InterOil, an independent operator in Papua New Guinea, recently prevailed over myriad logistical and downhole obstacles to safely and successfully manage a well control incident, and complete a wildcat well. The sidetracked well was Elk 1 ST #1. This prospect, identified from geophysical and limited offset data, was sited in such a remote area that no roads could be used to transport personnel, equipment or materials to the site. Transportation to the site was via helicopter. Thus, equipment selection was restricted by weight, and the operational schedule was often affected by weather.

A plugged bit, a fish in the BHA and severe losses encountered in a fractured limestone formation required mobilization of personnel, materials and equipment necessary for the selected intervention technique—use of reactive materials. A description of the well control operations, as well as explanations of the operational environment, logistical challenges, equipment limitations, and downhole configuration that defined the well control problem, are provided below.

**LOGISTICAL CHALLENGES**

Because of the lack of roadways in this heavily forested nation, over 530 landing strips are used to travel within Papua New Guinea. Set in the country’s southeastern portion, the site is in a rain forest on low coastal mountains, Fig. 1. Geophysical survey crews placed into this wilderness area by helicopter were preceded by crews of local residents who cleared the jungle sufficiently for survey operations.

Due to these logistics, use of local resources was often necessary. When construction of a drilling camp began, bulldozers and sawmills were brought in via heavy lift helicopter. On-site trees were felled and sawed into lumber to create the board location. Smaller trees cut on-site were used to construct buildings, hand rails, roof supports, etc. Water was pumped from nearby streams and treated for drinking.

**Transportation.** A staging camp, constructed earlier, was about 12 km from the site on the shore of a nearby river with access to the coast, Fig. 2. Rig components, fuel, casing, drill pipe, blowout preventers (BOPs), mud materials and other heavy cargo were barged up the river to the staging area to await transport to site. Personnel, mobilized from various locations, were flown via small aircraft from the capital, Port Moresby, to the Wabo airstrip, which is about 10 km from the site. From Wabo, personnel proceeded to site via helicopter.

**SELECTIVE INTERVENTION VIA MATERIAL SQUEEZE**

Due to difficult, remote jungle logistics, InterOil’s decision to undergo the expense and risk of a reactive material squeeze protected an important discovery well.

**John Reese**, Boots & Coots International Well Control, Inc., Houston

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**Fig. 1.** The wells site is in a heavy jungle of southeastern Papua New Guinea.

**Fig. 2.** A staging camp was constructed away from the wells site, along a river with access to the coast.
Equipment. To accommodate movement to multiple jungle locations, the operator purchased a drilling rig (heli-rig) that could be broken into lifts of 8,000 lb or less. Similarly, when pressure was encountered, and snubbing operations became a consideration, it was necessary to only consider snubbing units capable of being broken into manageable lifts.

Well Control Data

The fractured carbonate objective of this well was the Puri Limestone, which had an expected thickness in excess of 2,000 ft. A sub-economic Puri oil and gas field was discovered 16 km west of the subject location in 1959.

Sequence of events. Figure 2 depicts the well at the time of the well control incident. With a 7-in. liner set at a depth of 5,381 ft in this vertical hole, drilling proceeded with water-based mud past the top of the carbonate reservoir at 5,541 ft to a total depth of 5,558 ft. At this point, severe losses were encountered, a gas kick was taken, and annular pressure rose to about 3,000 psi. The well was shut-in on the annular and pipe ram. It is believed that the annulus was completely or nearly completely evacuated of mud in less than 4 min.

Flow performance through the 1-in. choke indicated an estimated flow rate of 50 MMcf/d. During an attempt to kill the well, the bit became plugged.

A wireline run was made to shoot perforations in the BHA at a depth of about 5,500–5,514 ft for a drillstem test. Upon perforating, the gun became stuck in the BHA, and the operator pulled out of rope socket. It was confirmed that communication with the annulus had been established, and drill pipe pressure rose to over 800 psi. Subsequent wireline runs indicated that a sufficient amount of barite had settled to partially plug the BHA at a depth of 5,189 ft. Gas was observed to escape slowly from the drill pipe with the TTW valve open, even with the drill pipe bled to zero pressure.

