Construction of a concrete plug in South Deep's main shaft to seal off a major water intersection

by M.F. Wells*

Synopsis

The method used to salvage South Deep's Main Shaft after it was flooded by an inrush of water at about 450 m below collar on 1 May 1996 is described. The individual techniques employed in the salvage were all proven technology, but the combination in which they were applied is considered to be novel. The operation 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
- 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

The shaft sinking contract at Western Areas Gold Mine, South Deep Division, is a twin shaft project. The main and ventilation shafts are being sunk to design depths of 2 765 m and 2 760 m respectively, making them the world's deepest single lift shafts. They have a finished lined diameter of 9 m.

The shafts have been sited to traverse the steeply dipping Broken Arrow fault at the intersection point of the giant chert breccia above the Malmani Dolomites of the Transvaal Series, as shown in Figure 1.

The sinking method utilizes seven boom sinking drill rigs with pneumatic drifters to advance 3 m 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 6 m 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 48m deep, dipping at 10° from the vertical with a 12° clockwise spin. When required in problem areas, additional umbrella holes were laid out, typically 24 m deep, dipping 20°, from the horizontal with a 20° anti-clockwise spin. Cover overlaps were maintained at no less than 8 m.

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

- sinking to stop 10 m short of any known large water intersection above 10 000 litres per hour as determined by previous cover holes, and the standard cover round then to be redrilled
- all holes injected to 2,5 times the static head and plugged with thick grout
- all holes yielding more than 100 litres per hour to be redrilled and deepened by 3 m.

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

On 1 May 1996 a round was drilled at -447 m 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. The inflow occurred at an estimated rate of approximately 10 000 litres per hour. Water was bailed by means of kibbles for approximately five hours, then split set rock support installation from the muck pile was started, while bailing continued for two further hours. 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 about 80 000 litres per

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 Paper received Jun. 1998; revised paper received May 1999.

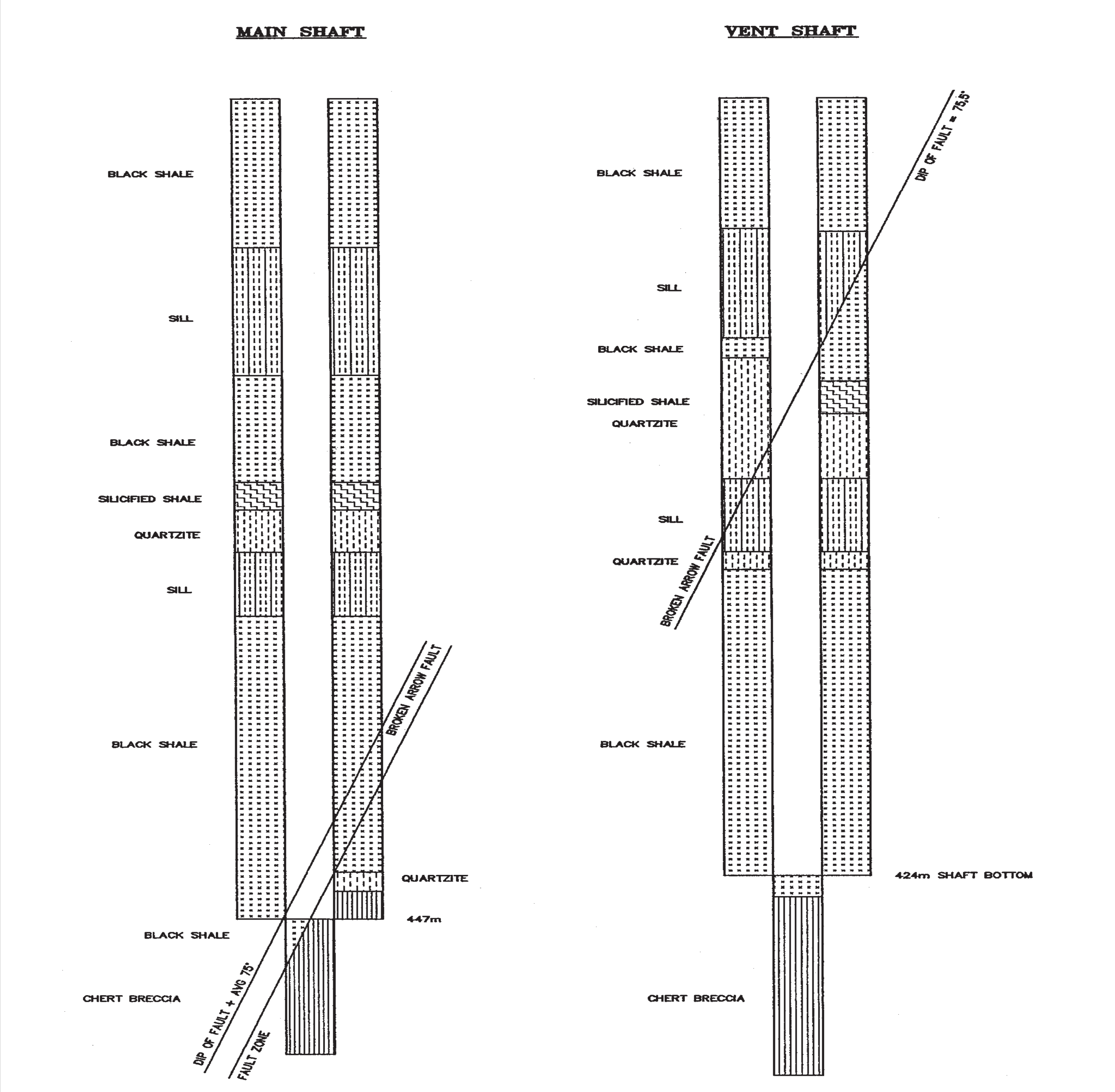

Figure 1—Geological section showing shaft elevations on 1 May 1996

hour, and eventually increased to 165 000 litres per hour. The water level was rising at a rate of 2 m 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 2,5 days during which time suitable Pleuger pumps were located at Freegold's store in Welkom. The sinking cables were, however, inadequate for the power required for pumping, so the stage was raised to surface, and then re-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. During this time the water level had risen by 138,4 m to -308,6 m below collar. After commissioning the pumps the water level was lowered to -433 m below collar in five days by bailing and pumping. The pump delivered approximately 250 000 litres per hour to surface. It took approximately 30 minutes to install a six metre length of pump column during which time the water level would rise by a metre. It therefore meant that the water level had to be lowered by eight metres to install a six metre length of pipe column.

