Cementing Problems when Setting Casing through Porous Gas & Water Bearing Formations

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ABSTRACT

Gas migration through cement has been a major problem in the drilling industry for the last two decades, while shallow water flow is a more recent problem. When shallow gas starts flowing it may be difficult to stop, and time consuming squeeze cementing jobs become necessary. In many instances this type of flow has turned into blowouts. When shallow water is flowing the flow may erode unconsolidated sand and disrupt the soil strength, the casing looses support and may buckle or collapse. Both shallow water and gas flow problems are related especially to offshore operations.

Improved insight into the physical process leading to flow of gas or water and chemical changes in a hydrating cement slurry has reduced the problem over the last years. Among the many physical/chemical factors which has been revealed to have an extensive influence on gas migration through cement are internal/external contraction of the slurry, fluid loss after initial set, and poor cement job (poor displacement).

Based on the knowledge gained through laboratory investigation and experience gained in the field, the recent methods to minimize the problem of shallow gas/water flow and to combat the problem when cementing through porous formations are presented.

1 INTRODUCTION

Deepwater conditions are commonly defined as water depths greater than 350 m (1000 ft). The pore pressure-ECD (equivalent circulating density) window is sometimes extremely narrow. The annular mud conduit is large for top hole drilling, resulting in a reduced transport velocity and accordingly solids/cuttings build up.

Shallow water flows (SWF) or shallow gas flows (SGF), can be a problem when drilling with seawater with return to the mudline (sea bottom) before the BOP and riser are installed. Pressurized zones may also be encountered after the BOP is set, but the difficulty of dealing with them is far less if they can be shut in safely with a BOP. SWF are therefore most troublesome in the upper two well sections. It is generally believed that shallow sand reservoirs are slightly overpressured. The pressure may arise from geopressured zones, from gas charging, tectonics etc. Once penetrated, the pressure causes an inflow of gas and/or water and/or sand into the wellbore. Gas is naturally easier to detect than water. Hence, an ROV (remot operated vehicle) should be regularly used to monitor both well and the vicinity of the well for evidence of flow.

If left flowing for some time, the flow can lead to large washouts, resulting in problems during the later cementing operation. Flow rates can range from very low (near levels of detectability) up to several barrels per minute, and often contain significant amounts of sand. Due to a combined effect of inadequate bonding/cement quality in washouts and gas/water migration through/along the cement sheet, the flow may continue during/after cementing and slowly remove the vertical support surrounding the casing and thereby allowing the casing to buckle. Even if the well experience no problems during drilling, i. e. the sand pressure was controlled, the potential of gas/water migrating through/along the cement during hydration is still high.

When the first and second control barriers are lost and the shallow flow turns into an uncontrolled blowout, the flow normally lasts only for short periods due to limited sand zone capacity. But there are cases where blowouts from shallow sands have lasted for more than a year.

2 CASE HISTORIES OF LEAKING FORMATIONS

Three different cases will examplify the problems; the first example shows how SWF was experienced in the mid 90's, the second one gives a recent example of SWF and the third one a successful case of handling SWF. All three cases are from the Gulf of Mexico (GoM). The two first cases are the combined effect of hole erosion/casing cement problems.

Case 1

One operator reports a rather dramatic experience while developing a field at 1207 m (4023 ft) water depth [1]. The first two exploration wells, drilled in 1992, were plugged and abandoned due to severe shallow casing wear resulting from buckling of the casing set across shallow sand zones. Severe flows during drilling of the shallow portion of the third appraisal well in 1996 led to abandonment of a possible location of the TLP (tension leg platform) due to the potential of not obtaining shallow annular isolation behind the casings. A successful well was later drilled through a shallow sand close by, leading to the decision of installing a TLP at this site. Twenty wells were batch set with 36/30" casings. After drilling 9 wells below the known shallow flow sand and setting the 24" casings, SWF was detected. One 24" casing had buckled and parted, and the remaining 8 casings had all mild to severe buckling damage across the shallow sand. The site of the TLP was then moved approximately 1.5 km away, and 11 wells have so far (1999) been successfully drilled.