Several times, mud and lost circulation material were successfully pumped down the annulus to reduce pressure, but pressure would return almost immediately as the reservoir continued to take in all fluid that was pumped.

Other considerations. When assessing the well control options available to the operator, consider the following facts:

• The heli-rig was equipped with a BOP stack consisting of a cross, a blind ram, a pipe ram and an annular; all 5K equipment. Clearance between the rotary beams and the annular was just 21 in.—not enough room to add another ram.
• A rig-assist snubbing unit was found in Asia, but significant time and expense were necessary to mobilize the unit to site. Some larger snubbing units were not considered, due to helicopter weight restrictions.
  • Coiled tubing units were also available, with similar considerations about time, expense and weight.
• It was known that the well could be put on losses simply by injecting WBM into the annulus.
• Mud materials were available but often took several weeks to arrive at the staging by barge, only to wait for clear weather for transport to site.
• Surface mud capacity was limited to roughly 460 bbls. Annular volume with the bit at TD was about 270 bbls.
• During the time necessary for mobilizing equipment, personnel and materials needed for any intervention technique, dry gas would be in contact with BOP elastomers, possibly compromising their effectiveness.
  • The bit was at TD and, therefore, could not be dropped. It was unknown whether the pipe was stuck.

Well Control Options

Initial goals for this wildcat included drilling through as much as possible of the expected 2,000-to-4,000-ft thickness of the carbonate reservoir. At the time of the well control event, only 1-to-3% of the reservoir had been penetrated.

The operator consulted various service providers—including Blade Energy Partners, Weatherford, Halliburton and Boots & Coots—regarding options for achieving both short-term and long-term objectives to protect the discovery’s potential commercial nature.

It was determined that either mud cap drilling or underbalanced drilling would be the optimal methods for drilling the remainder of the reservoir. Both of those methods would...
require mobilization of new equipment and modification of existing equipment. Therefore, the immediate concern was to place a barrier in the well, such that the drillstring could be removed. Then, a mechanical plug would be set to secure the well and allow preparations to be made to implement the chosen drilling technique to enhance the discovery.

As described below, three options were identified for placing a barrier in the well to allow drillstring removal.

**Option 1.** Recommended steps include:
- Rig up coiled tubing unit.
- Bullhead water to lower annular pressure.
- Strip pipe into 7-in. liner.
- Use coiled tubing to clean out drill pipe.
- Double-action reactive material job: Pump Diesel Oil Bentonite Cement (DOBC) gunk down drill pipe, and mud down annulus, to react at perforations.
- Displace reacted gunk into open hole, and pull drill pipe.

Cost considerations include rig time while awaiting transportation of the coiled tubing reels to location, transportation costs and rig-up time. The ability to mix reactive materials downhole is an advantage from a well control perspective. However, delays in mobilizing necessary equipment would mean additional exposure of the BOP elastomers to dry gas.

**Option 2.** The order of steps includes:
- Rig up rig-assist snubbing unit.
- Strip BHA into 9½-in. casing (TOL @ 3,268 ft).
- Perforate DP or BHA.
- Double-action reactive material job: Pump Diesel Oil Bentonite Cement (DOBC) gunk down drill pipe and mud down annulus to react at perforations.
- Displace reacted gunk into liner, and pull drill pipe

Obviously, several other options exist once a snubbing unit is rigged up, but the lack of a set of rams below the cross made a downhole barrier more attractive. Considerations similar to Option 1 apply to Option 2.

**Option 3.** The order of steps is as follows:
- Put well on losses by pumping two annular volumes of water at 16 bpm.
- Pump one annular volume of 13.5-ppg WBM at 16 bpm to displace gas.
- Continue pumping 13.5-ppg WBM at 3 bpm into annulus to prevent gas migration.
- Open BOPs and trip pipe as far as possible before pressure returns.
- Build mud volume and repeat pump-and-pull operations as necessary; move the bit into 9½-in. casing.
- Shut in well on pipe rams and annular.
- Build mud volume and prepare DOBC gunk.
- Put well on losses again by pumping water/mud as before.
- Follow mud with single-action reactive material job: Pump DOBC gunk down annulus and displace with mud to the liner bottom.
- Pull drill pipe.