On 11 May 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 m and -439 m.

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

Consideration of options

Several alternative options to overcome the flooding problem were considered. These included drilling and injecting grout, use of the ventilation shaft for access to -425 m, and the installation of a concrete plug to seal off the water inflow area. These alternatives are considered in turn below, and illustrated in Figure 2.

Drilling and injecting

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

The second option in this alternative was drilling from a cubby at -431 m. A 3 m x 3 m x 10 m cubby was considered. The advantage of this option was that a cubby lent itself to better diamond drill layouts, away from the shaft, to avoid the water loss problem. The disadvantages included the time to cover, excavate and support cubby. Since the cubby would be situated in the hangingwall side of fault, holes would have to traverse the fault zone, causing potential difficulties and

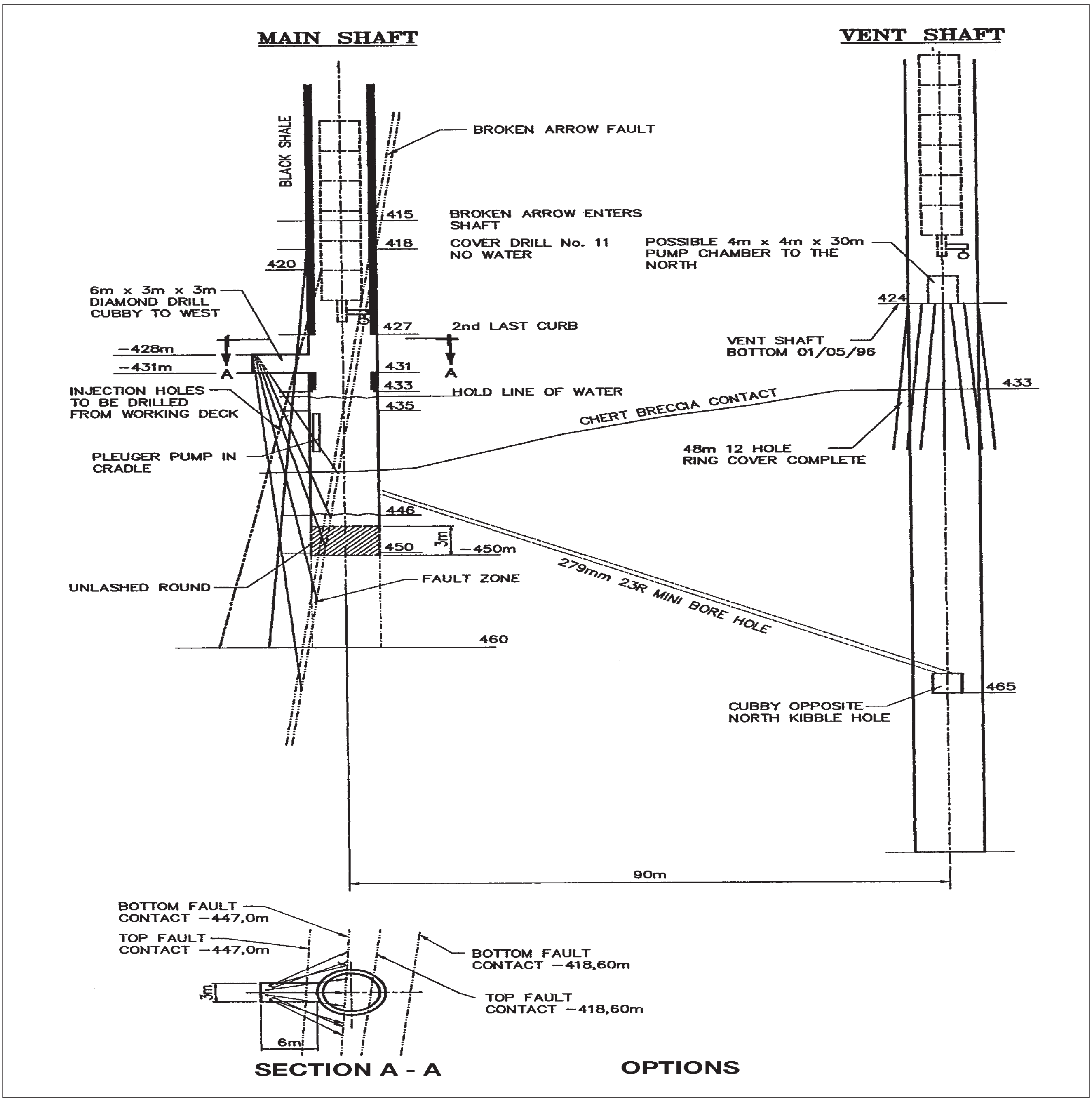

Figure 2—Considerations of options

drill steel losses. Holes could transfer water higher up the shaft bringing pressure closer to the sidewall and lining. If chemical injections were used, they could restrict the effectiveness of future reverse flow efforts.

Vent shaft solutions

The options included a pump chamber at -425 m and minibore hole, or a pump chamber and minibore hole at -475 m.

The advantage of the first option was that there was immediate access to -425 m elevation, the current ventilation shaft bottom. The disadvantage was the risk of flooding the ventilation shaft—the geology was adverse, drilling would have to take place in the shale and traverse the fault zone, the minibore hole could deflect in the shale and miss the shaft, and scaling in the hole could make it difficult to case.

The advantage of the second option was that the geology was favourable—the minibore hole would be in chert and the footwall of the fault, making casing easier, and more accurate drilling would be possible. The main disadvantage was the time required for the option—half a month would be required to sink to -475 m, and two months to cover, excavate, support and equip the pump chamber.

A deeper variation of this option was subsequently executed at -500 m in the ventilation shaft. This rendered the excavation of a temporary pump chamber in the main shaft unnecessary.

