquifer;
- The extensive probe drilling and sealing of the zone around the inrush point with cement and other specialized grouts;
- The mining out of the plug and the re-establishment of normal sinking routines.

INTRODUCTION

South Deep is a twin shaft project. The main and ventilation shafts are being sunk to design depths of 2765 meters and 2760 meters respectively, making them the world's deepest single-lift shafts. They have a finished lined diameter of nine meters. The shafts are being sunk at Western Areas Gold Mine for JCI Limited.

The method of sinking utilizes seven boom sinking drill rigs with pneumatic drifters to advance three meter rounds. Cactus grab units are used for mucking into 16 ton kibbles which are hoisted to surface by double drum winders. The hoisting is guided by a crosshead on the stage ropes. A six deck working stage provides access for concrete lining of the shaft. A six meter high shutter is used and a concrete lift is cast per day concurrent with sinking.

The initial cover drilling procedure was a standard ring cover round of eight holes, drilled 48 meters deep, dipping at 10° from the vertical with a 12° clockwise spin. When required, additional umbrella holes were laid out. Typically 24 meter deep, dipping 20° from the horizontal and 20° anti-clockwise spin in problem areas as designated by the Geologist.
Cover overlaps maintained at no less than eight meters. The detailed cover drilling procedure and injection procedures used during the project deserve a separate technical paper.

Some of the more important precautions detailed in the procedures are:

- Sinking to stop 10 meters short of any known large water intersection above 10 000 liters per hour as determined by previous cover holes. The standard cover round must then be redrilled.

- All holes injected to 2½ times static head and plugged with thick grout.

- All holes with more than 100 liters per hour to be redrilled and deepened by three meters.

The shaft is so sited that it traverses the steeply dipping Broken Arrow fault at the intersection point of the giant chert breccia above the Malmani Dolomites of the Transvaal series. (See Figure 1 Shaft Elevations on 1 May 1996).

The shaft bottom was within the standard 8 hole cover lift, drilled from -418m and which included four additional flat holes.

On 1 May 1996 a round was drilled at -447m and blasted at 08:30.

On re-entry water was noticed in the blasted rock. It was established that the water intersection was on the sidewall in the North West sector of the shaft on the Broken Arrow Fault. Estimated ingress of ±10 000 ℓph. Water was bailed by means of kibbles for approximately five hours, then split set support installation from the muck pile was started, while bailing continued for two hours. After a further two hours of bailing, four hours of shotcrete operations followed which were concurrent with bailing.

By midnight the bailing no longer matched the inflow and the bottom flooded. The inflow was now 80 000 ℓph and eventually increased to 165 000 ℓph. The water level was now rising at a rate of two meters per hour. This forced a tactical withdrawal up the shaft.

The concrete kettle and shutter turnbuckles were stripped, the stage raised, concrete, air and ventilation pipes stripped and sent out, while bailing continued. The kibbles were converted into bailers, by cutting holes and installing flaps in their bottoms.

Bailing and stripping of services continued for 2½ days while pumps were being sourced.

Pleuger pumps were located at Freegold's IMS store in Welkom. The sinking cables were inadequate for the power required for pumping so the stage was raised to surface, and then lowered whilst installing HT power cables.

Two bearer sets were installed to support the pump column and services were re-installed. The Pleuger pump was suspended below the ventilation recess in the stage by means of slings and chainblocks. The electrical reticulation was completed and after repairing a damaged gasket on the make up piece, pumping commenced on 6 May at 14:00, two days after raising the stage.
Figure 1
Geological Section showing Shaft Elevations on the 1st May 1996
During this time the water level had risen by 138.4 meters to -308.6m below collar. After commissioning the pumps the water level was lowered to -433 meters below collar in five days by bailing and pumping. The pump delivered, ±250 000 ℓph to surface. It took approximately 30 minutes to install a six meter length of pump column during which time the water level would rise by a meter. It therefore meant that the water level had to be lowered by eight meters to install a six meter length of pipe column.

On 11 May 1996 diamond drilling commenced off the stage after the north side kibble hole had been decked off.

Drilling continued for five days while the pump held the water between -433 meters and -439 meters.

On 16 May 1996 a site meeting was held to consider options, and decide on a course of action.

**DISCUSSION OF OPTIONS**

**Drilling and Injecting**

*Drilling from the Stage*

Five days were spent on this option from 11 to 15 May 1996. Repeated water losses demanded rod pulling, grouting, setting time and redrilling, only to again lose the water. This attempt eventually failed and this option was rejected.

*Drilling from a Cubby at -431m*

A 3,0 meter x 3,0 meter x 10,0 meter cubby was considered.

*Advantages:*

The cubby lent itself to better diamond drill layouts, away from the shaft to avoid the water loss problem.

*Disadvantages:*

Time to cover, excavate and support cubby.

- Since the cubby was situated in hanging wall side of fault, holes would have to traverse the fault zone causing difficulties and drill steel losses.
- Holes could transfer water higher up the shaft bringing pressure closer to the sidewall and lining
- Chemical injections could restrict the effectiveness of future reverse flow efforts.
Figure 2
Options
Vent Shaft Solutions

Pump Chamber at -425m and Minibore Hole

Advantages:
Immediate access to -425 meter elevation, current ventilation shaft bottom.

Disadvantages:
Risk flooding the Ventilation Shaft.

• Geology
  Have to drill in the shale and traverse the fault zone.
• Minibore hole could deflect in the shale and miss the shaft.
• Scaling in the hole could make it difficult to case.

Pump Chamber and Minibore Hole at -475m

Advantages:
Geology
Minibore hole in chert and footwall of fault casing easier, improved drilling accuracy.

Disadvantages:
Time
Half a month to sink, two months to cover, excavate, support and equip pump chamber.

A deeper variation of this option was subsequently executed at -500 meters in the Ventilation Shaft. This rendered the excavation of a temporary pump chamber in the Main Shaft unnecessary.