The operator had learned through various pumping operations that, using the above procedure, the reservoir could be reliably kept on losses long enough to pull a significant amount of pipe. It was unknown exactly how long it would remain on losses with the addition of a 3-bpm annular deluge.

**PREPARATIONS FOR REACTIVE MATERIAL OPERATIONS**

Option 3 was chosen as the preferred method to control the well while the drillstring was removed. The operator considered a variety of advantages and disadvantages before selecting this option.

**Advantages to Option 3.** The most significant advantage was avoiding long delays in waiting for equipment to become available, then waiting for it to be transported and rigged up. It also avoided associated costs for the equipment, including transportation.

**Disadvantages to Option 3.** There are several disadvantages to a single-action reactive material job. First, the most significant disadvantage was the inability to control the downhole mixing ratio of water/mud to gunk. This is normally achieved by pumping mud down the annulus, and gunk down the tubing or drill pipe. In most cases, the ratio that develops the highest viscosity is roughly 1 mud to 1 gunk (1:1). By altering the drill pipe and annular pump rates, the operator can adjust the mixture to develop more or less viscosity in response to pressure developments. A single-action gunk job relies on the presence of downhole water and whatever mixing can be developed in sub-turbulent flow.

Second, when a DOBC gunk is used, it is imperative that any opportunity for exposure to water is eliminated prior to the desired mixing point. Lead and tail diesel oil spacers of about 1,000 ft, each, are normally used inside drill pipe to isolate the gunk from water. Pump rates are designed to provide turbulence to sweep mud ahead of the gunk. In this case, annular capacity was such that turbulent flow could not be achieved, given the pumps available and the mud weights to be used. Also, the diesel volume required for spacer heights of 1,000 ft could potentially flood the near-borehole reservoir with oil so that insufficient water would remain to react with the gunk. During annular displacement of the gunk, contact with water could cause stuck pipe. Once the gunk had been displaced beyond the bit, however, the success of the job relied on the presence of residual mud or water from the reservoir with which the gunk could react.

A third disadvantage of this option was limited barite availability. A significant barite supply had begun arriving via barge by the time the other equipment was ready, but it was unknown how many pump-and-pull iterations would be required to get the bit into the 9½-in. casing. Also, it was not known how many gunk job attempts would be required.

Finally, surface mud and water pit volumes were insufficient for Option 3. Additional surface capacity would have to be manufactured in Port Moresby.

Even given some of this option’s obvious disadvantages, the operator chose to avoid the uncertainties, costs and delays associated with finding available snubbing or coiled tubing equipment and mobilizing it to site.

Boots & Coots’ specialists were mobilized to the site to conduct the reactive material operation and to provide general well control services. The following preparations were required prior to the gunk job.

**Water supply.** Fresh water was supplied to site via two pumps set at the nearby stream. With both pumps running at full capacity, 9 bpm could be supplied to storage tanks on-site. Roughly two annular volumes of water would be pumped to...
put the well on losses, so an easily replenished water supply was important.

**Water tank capacity.** Initially, a 430-bbl water tank capacity was available on-site. The operator purchased metal storage containers and modified them in a Port Moresby fabricating shop to provide additional surface mud and water capacity. The modified containers were barged to the staging area, while other preparations were made, minimizing delay. Thus, dedicated water storage was increased to about 740 bbl.

**Mud materials.** Many activities subsequent to the initial gas kick were limited by barite availability. Fortunately, some barite supplies had already been mobilized, and the operator wisely placed a substantial order for more mud materials, soon after the gas kick. Additional barite and bentonite began arriving at the staging area during gunk job preparations and were in adequate supply when operations began.

**Mud tank capacity.** Initial surface mud capacity was about 460 bbl. With the addition of fabricated storage tanks, that capacity was increased to roughly 1,100 bbl. Usable quantities were about 950 bbl.

**PUMPING SYSTEM**

Figure 4 depicts the site layout prior to the gunk job. Primary pumping equipment consisted of two frac pumps and one cementing unit.