Concrete plugs

Three options were considered for this alternative:

- Flood to equilibrium and cast an underwater plug. This method was used at Western Deep Levels South Shaft in 1982/83, Free State Geduld in 1953, and Blyvooruitzicht in 1937.
- It was considered that this method would take the longest time, though it had a good chance of success. The major disadvantages would be the difficulty of the operation and uncertainties associated with the remote construction of a plug beneath 300 m of flooded shaft.
- A plug constructed on the curb. This option was listed as a possibility, but was discounted because of construction difficulties arising from the underside of the plug being 20 m above the shaft bottom.
- Construct the plug above a French drain on top of the 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. The risk was that of pump failure before capping the draft columns.
- At the meeting held on 16 May it was decided to pursue this option, and design work began immediately. The solution was chosen because of its direct access and close proximity to the bottom. In addition, this option was based on proven technologies.

Concrete plug design

The plug design conformed closely with the 'Chamber of Mines' Code of Practice on Construction of Underground Plugs and Bulkhead Doors Using Grout Intrusion Concrete', dated February 1983.

The design parameters for the plug were as follows.

- maximum pressure likely to result from the reverse flow was 4,5 MPa
- plug length to be determined in accordance with the COM Code of Practice using a sidewall/concrete interface shear strength of 0,83 MPa
- required concrete strength of 30 MPa at 28 days;
- concrete to be poured continuously at a rate of between 10 m^3/hr and 20 m^3/hr, with 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, Further, the plug was regarded as unreinforced, though the sacrificial scaffold, 48 tightening pipes, seven injection pipes and two draft columns would provide substantial reinforcing.

Using these design parameters, a plug length of 13,5 m was calculated, and the minimum number of tightening pipes required determined to be 134.

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. 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 2 m spacer on top of the bottom section with the same specification as the bottom section of pipe.

Bottom draft column specifications

Pipe length	-	15 m
Pipe diameter	-	900 mm
Wall thickness	-	10 mm
Top flange	-	62 mm thick plate, with 24 holes 34 mm in diameter

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 4,5 MPa. The wall thickness calculations were based on 5 MPa. The pipe manufacturer was instructed to test the pipes to 6,4 MPa for two hours prior to delivery.

Pipe length	-	8 m
Pipe diameter	-	900 mm
Wall thickness	-	12 mm
Bottom flange	-	62 mm thick plate, with 24 holes 34 mm in diameter to match existing flange
Top flange	-	147 mm thick plate, with 28 holes 62 mm in diameter, for M59 Grade 8,8 bolts
Blank flange	-	as for top flange plus one 150 mm diameter, 100 mm long, weld-on pipe complete with flange for reverse flow, and three 50 mm diameter, 50 mm long weld-on sockets for grout injections

Flange grade - SABS 1431 Grade 43A
Gaskets - 3 mm thick Klingerite high pressure gaskets
Puddle flanges - Outside diameter 1100 mm, 16 mm thick plate, 6 mm continuous fillet weld 900 mm NB pipe with flanges and puddle flanges (See Figure 3)

The increased thicknesses of the blank flange and the walls of the large diameter pipe, required to withstand working pressures in excess of 10 MPa, discounted 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. As it turned out, the 10 mm thick walls of the north pipe bottom section collapsed during tightening, requiring that the columns be capped in the reverse sequence.

The structural concrete plug

Using the above design parameters, the Code of Practice developed by the Chamber of Mines, and allowing for a conservative factor of safety, a 14,6 m long structural concrete plug was designed and drawn up.

On completion of the design work, the design drawings and the recent cover drilling records were included with the formal application for permission to construct the plug.