Plugs

Flood to Equilibrium and Cast an Underwater Plug

This method was used at Western Deep Levels South Shaft 1982/1983, Free State Geduld 1953 and Blyvooruitzicht 1937.

It was decided this method would take the longest time, though it had a good chance of success.
Major disadvantages are the difficulty and uncertainties associated with the remote construction of a plug beneath 300 meters of flooded shaft.

*Plug Constructed on the Curb*

This option was listed as a possibility and discounted because of construction difficulties arising from the underside of the plug being 20 meters above the bottom.

*Plug above French Drain on Top of Muck Pile*

The plug would be of structural quality concrete cast in controlled conditions, and superior to a grout intruded plug formed underwater. The reverse flow technique was considered the best solution to seal off the water source.

Risk: Pump failure before capping the draft columns.

It was decided to pursue this solution at the meeting held on 16 May 1996, and design work began immediately. This solution was chosen because of its direct access and close proximity to the bottom. The underwater plug option was considered to be too remote. In addition to the advantages and disadvantages listed above, this option was based on proven technologies.

**PLUG DESIGN**

Regulation 2.10.14 states:

Submit for approval to the Government Mining Engineer plans and specifications giving details of construction and catchment area of any dam to be constructed for the purpose of conserving water and of any coffer-dam or other barricade which is to be constructed underground for keeping back water under a pressure exceeding 700 kilopascals.

Plug Design conformed closely with the Chamber of Mines’ Code of Practice on Construction of Underground Plugs and Bulkhead Doors Using Grout Intrusion Concrete of February 1983.

**Design Parameters**

- Maximum pressure likely to result from the reverse flow was 4.5MPa.
- Plug length determined in accordance with the COM Code of Practice using side wall/concrete interface shear strength of 0.83MPa.
- Concrete strength of 30MPa at 28 days.
- Concrete to be poured continuously at a rate of between 10m³/hr and 20m³/hr, vibration by normal vibrator pokers.

* The two substantial keys formed by the existing concrete lining were ignored for design purposes, though it was believed they would enhance shear resistance.

* The plug was regarded as an unreinforced, though the sacrificial scaffold, 48 tightening pipes, seven injection pipes and two draft columns would provide substantial reinforcing.
Calculations

**Plug Length**

\[ \text{Length of Plug} = \frac{\text{Area} \times \text{Pressure}}{\text{Perimeter} \times \text{Safe Shear}} \]

\[ = \frac{+d^2}{4} \times \frac{P}{+d} \]

\[ = \frac{+(10)^2}{4} \times \frac{4500}{+.10} \times 830 \]

\[ = 13.5\text{m} \]

**Number of Tightening Pipes**

A 15 meter high plug of 10 meters in diameter has a rock/concrete interface area of:

\[ = M \times d \times 1 \]

\[ = M \times 10 \times 15 \]

\[ = 471.4\text{ m}^2 \]

The minimum number of tightening pipes required for such a plug should be:

\[ = \frac{\text{Surface Area}}{3.5} \times \frac{471.4}{3.5} \]

\[ = 134 \text{ Pipes} \]

**The Large Diameter Heavy Walled Draft Columns**

The two draft columns, known as the North pipe and the South pipe, each consisted of a top and bottom section.

It was decided that the North pipe would be capped last, and therefore should stand higher above the top of the plug than the South pipe which would be capped first. This was to allow enough time after removing the pump from the North pipe for the column to be capped before the water rose above the top flange.
The additional height on the North pipe was effected by the inclusion of a two meter spacer on top of the bottom section with the same specification as the bottom section of pipe.

**Bottom Draft Column Specifications**

- **Pipe length**: 15m
- **Pipe diameter**: 900mm
- **Wall thickness**: 10mm
- **Top Flange**: 62mm thick plate, with 24 x 34mm Ø holes. Table D Flange

**Top Draft Column Specifications**

The maximum pressure that could be exerted on the top section which extended through the top of the plug by the reverse flow process from a reservoir on the bank would be 4.5MPa. The wall thickness calculations were based on 5MPa.

The pipe manufacturer was instructed to test the pipes to 6.4MPa for two hours prior to delivery.

- **Pipe length**: 8m
- **Pipe diameter**: 900mm
- **Wall thickness**: 12mm
- **Bottom Flange**: 62mm thick plate, 24 x 34mm diameter holes to match existing Table D Flange
- **Top Flange**: 147mm thick plate, 28 x 62mm diameter holes for M59 Grade 8.8 bolts
- **Blank Flange**: As for top flange plus one 150 x 100mm weld on pipe complete with flange for reverse flow, and three 50 x 50mm long weld on sockets for grout injections
- **Flange Grade**: SABS 1431 Grade 43A
- **Gaskets**: 3mm thick Klingerite high pressure gaskets
- **Puddle Flanges**: OD 1 100mm, 16mm, thick plate, 6mm continuous fillet weld 900mm NB pipe with flanges and puddle flanges. [See Figure 3].

The possibility of being able to supercharge the reverse flow process in order to improve the chances of success of this aspect of the treatment was discounted by the increased thicknesses of the blank flange and the walls of the large diameter pipe required to withstand working pressures in excess of 10MPa.

As it turned out the 10mm thick walls of the North pipe bottom section collapsed during tightening, requiring that the columns to be capped in the reverse sequence.
Figure 3
900mm Pipe with Flanges and Puddle Flanges Top Draft Column
The Structural Concrete Plug

Using the aforementioned design parameters and the Code of Practice developed by the Chamber of Mines a 14.6 meter structural concrete plug was designed and drawn up. This allowed for a conservative safety factor.

On completion of the design work by the Professional Engineers, the abovementioned drawings and the recent cover drilling records accompanied the formal application for permission to construct the plug.

The Application Seeking Permission to Construct a Plug

Regulation 2.10.14:

On 21 May 1996 an informal meeting was held with the Regional Director’s Office to communicate the novel aspects of the scheme and the parameters involved with the design. This was followed up with a formal meeting on 22 May 1996 with the official application. Senior representatives of the Regional Director’s Office, Mechanical and Civil Engineers, A Concrete Technologist and the direct role players were present.