**Pumps.** Each frac pump was capable of pumping water at about 8 bpm against the 3,000-psi annular pressure, and capable of pumping 13.5-ppg mud at a combined rate of roughly 15 bpm against zero annular pressure. The cementing unit was capable of pumping 10.7-ppg gunk at a rate of about 4 bpm against zero annular pressure.

These pumps were arbitrarily named Frac 1, Frac 2 and Cement. Note that pumps were equipped with rate meters but not barrel counters. Volumes were necessarily tracked by strapping tanks and tracking pumping times. Rate meters were considered to be only somewhat accurate.

Frac 1 would pump only water and mud. Frac 2 would pump water and mud, but it was also connected to the diesel/gunk manifold, such that it could be quickly flushed with oil and used as a back-up to pump gunk, if necessary. Cement was dedicated to pumping only the diesel spacers and gunk. Secondary pumps included various portable and fixed centrifugal units on triplex skids, mud pits, independent skids or trailers. These were used to charge fluids to the manifold or frac pumps, to allow the high rates necessary.

**Manifolds.** Two manifolds, designated Manifold #1 and Manifold #2, were fabricated to allow isolation of mud/water and gunk systems. As discussed previously, it was imperative that the gunk not be exposed to water prior to passing the bit.

As shown in Fig. 3, all water was distributed to Frac 1 and Frac 2 via Manifold #1. When mud was pumped, Manifold #1 fed mud only to Frac 2, and Frac 1 was fed mud by a centrifuge on a triplex skid. This arrangement achieved the 15-16-bpm rate desired. Manifold #2 was dedicated to diesel and gunk, and was connected to Cement and Frac 1.

**Gunk package.** Diesel fuel and gunk were handled by a package comprised of a 100-bbl diesel tank, a 50-bbl batch mixer and a dedicated centrifugal pump tied to Manifold #2, and routed to Cement and Frac 1.

**OTHER FABRICATION AND PREPARATIONS**

Note that in addition to the other materials required for this job, a significant amount of connections and fittings was required to manifold the water, gunk and mud systems togeth-er for effective use. Rig crews were very effective in fabricating any equipment that could not be ordered or transported, including the manifolds used to keep gunk, mud and water systems isolated.

Water tanks and mud tanks were manifolded together to allow ease of switching between tanks during pumping operations. Auxiliary mud tanks were also fitted with hard lines to allow agitation of the mud with portable centrifugal pumps. Water tanks were fitted with hard lines that allowed them to be refilled during pumping operations.

Hatches were removed from the diesel tank on the gunk package and the tank’s walls and floor were cleaned to ensure that no water was present. The batch mixer was also flushed with diesel to ensure that no water was present. All water, mud and diesel containers were manually measured. Capacities for each were calculated.

**BENCH TESTING**

Bench testing was conducted to determine the optimum gunk recipe. It is imperative to conduct such tests on-site, because of inconsistencies in the common mud and cement materials. More specifically, large variations in cement, bentonite and diesel fuel densities are common. Such variation can greatly change a gunk recipe’s effectiveness.

Boots & Coots’ specialists arrived with the equipment necessary to accurately measure densities of materials on hand, and to run numerous bench tests to identify the best
Immediately, it was noticed that the moist climate had affected much of the cement available. Mixtures of bentonite and diesel often reacted when cement was added. Means were found to access a source of dryer cement.

Once densities of the available products were determined through repeated measurements, numerous gunk recipes were reacted with 13.5-ppg mud to identify the one that offered the best viscosity and compressive strength development. Ultimately, due to concerns about a possible lack of water in a laminar flow regime, the chosen recipe was one that demonstrated the best response with a high gunk-to-mud ratio, and which reacted most favorably with minimal agitation. Table 1 provides the densities, volumes, and weights of the ingredients used in a 35-bbl gunk pill.

### PIPE PULLING OPERATIONS

Three pump jobs were performed to put the well on losses to facilitate pulling pipe into the 9%-in. casing.

As described above for Option 3, the first pump job consisted of pumping 450 bbl of water at 16 bpm and 260 bbl of mud at 15+ bpm, then continuing to pump 13.5-ppg mud into the kill line at 3 bpm. Partial returns were observed while pulling 16 stands. Pulling operations were suspended, when the well began to flow.