Application seeking permission to construct a plug

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

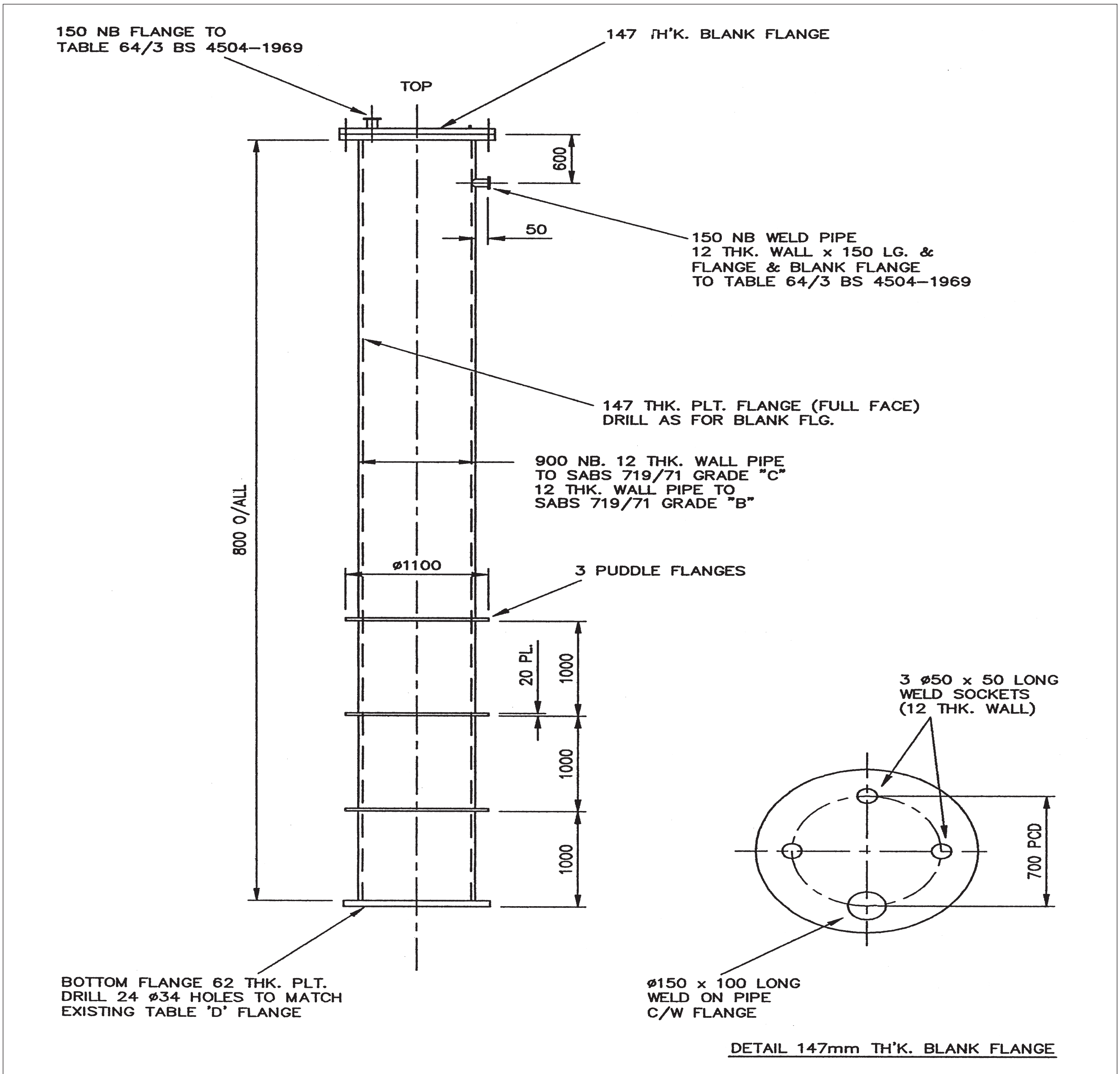

Figure 3—900 mm pipe with flanges and puddle flanges, top draft column

water under a pressure exceeding 700 kilopascals.'

On 21 May an initial meeting was held with the Regional Director to communicate the novel aspects of the scheme and the parameters involved with the design. This was followed up with the formal application at a second meeting on 22 May. 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 off the water was debated at length, with two main reservations coming to the fore.

- The selection of the plug location: 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 above the plug at the -415 m elevation.
- In response to these concerns, the cover drilling records at the -380 m, -400 m, and -418 m elevations were examined, and 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 7,5 MPa, indicating that 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 numbers 9, 10 and 11).

When tightening the plug through the proposed holes, the fault would be further sealed.

- Sealing of the rock plug interface: the reservation was that the 48 tightening pipes laid out in the proposal were less than the number recommended by the formula in the Code of Practice.
  In consideration of this reservation, the consultants, designers and constructors were of the opinion that they were more than adequate for a structural concrete plug.

The following points regarding a comparison between structural concrete and grout intruded plugs were also taken into account.

- Grout intruded plugs are commonly filled with hand packed plums and are usually constructed in the horizontal plane. The proposed plug was an unreinforced 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, which would ensure plug quality
- The proposed plug was temporary, 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:

- the concrete lining was monitored from the stage, and any indication of increased seepage was immediately treated
- concrete placing was carried out according to a written procedure
- flange tightening and bolt torqueing 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 procedures had been formalized for the Additional Precautions, the Regional Director gave permission for the plug to be constructed.

Concrete plug construction

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

The method, illustrated in Figure 4, entailed the construction of a French drain and structural concrete plug, whilst continuing to pump using one submersible pump, with another commissioned as a standby. A spare pump was kept on surface.

The steps involved in the plug construction were:

- install two 900 mm diameter draft columns above the muck pile
- install seven 50 mm diameter vertical cementation injection pipes
- tip 4 m of washed plums on top of the muck pile
- discharge 2 m of washed 19 mm 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 m 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 900 mm draft columns were positioned on top of the muck pile. Seven 50 mm 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 by one pump suspended from the stage on the north side of the shaft.

The tipping of washed plums was then started, but had to be interrupted to install a second HT cable for the second pump. A depth of 4 m of plums was discharged into the water and built up above the muckpile around the pipes. The plums and stones were washed because the Pleuger pumps can only handle clean water and are not designed for dirty water pumping.

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 pumps 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 then 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.

A depth of 2 m of 19 mm 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 litres per hour that the aquifer was making.