The methodology for sealing the water was debated at length, with two main reservations coming to the fore.

The Selection of the Site

Reservations:

The proposed plug was within a fault zone. Concern was expressed regarding, the anchoring of the plug, its water tightness and the possibility of water rising along the fault and breaking back into the shaft at the -415 meter elevation above the plug.

Remedial Considerations:

Examining the cover drilling records at the -380m, -400m, and -418m elevations it was established that the fault was more than adequately tightened in this area of concern.

The cover holes were sealed at a pressure of 7.5MPa, indicating the fault was well treated and very unlikely to transfer water where tightened. This was confirmed by previous drilling and injections in the tightened fault zone. See Figure 5, Cover Drill No’s 9, 10 and 11.

When tightening the plug through the proposed holes the fault would be further sealed.
Figure 4
Structural Concrete Plug
Sealing of the Rock Plug Interface

Reservations:

The 48 tightening pipes laid out in the proposal were less than recommended by the formula in the Code of practice.

Remedial Considerations:

Although the proposed tightening pipes were less than recommended by the Code of Practice for a grout intruded concrete plug, the consultants, designers and constructors were of the opinion that they were more than adequate for a structural concrete plug.

Differences between the Proposed Structural Concrete Plug and a Grout Intruded Plug

Grout intruded plugs are commonly filled with hand packed plums and are usually constructed in the horizontal plane.

The proposed plug was an un-reinforced structural concrete plug in the vertical plane.

Grout intruded plugs have previously been cast underwater in flooded shafts.

The proposed plug would be cast in controlled conditions and vibrated.

The proposed plug was to seal the inflow and was not a permanent plug designed to withstand a large head for a long time.

Additional Precautions

- The following additional precautions were taken during plug construction.
- Concrete lining was monitored from the stage, any indication of increased seepage was immediately treated.
- Concrete placing was carried out according to a written procedure.
- Flange tightening and bolt torquing was supervised by a certificated engineer.
- Pressure gauges and valves were installed on the stage as well as the plug.
- Ladders were installed from the stage to the top of the plug.

Concurrent with the meetings and debate with the Regional Director’s office the placement of plums for the construction of the French drain around the draft columns was taking place. Once the Additional Precautions were proceduralised the Regional Director’s office gave permission for the plug to be constructed.
Figure 5
Cover Elevations 9, 10, 11
On 27 May 1996 while the sacrificial scaffold and final preparations were being made, a last meeting was held with the Civil Engineering Department of the University of the Witwatersrand as well as the designers. This meeting served to confirm what had already been established by the role players.

**PLUG CONSTRUCTION**

After dewatering the shaft the water level was maintained at -439 meter elevation, the shutter was stripped out and the scheme developed for the salvaging of the shaft could be implemented.

This method entailed the constructing of a French drain and structural concrete plug, whilst continuing to pump with one submersible pump with another commissioned as a standby. A spare pump was kept on surface. (See Figure 4)

The steps involved in the plug construction were as follows:

- Install 2 x 900mm draft columns above the muck pile.
- Install 7 x 50mm vertical Cementation injection pipes.
- Tip 4 m of washed plums on top of the muck pile.
- Discharge two meters of washed 19mm stone down the concrete pipe on top of the plums.
- Place PVC and geofabric sheets on top of the French drain above the water line.
- Erect sacrificial scaffold and tightening pipes.
- Cast 15 meter concrete plug.
- Cure the plug.
- Tighten the plug.
- Remove pumps and blank flange draft columns.
- Start reverse flow accompanied by cement grout intrusions.

**Construction of the French Drain**

The two bottom sections of the 900mm draft columns were positioned on top of the muck pile. Seven 50mm injection pipes were placed around the circumference of the shaft.

Three of these injection pipes were located in the North West Sector where the water inrush was believed to have occurred.

During this time the water was being pumped from No. 1 pump suspended from the stage on the North side of the shaft. The tipping of washed plums started, but had to be interrupted to install a second HT cable for the second pump.

Four meters of plums were discharged into the water and built up above the muckpile around the pipes.

A modified lazy chain type tipping arrangement was improvised at the bottom of the stage, so that the machine kibble could tip the plums into the centre of the shaft. Hand positioning of plums took place around the large diameter pipes and away from the suspended pump(s) to avoid damaging them.
During the placement and tipping of the plums the third Pleuger pump was tested on the second HT cable and took over the pumping duty, suspended from the stage.

The first pump was now installed in the bottom section of the North pipe, the column extended to the lateral and the pumping was again switched over to the North side.

Two meters of 19mm washed stone from the batch plant was discharged down the concrete pipes on top of the plums. Once the stone was above the water line it was possible to stand on the French drain and level it. This allowed men to stand on a “false” bottom, whilst a submersible pump maintained the water level just under this surface by handling the 160 000 ℓ that the aquifer was making.

During the tipping of the stone, the top eight meter high pressure section of the South pipe was lowered and installed and the second pump inserted in the now completed South draft column. The pumping was changed over to the South side.

The plums and stones were washed because the Pleuger pumps can only handle clean water and are not designed for dirty water pumping.

A 50mm balancing pipe was installed to discharge water back into the North pipe. This facility basically dumped water back to the French drain to ensure the water level remained constant so the pumps could not run dry. This was monitored and controlled by a man on top of the South pipe in radio contact with another on the stage operating a valve on the balancing pipe.

The No. 1 pump was removed from the bottom section of the North pipe, the top section lowered, fastened and the pump re-installed. On completion the pumping was switched back to the North side.

The preparation, installation of the draft columns, the second HT cable run and the construction of the French drain took eight days from 18 to 26 May 1996.

**Erection of Scaffold and Tightening Pipes**

From 26 to 28 May 1996 geofabric and PVC sheets were placed on top of the stone of the French drain, followed by the erection of the sacrificial scaffold, platforms and ladderway.