In the interest of removing as much pipe as possible before the inevitable delay while building additional mud, it was decided that a second pump job would commence immediately, using some of the remaining mud. The second pump job consisted of 160 bbl of 13.5 mud pumped at 15+ bpm. Again, 3 bpm were pumped down the kill line while pipe was being pulled. This time, however, only three stands could be pulled before the well began to flow. The well was shut-in to allow mud volumes to be rebuilt.

The third pump job consisted of pumping 630 bbl of water at 16 bpm and 268 bbl of 13.5 mud at 15+ bpm. Twenty additional stands of drill pipe were pulled while deluging the annulus with mud at 3 bpm. The well was shut-in to build mud with the bit at 3,049 ft, about 219 ft above the 7-in. liner top.

### GUNK OPERATION

The gunk operation intent was to displace reactive material past the bit and into the 7-in. liner at the highest possible pump rate for two reasons. First, it was important to get the gunk past the bit before it could react with any residual mud in the annulus. Second, higher pump rates would tend to sweep the mud out of the annulus more efficiently.

Concerns about having sufficient mud volume present to react with the mixture were addressed by reducing lead and tail spacer heights in the annulus from the standard 1,000 ft to 750 ft and 600 ft, respectively. Displacement of the gunk was designed to place 10 bbl of gunk mixture into the formation, fill the openhole section completely with gunk mixture, and leave about 500 ft of gunk mixture in the 7-in. liner.

Displacement of the gunk at 15+ bpm was designed to continue until the top of the gunk reached a point roughly 100 ft below the top of the 7-in. liner. The remainder of the displacement would proceed at a lower rate, depending on the pressure response.

### FINAL PREPARATIONS

Mud volumes were again rebuilt to surface capacity in preparation for the gunk job. It was unknown whether more than one attempt would be necessary. Similarly, all water tanks were completely refilled, and water pumps at the river were serviced to ensure uninterrupted supply.

Continuous rain made it necessary to construct a roof over the batch mixer, where crew members would add bentonite and cement to the gunk mixture from sacks. Any rainfall contacting the components during the mixing process could have severe consequences for the results. Similarly, much time was spent briefing crew members, who were of various international origins, to ensure proper valve operation when switching between water, mud, spacer and gunk.

The cementing unit pump was flushed with diesel to ensure that it was oil-wet, and waste oil from that operation was spent briefing crew members, who were of various international origins, to ensure proper valve operation when switching between water, mud, spacer and gunk.

The suction line from Header #2 through which Frac 2 could be charged with diesel or gunk was disconnected, to ensure no unintentional exposure of gunk to water occurred.

Note that mud density was reduced to 13.0 ppg, and gunk density was 10.4 ppg. The intended result was to have an underbalance at surface on completion of the gunk operation, so that pressure could be monitored more easily.

### GUNK MIXING

After water pumping operations had begun, diesel fuel was added to the batch mixer, and crew members began adding the required amount of bentonite, as shown in Table 1. Prior

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**TABLE 1. DOBC gunk recipe**

<table>
<thead>
<tr>
<th>35-bbl Gunk</th>
<th>S.G.</th>
<th>Weight per bbl, diesel, lbs</th>
<th>Volume in mixture, bbls</th>
<th>Weight in mixture, lbs</th>
<th>Density of mixture, ppg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>0.82</td>
<td>287</td>
<td>26.0</td>
<td>6,598</td>
<td>6.83</td>
</tr>
<tr>
<td>Bentonite</td>
<td>2.04</td>
<td>150</td>
<td>5.4</td>
<td>3,896</td>
<td>8.59</td>
</tr>
<tr>
<td>Cement</td>
<td>3.12</td>
<td>150</td>
<td>3.6</td>
<td>3,896</td>
<td>10.37</td>
</tr>
</tbody>
</table>

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**Elk1-ST #1: Annular pressure buildup comparison**

- **Last SCP 3146 psi**
  - Pumping water and mud
  - Pumping gunk
  - POOH w/20 stands
  - Stop pump
  - Shut in

**Fig. 5.** Pressure buildup comparison.
to reaching the target volume, mud scales were used to test the mixture density. When the target density was reached, crew members began adding cement. The mixture density was again checked as the target cement volume approached.