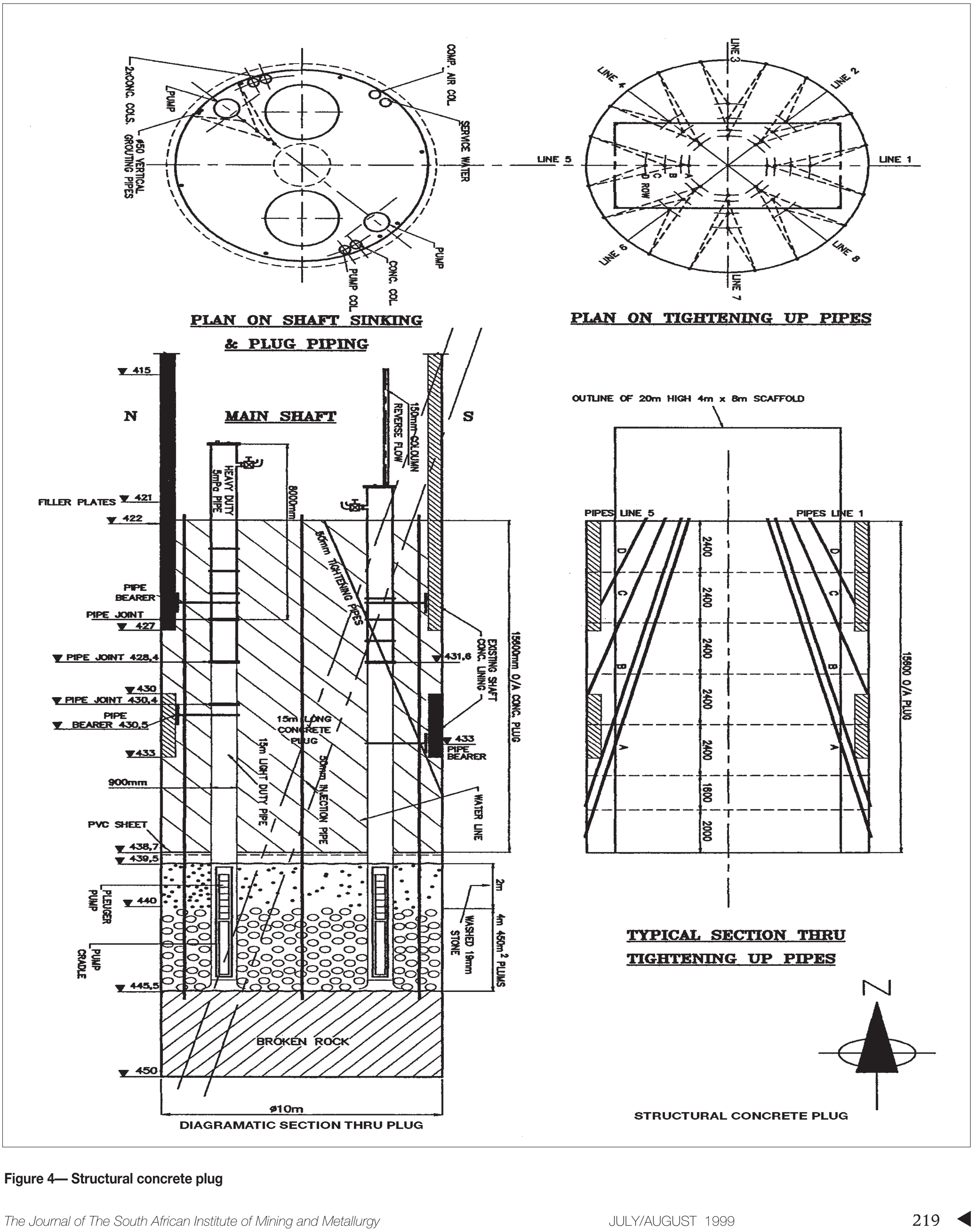

Figure 4— Structural concrete plug

During the tipping of the stone, the top 8 m 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.

A 50 mm balancing pipe was installed to discharge water back into the north pipe. This facility dumped water back to the French drain to ensure that the water level remained constant and that 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 first pump was removed from the bottom section of the north pipe, the top section lowered, fastened, and the pump reinstalled. 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 8 days from 18 to 26 May.

Erection of scaffold and tightening pipes

From 26 to 28 May 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 concrete mix was designed for a strength of 30 MPa 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. Initially a pouring rate of 10 m^3/hr was achieved. A calcium chloride accelerator was added to the first 500 mm to form a blinding screed. The pour progressed well and it was decided to increase the rate to 20 m^3/hr once the first 5 m had been 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. In fact, even during the curing no discernable increase in temperature was noted on top of the plug.

On the second day, the pour was stopped temporarily for 5 hours to carry out 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 there was some concern when the kibble winder tripped for three hours. The first pump in the north pipe dropped its delivery rate and water pushed up the draft columns onto the plug. Switching over to the second pump in the south column resulted in a gasket failure. The pumping was immediately switched back to the first pump, which fortunately resumed its normal delivery. Later it was established that the pump output had been adversely affected by fine black grit which entered the pump from the fault, 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 1132 m^3 had been placed in 3,2 days, resulting in an average pour rate of 14,7 m^3/hr including maintenance, blockage and pump delays.

The plug was allowed to cure for 5,1 days from 31 May to 5 June. 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 tightening commenced on the bottom ring (A ring, see Figure 4) 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 first pump cable developed a fault in the shaft, at a joint box and along the cable above the stage. Pumping was switched to the second pump in the south pipe. It was then established that the first pump and its shroud were stuck in the 900 mm 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 established that the bottom pipe in the north draft column had collapsed 10 m below the top of the uppermost flange and the pump was trapped.

The sequence of capping the draft column had to be reversed, with the lower south pipe having to be blank flanged last. The problem 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 rise above the flange.

The solution lay in an improvised water handling arrangement. The third Pleuger pump was installed on top of the plug in a vent pipe which served as a water tank. A Flygt pump and several Quimbys were placed on top of the plug. This solution was tested by allowing the top of the plug to flood, and then transferring the water with the Flygt to the Pleuger in the ventilation pipe. This method proved capable of handling 160 000 litres per hour. Pumping was then switched back to the second pump in the south pipe.

Three 25 mm injection pipes were installed in the north pipe past the side of the trapped pump for future use. 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 for the final preparations was to stop the second pump, remove it and cap the south pipe. These preparations included arranging for two professional divers to be present to undertake the final bolting should the water rise above the flange. With the divers, senior site supervisors and project leaders present, the second pump was stopped and withdrawn from the south column. The water rose, flooded onto the top of the plug through the 150 mm 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 at 22:00 the columns were successfully capped, which was a significant accomplishment. The water inflow was under control, and there was no longer dependence on the pump, thus removing the concern of pump failure.

The initial pressure on the plug was only 2,0 MPa. A more accurate gauge subsequently recorded 2,9 MPa,