Thirty two tightening pipes were positioned in four vertical rings over the length of plug, each consisting of eight pipes equally spaced around the circumference of the shaft. The sacrificial scaffold was required for access whilst casting and vibrating the concrete and to support the tightening pipes in a specific configuration.
Casting and Curing of the Structural Concrete Plug

A mix was designed by a Concrete Technologist for a strength of 30MPa at 28 days and a procedure for the placing of the concrete was drawn up.

Preparations that had to be completed before casting the plug were:

- The placing of the Geofabric and PVC sheets on top of the French drain so as to prevent cement getting through to the pumps and
- The positioning of the sacrificial scaffold for access during the placement and vibration of the concrete.

Casting began at 10:00 on 28 May 1996.

Initially a pouring rate of 10m³/hr was achieved. A calcium chloride accelerator was added to the first 500mm to form a blinding screed. The pour progressed well and it was decided to increase the rate to 20m³/hr once the first 5m was cast so as to reduce the time that the pumps would be at risk from dirty water. The increase in heat generation from hydration with this high rate of pouring did not prove to be problematic as was feared.

In fact, even during the curing of the plug no marked or discernable increase in temperature was noted on top of the plug.

On the second day the pour was stopped temporarily for 5 hours to do maintenance on the Batch Plant and kettle and to change concrete hoses. The last two rows of tightening pipes were installed from the scaffold concurrent with the pouring operations.

On 30 May 1996 there were a few scares when the kibble winder tripped for three hours. The No. 1 pump in the North pipe dropped its delivery rate and water pushed up the draft columns onto the plug. Switching over to No. 2 pump in the South column resulted in a gasket failure. The pumping was immediately switched back to No. 1 pump, which fortunately resumed its normal delivery.

Later it was established that the pump output had been adversely affected by fine black grit from the fault entering the pump and clogging the suction. Switching the pump off settled the grit, clearing the suction. The night shift crew had to contend with a minor concrete blockage at the kettle.

The pour was completed at 15:00 on 31 May. A total of 1 132m³ had been placed in 3,2 days, resulting in an average pour rate of 14,7m³/hr including maintenance, blockage and pump delays.

The plug was allowed to cure for 5.1 days from 31 May to 5 June 1996. During the curing period the pump delivery and amperage were monitored and preparations were made for tightening.

Tightening of the Plug and Capping of the Draft Columns

On 5 June 1996 tightening commenced on the bottom ring (A ring) according to the tightening procedure.

Tightening was required to ensure adequate sidewall/concrete interface sealing and to take up any void caused by shrinkage. On 9 June, whilst tightening the first two B holes, the No. 1 pump cable
developed a fault in the shaft, at a joint box and along the cable above the stage. Pumping was switched to No. 2 pump in the South pipe.

It was then established that the No. 1 pump and its shroud were stuck in the 900mm North pipe. The tightening was stopped. Without a standby pump it was now considered imperative to cap the draft columns.

The third Pleuger pump was lowered onto the plug. The stage was raised, the faulty cable and joint box removed and a new cable installed and connected.

The blank flanges were suspended below the stage. All the tightening pipes were closed.

It was now established that the bottom pipe in the North draft column had collapsed 10 meters below the top of the uppermost flange and the pump was trapped.

The sequence of capping the draft column now had to be reversed, with the lower South pipe having to be blank flanged last.

The problem now was that there would not be enough time between stopping and removing the pump to position the blank flange and torque the bolts before the water level would have risen above the flange.

The solution lay in an improvised water handling arrangement. The third Pleuger pump was installed in a vent pipe on top of the plug which served as a water tank. A Flygt pump and several Quimbys were placed on top of the plug.

This solution was first tested by allowing the water to flood on top of the plug and then transferring it with the Flygt to the Pleuger in the ventilation pipe. This method proved capable of handling 160,000 ℓph. Pumping was then switched back to the No. 2 pump in the South pipe.

Three 25mm injection pipes were installed in the North pipe past the side of the trapped pump for future use. A short concrete blinding was cast on top of sandbags on top of the pump. The blank flange was bolted onto the North pipe and the column pumped full of cement grout.

The water handling system on top of the plug had been tested and all that remained was for the final preparations to stop Pump 2, remove it and cap the South pipe.

These preparations included arranging for two professional divers to be present to do the final bolting should the water rise above the flange.

With the divers, senior site supervisors and project leaders present, the No. 2 pump was stopped and withdrawn from the South column. The water rose, flooded onto the top of the plug through the 150mm T piece, was picked up by the Flygt and Quimby pumps, delivered to the Pleuger in the vent pipe tank and pumped to surface.

On 12 June 1996 at 22:00 the columns were successfully capped.

This was a significant accomplishment. The water inflow was now under control. We were no longer dependent on the pump thus removing the concern of pump failure.
The initial pressure on the plug was only 2,0MPa. A more accurate gauge subsequently recorded 2,9MPa, indicating the water table at -133 meters below collar.

Immediately following the capping the reverse flow pump column changeovers were done on the sub-bank and shaft bottom and the reverse flow process initiated.

**REVERSE FLOW AND CEMENT GROUT INTRUSIONS**

On 12 June 1996 the reverse flow tank was commissioned on surface with a flow meter on the 100mm column from the dams. The 150mm valve on the reverse flow column, just above the blank flange, was opened and the water allowed to rise to its equilibrium level.

A T-piece was installed on the pump column so that a probe could be lowered to determine the level of the water table. The probe indicated the level at -156 meters below collar. This meant there was a 300 meter head and a pressure of 3,0 MPa was expected. A 40 bar gauge was installed on the South side draft column via a hydraulic hose to the stage.

This gauge recorded 2,9MPa. A gauge on the reverse flow column on the stage recorded 2,7MPa.

The reverse flow was started at a rate of ±60 000ℓph after one additional 50mm water delivery feed was installed. On the evening of 13 June 1996 cement intrusions began and supplemented the reverse flow. This process continued for the next 34 days until the aquifer stopped accepting water on 18 July 1996. A further six days of grout injections followed. All the cementation pipes were finally sealed on 23 July 1996, 40 days after starting. Over this period 7 340 000kg of cement and 11 megalitres of reverse flow water were introduced below the plug.