Calculated values of bentonite and cement volumes proved to be correct, as the targeted densities were achieved after adding the calculated volumes. Gunk mixture samples were collected and reacted at various ratios with mud. Excellent results were observed when mixing the gunk with a very small amount of mud, with minimal agitation.

THE PUMP JOB

Following the previous pump job, during which pipe was pulled into the 9½-in. casing, annular pressure had returned to about 3,150 psi.

The pump job can be summarized as follows:
- Pumped 600 bbl water at 16 bpm
- Pumped 280 bbl 13.0-ppg mud at 15.5+ bpm
- Pumped 50 bbl lead diesel spacer
- Pumped 35 bbl gunk (150-ppb bentonite; 150-ppb cement)
- Pumped 40 bbl tail diesel spacer
- Pumped 235 bbl displacement mud (13.0 ppg)
- No apparent squeeze pressure.

After an estimated 195 bbl of displacement (top of gunk 100 ft below top of liner), the pumps were shut down for 10 min. The remaining 40 bbl of displacement mud were then pumped at 1 bpm, and the job was shut down to wait on the gunk to react. Annular pressure was 320 psi, when the well was shut in, which was roughly the calculated underbalance.

No pressure development other than underbalance was seen at any point during displacement.

RESULTS

Figure 4 compares the pressure buildup character following the final two pump operations. After pulling 20 stands of pipe from the well on Aug. 18, annular pressure built nearly linearly, more than four hours, at 3.2 psi/hr, eventually returning back to a stable value of 3,150 psi. After the gunk operation, pressure built at a much lower and decreasing rate, such that annulus pressure observed after 13 hr was only 1,050 psi. This pressure behavior was seen as evidence of the existence of a downhole barrier.

Pressure was bled to 280 psi, to relieve pressure on the gunk plug. No gas was present at surface. Pressure built linearly for another two hours, then was bled to zero with no gas. All fluid bled from the well appeared to be clean diesel fuel. With the rams open, 15-ppg mud was pumped into the kill line at 0.25 bpm, and 14 bbl of clean diesel fuel were circulated from the well before mud was seen in the flowline.

The pipe was then tripped out of the hole while filling with 15-ppg mud, and a retainer was successfully installed in the liner to complete the well control solution. The drill pipe was observed to be coated with a thin sheath of partially-reacted gunk, probably due to mud clinging to the pipe.

CONCLUSIONS

InterOil’s decision to attempt a single-action reactive material squeeze was influenced by the logistically difficult, operational environment. The risks and expense that the firm’s management accepted by selecting this option protected a possible major discovery. Their patience throughout the preparations eventually was rewarded by avoiding other much more costly alternatives, while protecting the value of a major discovery for the company and Papua New Guinea.

Keys to the operation’s success included:
- A resourceful drilling contractor that responded to every challenge
- Mud and gunk systems were almost completely isolated from each other
- Bench testing identified the proper gunk recipe
- All on-site personnel worked together safely.

When completed, the well flowed at more than 100 MMcf of gas and liquid equivalent per day, which is a record for Papua New Guinea. The gas flow, alone, is 400% higher than any previous well in PNG, with a CAOF of 2.85 Bcfd. This significant find confirms a new basin in PNG and validates a new reservoir system.

THE AUTHOR

John Reese, senior well control engineer for Boots & Coots International Well Control, holds a BS degree in petroleum engineering from the University of Texas at Austin. Since joining Boots & Coots in 2000, he has served as well control engineer on numerous underground and surface blowouts on the Texas and Louisiana Gulf Coast. He has undertaken emergency responses to blowouts in Iraq, Indonesia and Algeria, and has represented Boots & Coots as a reactive fluids specialist in Kazakhstan’s Caspian Sea fields. Prior to joining Boots & Coots, he served as project engineer for Avanti Consulting, where he developed drilling and well control plans for PEMEX in Mexico’s Burgos basin. He is a member of the Society of Petroleum Engineers and the American Petroleum Institute.