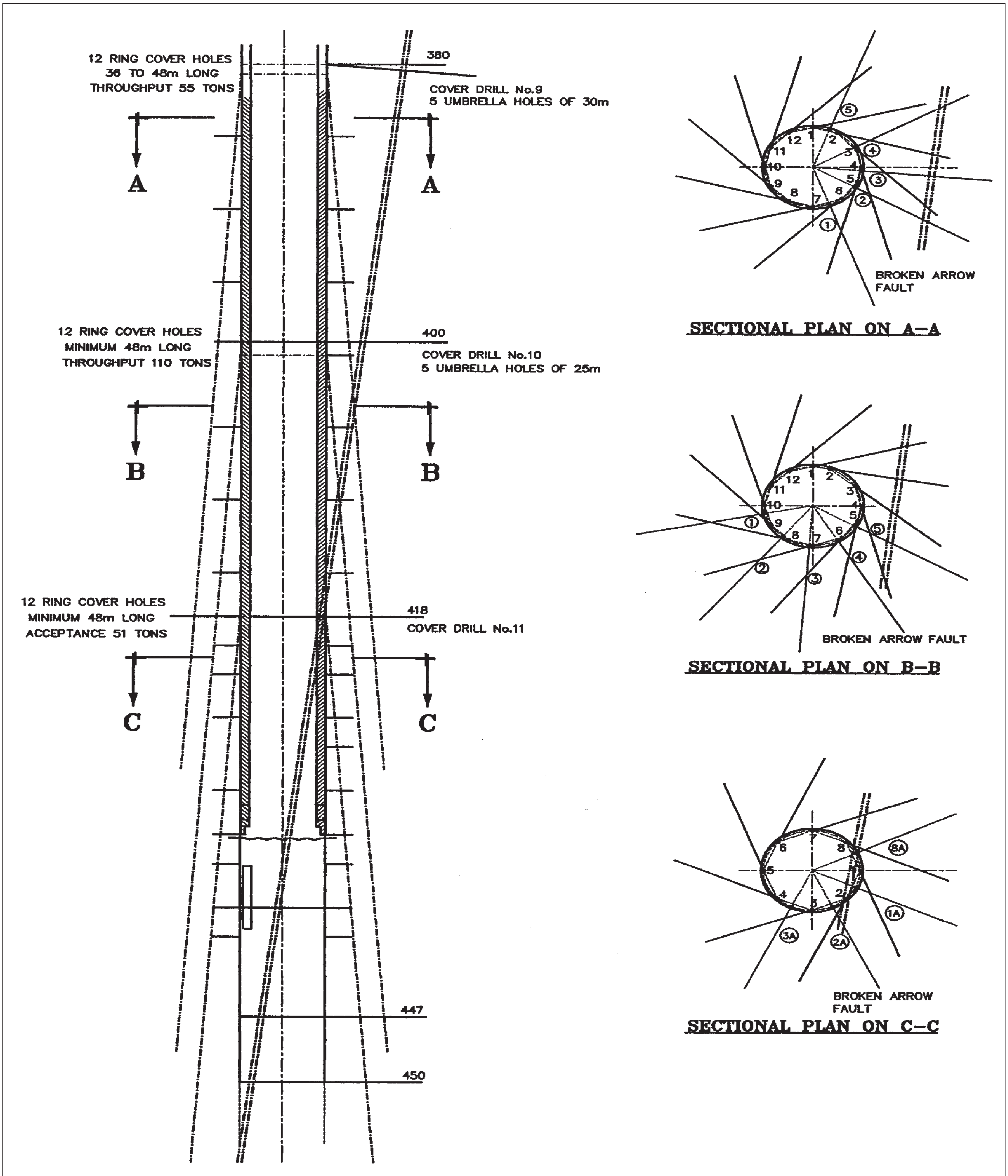

Figure 5—Cover elevations 9, 10, 11

indicating the water table at -133 m 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 the reverse flow tank was commissioned on surface with a flow meter on the 100 mm column from the dams. The 150 mm 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. This probe indicated the level at -156 m below collar. This meant that there was a 300 m 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 and this gauge recorded 2,9 MPa. A gauge on the reverse flow column on the stage recorded 2,7 MPa.

The reverse flow was started at a rate of approximately 60 000 litres per hour after one additional 50 mm water delivery feed was installed. On the evening of 13 June cement intrusions began and supplemented the reverse flow. (See Figure 6 plan view of reverse flow process pipes.) This process continued for the next 34 days until water acceptance by the aquifer stopped on 18 July. A further 6 days of grout injections followed. All the cementation pipes were finally sealed on 23 July, 40 days after the process had started. Over this period 7 340 000 kg of cement and 11 mega litres 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 100 kg/300 litre barrel to 150 kg/barrel with a reverse flow of approximately 42 000 litres per hour. On 15 June a high shear electric mixer with a storage tank and two pumps were erected. The plug pressure gauge was now reading 2,5 MPa. From 16 to 28 June the mix ratio was increased to 450 kg/barrel (1,5:1), with the reverse flow reduced from approximately 40 000 to 12 500 litres per hour, and with two to three pumps running via grout ranges to the various intrusion pipes. During this period the pressure at the plug rose from 2,5 MPa to 3,8 MPa.

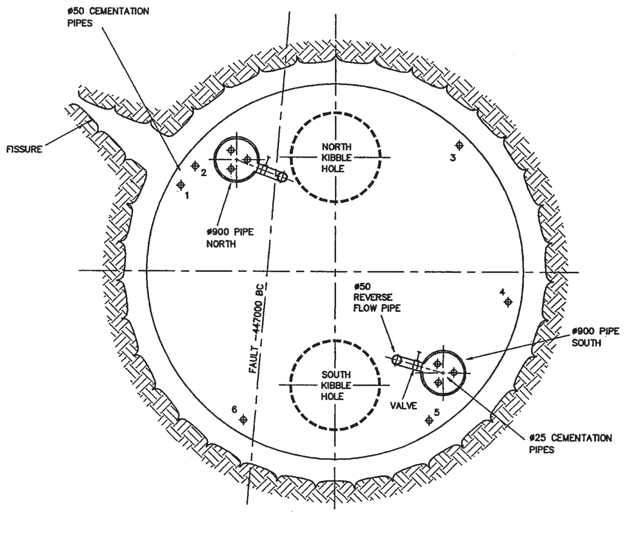

Figure 6—Plan view of reverse flow process pipes

On 28 June the cement mix ratio was increased to 525 kg/barrel (1,8:1), and again on 29 June to 600 kg/barrel (2:1). By 30 June the reverse flow was down to 10 000 litres per hour and about 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 50 mm valve. The inflow was now only 15 120 litres per hour, down from the original 165 000 litres per hour, and the water pressure head was only 2,0 MPa. The reverse flow with the valve fully open would only take 15 600 litres per hour.

When the reverse flow and injection process started up again, the plug pressure had dropped from 3,8 MPa to 3,4 MPa. The cement mix was increased to 750 kg/barrel (2,5:1). On 4 July a record 363 tons of cement were intruded in a 24-hour period. The plug pressure recorded was 3,5 MPa.

On 5 July the reverse flow and intrusion process was stopped for the second time to test the inflow through a 150 mm opening. This time the fissure inflow was measured at 19 895 litres per hour. On starting the process again the plug pressure had reduced from 3,5 MPa to 3,0 MPa.

On 7 July the intrusion operation changed to bulk cement instead of 50 kg pockets, 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 with a reverse flow of approximately 8000 litres per hour. Heating elements were installed in the reverse flow tank.

Over the 11, 12, 13 July the grout mix ratio was reduced to 1,5:1 with approximately 7 000 litres per hour reverse flow.

On 12 July the intrusion pipes blocked and had to be redrilled. The fissure inflow was checked for the third time and recorded at 14 000 litres per hour. Some sodium silicate was pumped into the intrusion pipes. Reverse flow and intrusions continued until the reverse flow choked off. On 13 July two cementation ranges blocked and had to be opened and repaired. Two cementation pumps were put onto the reverse flow on the blank flange, but this just pushed the water back to surface. Using one cementation pump, a reverse flow of approximately 5000 litres per hour into the fissure was achieved. On 15 July 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, 100 tons of cement per day being accepted. Plug pressure was steady at 3,9 MPa.