Initially three double drum mixers and pumps were used for the cement intrusions; and the mix ratio was increased from 100kg/barrel to 150kg/barrel with a reverse flow of ±42 000ℓph. On 15 June 1996 a high shear electric mixer with a storage tank and two pumps were erected. The plug pressure gauge was now reading 2,5MPa. From 16 to 28 June 1996 the mix ratio was increased to 450kg/300ℓ barrel, [1,5:1] with the reverse flow reduced from ±40 000ℓph to 12 500ℓph, with two to three pumps running via grout ranges to the various intrusion pipes. During this period the pressure at the plug rose from 2,5MPa to 3,8MPa.

On 28 June 1996 the cement mix ratio was increased to 525kg / 300ℓ barrel 1,8:1 and again on 29 June 1996 to 600kg / 300ℓ barrel 2:1. By 30 June 1996 the reverse flow was down to 10 000ℓph and in the order of 300 tons of cement was being intruded per day. On 2 July 1996 the reverse flow and intrusions were stopped and the quantity and pressure of the inflow checked through a 50mm valve. The inflow was now only 15 120ℓph down from the original 165 000ℓph and the water table pressure only 2,0MPa. The reverse flow with the valve fully open would only take 15,600ℓph.

When the reverse flow and injection process started up again, the plug pressure had dropped from 3,8MPa to 3,4MPa.

The cement mix was now increased to 750kg/300ℓ barrel [2,5:1]. On 4 July 1996 a record 363 tons of cement were intruded in a 24 hour period. Plug pressure 3,5MPa.

On 5 July 1996 the reverse flow and intrusion process was stopped for the second time to test the inflow through a 150mm opening. This time the fissure inflow was measured at 19 895ℓph. On starting the process again the plug pressure had reduced from 3,5MPa to 3,0MPa.
On 7 July 1996 the intrusion operation changed to bulk cement instead of 50kg pockets by using the batch plant silos and mixers and then feeding the high shear mixer and storage tank. Extremely thick grout mixes of 2,1:1 to 2,3:1 were intruded on 8, 9 and 10 July 1996 with a reverse flow of ±8 000ℓph. Heating elements were also installed in the reverse flow tank.

Over the 11, 12, 13 July 1996 the grout mix ratio was reduced to 1,5:1 with ±7 000ℓph reverse flow.

On 12 July 1996 the intrusion pipes blocked and had to be redrilled. The fissure inflow was checked for the third time and recorded at 14 000ℓph. Some sodium silicate was pumped into the intrusion pipes. Reverse flow and intrusions continued until the reverse flow choked off. On the 13 July 1996 two cementation ranges blocked and had to be opened and repaired. Two cementation pumps were put on to the reverse flow on the blank flange, but this just pushed the water back to surface. Using one cementation pump, a reverse flow of ±5 000ℓph into the fissure was achieved. On the 15 July 1996 the grout mix was set at [1,8:1], the blocked cementation ranges were redrilled and intrusion resumed with one pump on grout and 3 pumps on water only. This continued for three days accepting 100 tons of cement a day. Plug pressure was steady at 3,9MPa.
Figure 7
Reverse Flow and Cement Intrusions

- Kg's CEMENT INJECTED /DAY
- REVERSE FLOW WATER
- FISSURE FLOW 15,000 l/hr
- FISSURE FLOW 19,000 l/hr
- INJECTION HOLES BLOCKED
- CEMENTATION RANGES BLOCKED
- REVERSE FLOW STOPPED
- No 4 HOLE ONLY

DATE
[1/hr] [kg] [MPa]

FLOW-I/HR (*1,000)  CEMENT-kg (*10,000)  PRESSURE - MPa
At a meeting on 17 July 1996 it was decided to stop the reverse flow and just inject cement grout until it sealed the fissure. Leakage occurred on the gasket of the blank flange and was repaired. Holes 6, 2 and 1 sealed off at 6MPa on 17 and 18 July 1996. On 19 July 1996 holes 5A and A were reinjected and sealed. Holes 1, 4, 5, 6 were redrilled and injected with holes 1.5 and 6 resealing on the same day. No.4 hole took another three days and 56 tons of cement and finally sealed on 23 July 1996.

At this point the reverse flow and intrusion phase was considered complete, and the probe drilling began.

During this period an intermediate pump station was excavated at -500m in the Ventilation Shaft.

**DRILLING PROGRAMME**

It now had to be established if in fact the fissure had been effectively sealed. Confirmation was to come from an extensive drilling and consolidation programme.

This programme eventually consisted of:

- 33 Vertical holes
- 32 Tightening holes
- 12 Complementary holes of 45,0m
- 12 Umbrella holes of 27,0m
- 12 Ring cover holes of 43,0m
- 2 Additional holes

A total of 3 754 meters of diamond and percussion drilling Super Grout injections in vertical holes 24 640kg - Total cement injections 159 683kg.

The probe drilling which began on 23 July 1996 proved to be time consuming. The extent of the drilling required to confirm that the water had been sealed was completed on 7 September 1996, some 46 days later.

**Vertical Holes**

The first step in the vertical hole drilling was redrilling through the grout intrusion pipes onto the muckpile and cementating to consolidate the plug, French Drain and other loose material. Initially screw feed compressed air diamond drill machines were used to drill, redrill and deepen these holes to 10 meters into the solid footwall to obtain core for Geological evaluation. No chemicals were used at this stage.

The grout intrusion pipes No’s. 2 and 3 contained stuck drill rods from periodic blocking and redrilling during reverse flow and intrusions.

The core drilling had very limited success due to the presence of the gritty fault material not bonding with cement and making consolidation extremely time consuming. Often core loss was complete because of the grit.
The only water intersected was 300ℓ ph in hole 6 and 100ℓ ph in holes 4 and 5, indicating a successful seal.

Following the deepening of the grout intrusion pipe holes a further series of 27 vertical holes were laid out, running North-South mainly on the Western side of the shaft. These new holes were cased with six meter casings into the plug, and pressure tested to 10MPa.

Drilling through the concrete was slow and advance rates below the concrete plug were severely restricted as a result of the consolidation work required in the French drain and blasted rock.

Some of the holes struck the steel of the scaffolding and tightening pipes and had to be abandoned. Holes meeting the gritty fault material either got the bit or rods stuck as a result of water loss. To speed up the time consuming consolidation process a specialised micro-silica based grout called Super Grout was used.

This grout was able to bond to the grit and enabled the holes to penetrate into the solid footwall. Of these 27 additional vertical holes only No.14 intersected any water, 150ℓ ph, all the remaining holes were dry confirming successful treatment of the zone below the shaft.

**Tightening Holes, Complementary, Umbrella & Ring Cover Holes**

The 32 tightening holes were then deepened to an average of 40m with only the following five holes intersecting any water:

- **A5** - 900ℓ ph
- **A6** - 2 100ℓ ph
- **C** - 300ℓ ph
- **D5** - 290ℓ ph
- **C4** - 1 290ℓ ph

75 220kg of cement was injected into these holes.

The bottom was now becoming cluttered with casing pipes, wedge bolts and tightening pipes as well as machines, cradles, rigs and controls.

After ensuring that all the vertical holes were to depth and sealed the casing pipes were cut off on top of the plug.

On 25 August 1996 a 12 hole umbrella cover with a dip of +5°, a depth of 27 meters and an anti-clockwise spin was drilled from the top of the plug. One hole intersected 1 440ℓ ph and 44 800kg was injected for the whole cover.

On 29 August 1996 the Jumbo drill rig was lowered and an additional 12 holes at a dip of -70° and 45 meters deep were drilled to complement the tightening pipes and fill the gaps. All the holes were dry and 28 980kgs of cement were injected. The 900mm draft columns and remaining casings were cut off on top of the plug.

The drill rig was taken down for a 12 hole ring cover, with only two holes intersecting a trace and 90ℓ ph. 10 690kgs of cement were injected, completing the cover on 6 September 1996.
It was now confidently confirmed that the zone from 40m below the plug and radially from 20m beyond the barrel was dry and the excavation of the plug could commence.

During the recovery of the Main shaft the Ventilation shaft had completed the pump station, commissioned the pumps and sunk to -560m.

**SHAFT RECOVERY**

The removal of the plug began on 7 September 1996. The Plan of Action for the final recovery of the shaft involved:

Excavation of the plug to -432,5m elevation. The drilling and blasting of the concrete went better than expected. Initially daily blasts yielded 1,4m advances. The drill rig achieved good penetrations whilst the lashing cycles were extended due to the cutting out of the steel and 900mm draft columns, tightening and intrusion pipes and the scaffolding. Cement contaminated blow overs were particularly harsh on the crew.

On 12 September 1996 a 12 hole 43,0m deep ring cover at -80° was started at -432,5m elevation. Of the 12 holes only No.9 intersected trace water. Eleven additional holes were drilled, all dry, confirming the effectiveness of the seal.

Whilst this cover was being drilled, a diamond drill machine in the Ventilation shaft pump chamber drilled a cover hole in the line of the minibore hole from the Ventilation shaft pump chamber to the Main shaft. A second machine was aiming at the fault and previous water intersections. During Main shaft injections coupling occurred with these approaching holes.

The remaining +6m of the concrete plug and +3 meters of the French drain was removed in advances of 1,3 meters per blast. The cycle time now down to fifteen and a half hours. The 19mm stone section of the French drain was found to be well consolidated. The miniborer in the Ventilation shaft had collared and begun boring. The curb and shutter were reinstalled in the shaft. Five cores were taken from the concrete removed from the plug for testing.

The average strength was 33,0MPa.

On 23 September 1996 at -442m elevation near the top of the French drain a 12 hole by 48m -80° ring cover was started.

The following 3 holes intersected water:

- No.7 - 900ℓph
- No.7A - 300ℓph
- No.9 - 720ℓph

86 246kgs of cement and 3 600kgs Super Grout were injected into this lift.

Twelve additional holes were laid out. No.19A intersected 7 200ℓph and No.20 intersected 250ℓph.
On 3 October 1996 these additional holes were sealed with progressive injections of 10 260kgs cement and 500kgs Super Grout.

The remaining plum section of the French drain was removed recovering the trapped Pleuger pump, damaged but complete. The muck pile was removed, uncovering the solid shaft bottom at -450m and exposing the breach zone.

The sidewalls and bottom were examined on 8 October 1996. The steeply dipping boundary planes of the Broken Arrow fault could distinctly be seen on the sidewalls with typical gritty, friable, decomposed infill between the top and bottom boundaries.

On the northern sidewall a roughly horizontal fissure of 3.5 meters in length varying between 3cm and 8cm was evident running across the steeply dipping fault planes.

This fissure was filled with both cement and Super Grout.

The shaft was now recovered to the elevation attained at 1 May 1996 some five months and one week after flooding. Normal sinking routines turned out to be a long way off due to the intensive cover drilling at close intervals which were carried out for the next 120 meters of sinking.

The day after the shaft was recovered the miniborer from the Ventilation shaft pump chamber holed into the Main shaft. This hole was subsequently reamed to 279mm diameter sleeved and now provides an emergency water handling service for both shafts from the intermediate pump chamber in the Ventilation shaft.

**COVER DRILL ROUNDS USED IN THE DOLOMITES**

The cover drilling and injection procedures developed during the sinking of the South Deep shafts could be the subject of a technical paper on its own. All that is described here is the design of the round. The cover round consists of a 16 hole ring cover, a 16 hole umbrella cover and one stab hole.

The 16 umbrella cover holes numbered U1 to U16 are drilled radially out from the centre of the shaft, collaring at the sidewall/footwall intersection.

These holes dip at -65° from the horizontal and drilled to a depth of 24 meters.