At a meeting on 17 July it was decided to stop the reverse flow and just inject cement grout until the fissure was sealed. Leakage occurred on the gasket of the blank flange and was repaired. Holes 6, 2 and 1 sealed off at 6 MPa on 17 and 18 July. On 19 July holes 5A and 3 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.

At this point the reverse flow and intrusion phase was considered complete, and the probe drilling began. Figure 7 gives a summary of the reverse flow and cement intrusion phase.

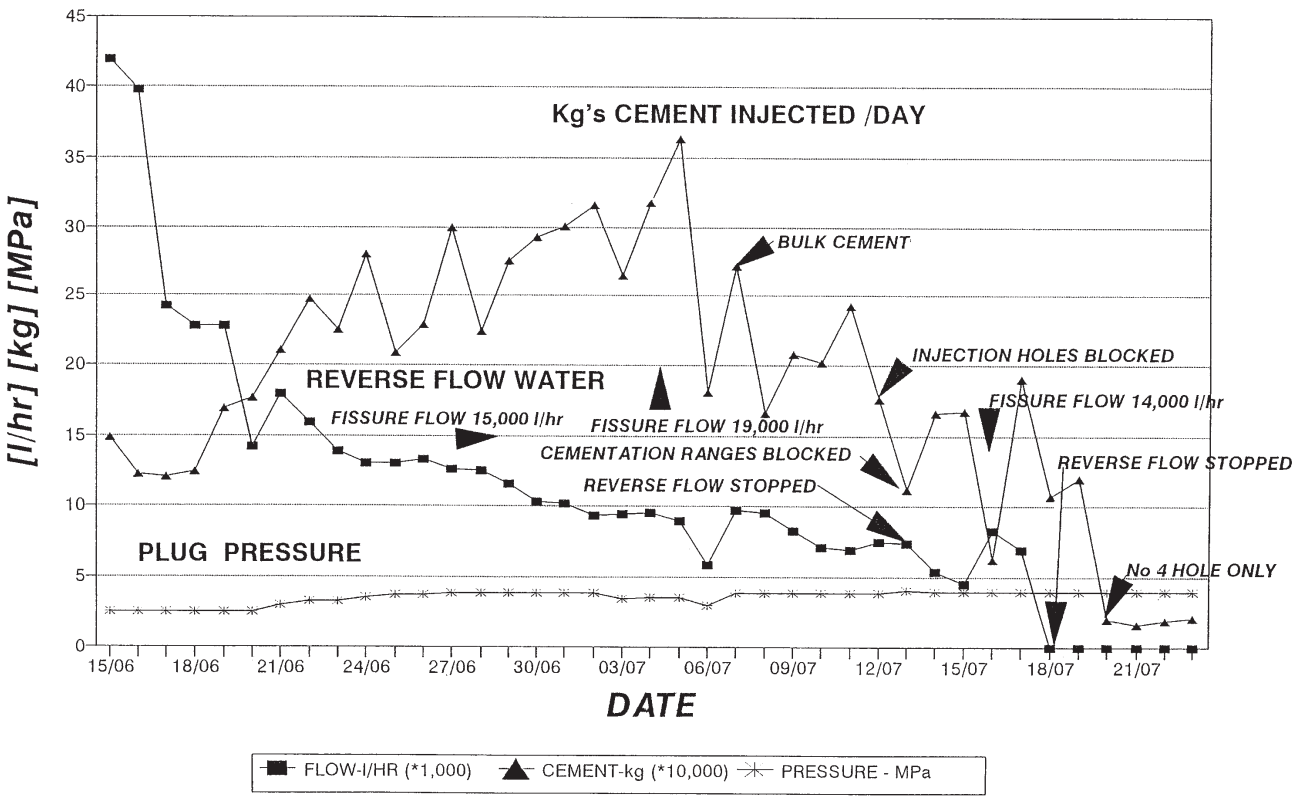

Figure 7—Reverse flow and cement intrusions

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

Drilling programme

It now had to be established, from an extensive drilling and consolidation programme, if in fact the fissure had been effectively sealed. This programme eventually consisted of 33 vertical holes, 32 tightening holes, 12 complementary holes of 45,0 m, 12 umbrella holes of 27,0 m, 12 ring cover holes of 43,0 m, and 2 additional holes. A total of 3 754 m of diamond and percussion drilling was carried out. Super grout injections in vertical holes involved 24 640 kg of grout. Total cement injections were 159 683 kg.

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

Vertical holes

The first step in the vertical hole drilling was re-drilling through the grout intrusion pipes onto the muckpile and cementating to consolidate the plug, French drain and other loose material. Screw feed compressed air diamond drill machines were initially used to drill, re-drill and deepen these holes to 10 m into the solid footwall to obtain core for geological evaluation. No chemicals were used at this stage.

The number 2 and 3 grout intrusion pipes contained stuck drill rods from periodic blocking and re-drilling 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 300 litres per hour in hole 6 and 100 litres per hour in holes 4 and 5, indicating a successful seal. Following the deepening of the grout intrusion pipe holes, a further 27 vertical holes were laid out, running north-south, mainly on the western side of the shaft. These new holes were cased with 6 m casings into the plug, and pressure tested to 10 MPa.

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. In holes meeting the gritty fault material, the bit or rods jammed as a result of water loss. To speed up the time-consuming consolidation process, a specialized 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 hole number 14 intersected any water, 150 litres per hour. All the remaining holes were dry, confirming successful treatment of the zone below the shaft.

Tightening holes, complementary, umbrella and ring cover holes

The 32 tightening holes were deepened to an average of 40 m. Only five of these holes intersected water—hole A5, 900 litres per hour; hole C, 300 litres per hour; hole A6, 2100 litres per hour; hole D5, 290 litres per hour; hole C4, 1290 litres per hour. 75 220 kg of cement were injected into these holes.

The bottom was 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 a 12 hole umbrella cover with a dip of +5°, a depth of 27 m, and an anti-clockwise spin was drilled from the top of the plug. One hole intersected 1 440 litres per hour and 44 800 kg of cement were injected for the whole cover.

On 29 August the Jumbo drill rig was lowered and an additional 12 holes, 45 m deep at a dip of -70°, were drilled to complement the tightening pipes and fill the gaps. All the holes were dry and 28 980 kg of cement were injected. The 900 mm 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 water—a trace and 90 litres per hour. 10 690 kg of cement were injected, completing the cover on 6 September.