The stab hole is drilled vertically to a depth of 48 meters and is positioned within 1.5 meters of the shaft centre.

The cover consists of two rings, one at a radius of 4.5 meters and the other at 4.0 meters from the centre of the shaft. The outer holes are odd numbered R1, R3 to R15 and the inner holes even numbered, R2, R4 to R16.

All these holes are spun clockwise at 45° to the tangent and drilled to 48 meters.

The outer ring holes dip at 75° whilst the inner ring dips at -80°.
SUMMARY AND CONCLUSIONS

The salvaging of the shaft was a success and a tribute to all those involved. The experience was not only an example of the benefits of client / contractor cooperation and joint participation in problem solving but was a technological achievement which involved the application of all the specialised Mining, Drilling and Engineering skills of the project team and contractor.

Having said this, should this method be considered for future shaft water intersections? Was it efficient?

Each water intersection has to be assessed for its own peculiar characteristics, depth, pressure, volume and pumping facilities. The method utilised here, might not suit another set of conditions. The greatest risk was the possibility of failure of the Pleuger pump during plug construction. This risk was effectively minimized by the initial availability of three commissioned pumps.

In terms of duration, the construction of the French drain, plug, curing, tightening and capping took only 26 days of the five months and one week salvage period.
The drilling, blasting and mucking of the 26 meter of plug, French drain and grouted muck pile from -424m to -450m only took 14 days.

The bulk of the time, nearly three and a half months was taken up with the reverse flow and injections, which took 40 days; and the redrilling, injections and additional covers took 63 days.

The reverse flow technique is the key to sealing exposed aquifers of this nature. Could the reverse flow and grout intrusion process have been made more efficient in terms of time? Supercharging the reverse flow process by increasing the feed pressure through a battery of pumps was considered, but the draft column pipes were limited to 7MPa and there were water supply quantity constraints.

Due to the large grout acceptances a number of additives were considered to reduce cement costs.

Slagment and OPC in a 50:50 mix, but slagment has no mechanical strength.

Pulverized Fuel Ash (PFA) could be mixed with the grout, this provides a more pumpable grout but increases setting time.

Tailings were considered but rejected on environmental grounds as they could contaminate the water table and choke off fine fissures.

Cement / water ratios were debated at length, most of the grout was intruded at between 1.5:1 and 1.8:1.

Extremely thick grouts of as high as 2.3:1 to 2.5:1 were pumped for short periods.

Greater acceptance was achieved at the lower ratios where the pumps were more efficient.

Specialized chemical grouts were considered but not employed as it was feared they may have jeopardized the ultimate success of the reverse flow intrusions.

Coloured dyes were used to indicate coupling between intrusion pipes and independent pathways into the fissure.

Isotopes were considered to establish cement travel but not used.

On three occasions the reverse flow process and grout intrusions were stopped to determine the fissure flow. This confirmed that the intrusions had reduced the flow to 19 000 ℓ/ℎ and later to 14 000 ℓ/ℎ giving some faith in a seemingly eternal and possibly fruitless process. In retrospect these checks probably dislocated some of the accretion that had taken place and this was noticed in reduced pressures when the flowback was stopped and the reverse flow started up again.

The introduction of sodium silicate just before the reverse flow stopped and the intrusion pipes blocked was probably coincidental and not the reason for the final seal.

Pumping of high pressure water to re-open pathways through the grouted shaft bottom to extend the reverse flow and intrusions probably caused the South Pipe gasket to leak.

The reverse flow and grout intrusions seemed to run their own natural course and eventually a seal was obtained after a Biblical 40 days and 40 nights. How this process could have been accelerated is the subject of continuing debate. The extended drilling programme did confirm that the reverse flow had effectively sealed the fissure.
The probe drilling, injections and additional cover drilling took the lion's share of the time and it is a moot point as to whether this period could have been shortened without endangering the success of the programme. Initial consolidation problems below the plug were later resolved by the utilization of a specialised chemical grout. The drilling programme was extensive and time consuming but necessary to establish the confidence that the water had been sealed. Utilizing the S-140 drifters on cradles with controls proved more effective than S-36, Kempe and S-30 machines.

No significant water was intersected after the 7,360 tons of cement were intruded by the reverse flow process. The additional covers at -424.1m, -432.5m and -442m were basically all dry and accepted a further 204 tons of cement and 4.1 tons of Super Grout.

The concern that water might travel back along the fault and break back into the shaft at the lining fault intersection proved to be groundless, confirming the fact that the fault had been adequately tightened and treated on the previous covers.

The fact that the tightening phase was cut short by the collapse of the bottom North pipe proved not to be a problem, as the 416 tons of cement injected during the drilling phase more than adequately tightened the plug and was confirmed during the plug removal. The cause of collapse of the bottom draft columns as to whether this was due to tightening and/or casting continues to be deliberated.

The trapped pump was recovered.

The grit within the fault proved extremely difficult to consolidate and was responsible on numerous occasions for choking the suction on the pump. The inflow point turned out to be at the intersection of some significant geological features. It occurred where the steeply dipping Broken Arrow fault intersected the giant chert breccia above the Malmani dolomites of the Transvaal series. The chert-breccia-dolomite contact also turned out to be 39 meters higher than originally projected.

The revised cover round described for the dolomitic sequence is a more intensive pattern, leaving little to chance but taking significantly longer to drill and inject.

The connection of the Main shaft with a sleeved large diameter hole to a pump chamber in the Ventilation shaft to provide an emergency water handling facility to surface also proved to be a success, saving the excavation of an intermediate pump chamber in the Main shaft.

Shaft floodings are relatively infrequent occurrences and certainly to be avoided. Full cover precautions were only expected to be taken in the dolomites.

Nevertheless the salvaging of the shaft was a success and this paper adds to the few documented precedents.
DEFINITIONS

Mortar
A mixture of cement, sand and water.

Grout
A mixture of cement and/or chemicals and water.

Plum
(Civ.Eng.) A large undressed stone embedded with others in mass concrete on large work, such as dams in order to save concrete. In mortar intruded plug construction plums form the coarse aggregate.

Intrusion
The process of introducing grout/mortar into an aquifer/fissure or previously placed aggregate such that the pressure at the grout/mortar outlet pipe is no more than is just required to introduce the grout/mortar to flow into the aquifer/fissure or over the full depth of aggregate.

Injection
The process of introducing grout into porous concrete, the space between concrete and surrounding rock, or into the fractured or fissured rock at a pressure sufficient to cause the inflow of grout against the full static head of water at the point of injection.

ACKNOWLEDGEMENTS

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The paper has been presented eight times and published four times:
1 The University of the Witwatersrand Mining Students – August 1996.
3  Association of Mine Managers of South Africa – August 1997.

4  Association of Mine Resident Engineers of South Africa - November 1997.


7  International Mine Water Association- Johannesburg September 1998
    Symposium on Mine Water and Environmental Impacts, Proceedings Volume 1

8  South African Institute of Mining and Metallurgy
    Journal Volume 99 No 4 July /August 1999

The paper was awarded the coveted Gold Medal for The Best Technical Paper presented to The

The paper was awarded a Silver medal by the SAIMM in August 1999.

The paper was also published in the Journal of the South African Institute of Mining and Metallurgy
and awarded a silver medal in 1999.

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3  Solms R L de G
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    Chamber of Mines Code of Practice February 1983
### APPENDIX I – CHRONOLOGY OF EVENTS

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wed, 01-May-96</td>
<td>Last blast at 08:30. Bottom abandoned 23:00. Stage withdrawn and services stripped. 14:00 Pleuger pump commissioned below stage, dewatering begins 15:00 Meeting with Consulting Engineer</td>
</tr>
<tr>
<td>Mon, 06-May-96</td>
<td>10:00 Dewatered to -439m. Drilling from stage commences</td>
</tr>
<tr>
<td>Sat, 11-May-96</td>
<td>Drilling from stage abandoned</td>
</tr>
<tr>
<td>Wed, 15-May-96</td>
<td>Meeting with JCI’s Managing Director, options considered</td>
</tr>
<tr>
<td>Thur, 16-May-96</td>
<td>Decision taken to proceed with plug</td>
</tr>
<tr>
<td>Thu, 21-May-96</td>
<td>Initial meeting held with Regional Director’s office</td>
</tr>
<tr>
<td>Wed, 22-May-96</td>
<td>Formal meeting seeking permission to cast a plug</td>
</tr>
<tr>
<td>Mon, 27-May-96</td>
<td>Reservation Meeting held</td>
</tr>
<tr>
<td>Tue, 28-May-96</td>
<td>10:00 Commenced throwing concrete plug</td>
</tr>
<tr>
<td>Fri, 31-May-96</td>
<td>15:00 Concrete plug complete</td>
</tr>
<tr>
<td>Wed, 05-Jun-96</td>
<td>18:00 Tightening of the plug commences</td>
</tr>
<tr>
<td>Sun, 09-Jun-96</td>
<td>06:15 Cable blow out and fire on switching from one Pleuger to the other</td>
</tr>
<tr>
<td>Mon, 10-Jun-96</td>
<td>No.1 Pleuger pump stuck in North draft column</td>
</tr>
<tr>
<td>Tue, 11-Jun-96</td>
<td>Commission 3rd Pleuger pump on top of plug</td>
</tr>
<tr>
<td>Wed, 12-Jun-96</td>
<td>Discover pipe sidewall of North draft column has collapsed. Install 3x25mm cementation ranges in North column and grout up. Remove 2nd Pleuger pump, and blank flange South column 10:00</td>
</tr>
<tr>
<td>Thur, 13-Jun-96</td>
<td>Record Pressure at 2MPa, change gauge record 2,9MPa</td>
</tr>
<tr>
<td>Mon, 01-Jul-96</td>
<td>Start reverse flow and injection process</td>
</tr>
<tr>
<td>Thur, 04-Jul-96</td>
<td>Stop reverse flow, check fissure flow 15,100 ℓph through 50mm. Plug meeting held to discuss cement water ratio and reverse flow ratio and use of chemicals.</td>
</tr>
<tr>
<td>Fri, 07-Jul-96</td>
<td>Stop reverse flow, check fissure flow, 19 000ℓph through 150mm</td>
</tr>
<tr>
<td>Sun, 07-Jul-96</td>
<td>Bulk cement used through batch plant silos</td>
</tr>
<tr>
<td>Fri, 12-Jul-96</td>
<td>Intrusion pipes blocked and redrilled. Test fissure flow 14,000 ℓph. Reverse flow blocked</td>
</tr>
<tr>
<td>Sat, 13-Jul-96</td>
<td>Cementation ranges block, opened and repaired</td>
</tr>
<tr>
<td>Wed, 17-Jul-96</td>
<td>10:00 Plug meeting decision taken to stop reverse flow with cementation pumps and inject straight grout to effect seal</td>
</tr>
<tr>
<td>Tue, 23-Jul-96</td>
<td>03:40 Last injection pipe No.4 sealed. Probe drilling commences</td>
</tr>
<tr>
<td>Tue, 30-Jul-96</td>
<td>14:00 Meeting to discuss probe drilling and sealing procedure</td>
</tr>
<tr>
<td>Tue, 19-Aug-96</td>
<td>Miniborer in Ventilation shaft collars</td>
</tr>
<tr>
<td>Tue, 29-Aug-96</td>
<td>Jumbo drill rig down for complementary holes</td>
</tr>
<tr>
<td>Sat, 07-Sep-96</td>
<td>Probe drilling complete, plug removal begins</td>
</tr>
<tr>
<td>Tue, 08-Oct-96</td>
<td>Inflow point exposed and shaft bottom recovered</td>
</tr>
<tr>
<td>Wed, 09-Oct-96</td>
<td>Miniborer from Ventilation shaft holes</td>
</tr>
</tbody>
</table>
APPENDIX II – MAIN SHAFT PLUG & RECOVERY
May 1996 to October 1996