It had now been confirmed with confidence that the zone, from 40 m below the plug and radially to 20 m 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 -560 m.

Shaft recovery

The removal of the plug began on 7 September. During excavation of the plug to -432,5 m, the drilling and blasting of the concrete went better than expected. Initially, daily blasts yielded 1,4 m advances. The drill rig achieved good penetrations, whilst the lashing cycles were extended due to the cutting out of the steel and 900 mm draft columns, tightening and intrusion pipes and the scaffolding. Cement-contaminated blow overs were particularly harsh on the crew.

On 12 September a 12 hole, 43 m deep ring cover at 80° was started at -432,5 m elevation. Of the 12 holes, only hole number 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 miniborer 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 +6 m of the concrete plug and +3 m of the French drain was removed in advances of 1,3 m per blast. The cycle time was 15,5 hours. The 19 mm 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 plug concrete for testing. The average strength was 33 MPa.

On 23 September at -442 m elevation, near the top of the French drain, a 12 hole, 48m -80° ring cover was started. 3 holes intersected water—hole 7, 900 litres per hour; hole 7A, 300 litres per hour; hole 9, 720 litres per hour; 86 246 kg of cement and 3 600 kg Super Grout were injected into this lift.

Twelve additional holes were laid out, of which hole 19A intersected 7 200 litres per hour, and hole 20, 250 litres per hour. On 3 October these additional holes were sealed with progressive injections of 10 260 kg of cement and 500 kg of 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 -450 m and exposing the breach zone.

The sidewalls and bottom were examined on 8 October. The steeply dipping boundary planes of the Broken Arrow fault could be seen distinctly on the sidewalls, with typical gritty, friable, decomposed infill between the top and bottom boundaries. On the northern sidewall a roughly horizontal fissure, 3,5 m in length varying from between 3 cm and 8 cm in width, was evident running across the steeply dipping fault planes. This fissure was filled with cement and Super Grout. The shaft had been recovered to the elevation attained at 1 May 1996 some five months and one week after flooding. Normal sinking routines could not be resumed, however, owing to the intensive cover drilling at close intervals which was carried out for the next 120 m 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 279 mm in diameter, sleeved, and 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 round consisted of a 16 hole ring cover, a 16 hole umbrella cover and one stab hole as shown in Figure 8. The 16 umbrella cover holes numbered U1 to U16 were drilled radially out from the centre of the shaft, collaring at the sidewall/footwall intersection. These holes dipped at -65° from the horizontal, and were drilled to a depth of 24 m.

The stab hole was drilled vertically to a depth of 48 m and positioned within 1,5 m of the shaft centre.

The cover consisted of two rings, one at a radius of 4,5 m and the other at 4,0 m from the centre of the shaft. The outer holes were odd numbered R1, R3 to R15 and the inner holes even numbered, R2, R4 to R16. All of these holes were spun clockwise at 45° to the tangent and drilled to 48 m. The outer ring holes dipped at 75° whilst the inner ring dipped at -80°.

Discussion and conclusions

The salvaging of the shaft was a success and is 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 specialized mining, drilling and engineering skills of the project team and contractor.

In consideration of whether the method could be considered for future shaft water intersections, and whether it was efficient, it is necessary for each water intersection to be assessed for its own peculiar characteristics, depth, pressure, volume and pumping facilities. The method utilized in this case 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 and plug, and the 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 m plug, the French drain and the grouted muck pile from -424 m to -450 m 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 7 MPa and there were water supply quantity constraints.

Owing to the large grout acceptances 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, which provides a more pumpable grout, but increases setting time
- tailings were considered, but rejected on environmental grounds, as they could contaminate the groundwater and choke off fine fissures.

Cement/water ratios were debated at length, and 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. It was found that greater acceptance was achieved at the lower ratios where the pumps were more efficient.

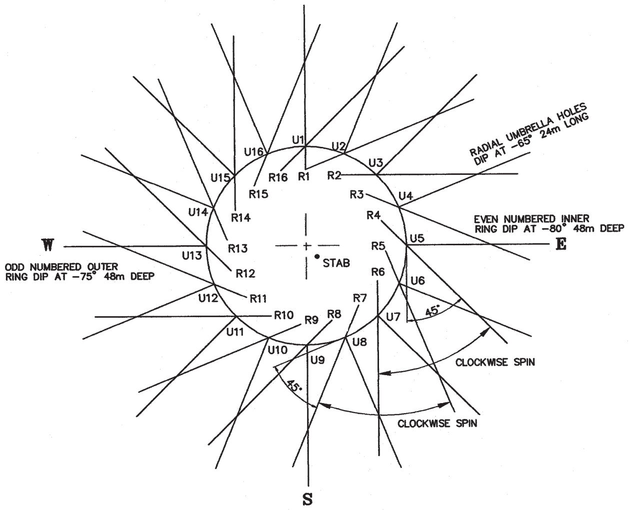

Figure 8—Typical cover drill rounds used in dolomites

Specialized chemical grouts were considered, but not employed as it was feared they might jeopardize 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, and later to 14 000 litres per hour, 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, which was noticed in the reduced pressures measured 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 most of the time and it is doubtful 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 specialized chemical grout. The drilling programme was extensive and time consuming, but necessary to establish the confidence that the water had been sealed.

No significant water was intersected after the 7 360 tons of cement were intruded by the reverse flow process. The additional covers at -424 m, -432 m and -442 m were basically all dry and accepted only 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 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, which was confirmed during the plug removal. Whether the collapse of the bottom draft columns 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 for choking the suction on the pump on numerous occasions. The inflow point turned out to be at the intersection of some significant geological features—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 turned out to be 39 m higher than originally projected.

The revised cover round described for the dolomitic sequence was a more intensive pattern, which left little to chance but took 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, proved to be a success, saving the excavation of an intermediate pump chamber in the main shaft.

Acknowledgements

The author wishes to thank the Managing Director and Consulting Engineer of JCI Limited for permission to publish this paper. Assistance is acknowledged from members of the South Deep Project Team; site personnel; Cementation Mining, Drilling Division; the Design Engineers; the Concrete Technologist; and the Geology Department of Western Areas Gold Mine.

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