Case 2

In this case from 1988 an exploration well was spudded in 1086 m (3620 ft) water depth in May 1998 [2]. The 30" casing was jetted down to 100 m below the mudline. While drilling the 28" x 30" hole at 1404 m (4680 ft) depth, a small flow was detected. The 26" casing was set at 1401 m (4670 ft) and cemented in place with high quality cement/cementing technique. A 24" hole was drilled with 10.8 ppg mud and water flow through the well was detected while drilling at 1722 m (5740 ft). Before running the 20" casing, mud was lost and flow was now detected at the seabottom 20 and 36 ft from the well. The 20" casing was cemented with high quality tail/lead cement, returning at the wellhead. Six hours after cementing the well was flowing both in the 20" and 26" annulus. The BOP was set, the well squeeze cemented several times, and water flow was finally stopped two months later.

Case 3

A successful case of killing a SWF was reported by ExxonMobil while drilling an exploration well at 1386 m (4620 ft) waterdepth [3]. While drilling at 1647 m (5489 ft) as indicated in Figure 1, a sudden drop in formation resistivity accompanied by an increase in ECD from 1.04 to 1.07 kg/l (caused by sand production) were detected. This shallow sand was then flow checked for 45 min, and when

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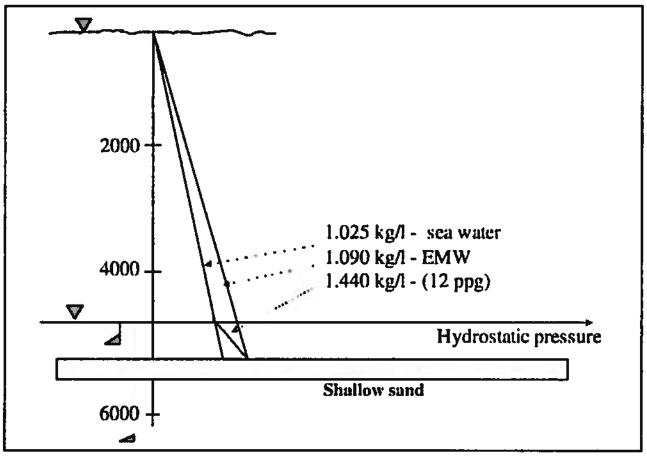

Fig. 1 Pressure conditions in "Case 3" well.

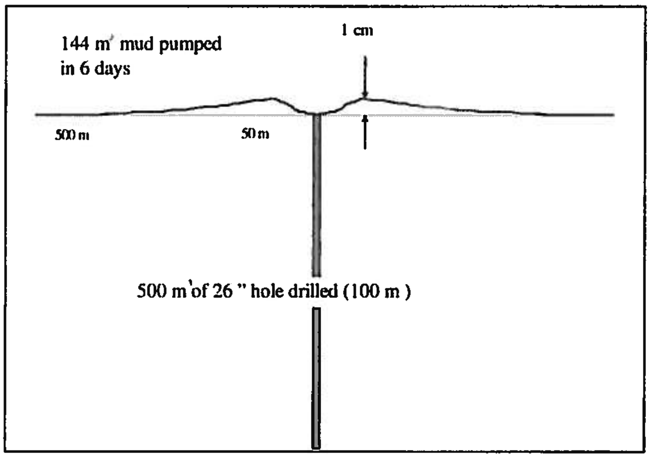

Fig. 2 Solids (barite) and cuttings accumulation. After Schubert & Walker [3].

visiability allowed, a small stream of spud mud was observed from the wellhead. The well was immediately killed with 1.68 kg/l mud, and later drilled to planned 20" casing shoe with 1.44 kg/l mud in 6 days. In 1647 m (5489 ft) depth the 1.44 kg/l mud corresponds only to an equivalent mud weight of 1.090 kg/l (see Figure 1). During those 6 days 9800 bbls of 1.98 kg/l mud were supplied by three supply boats (deluted to 1.44 kg/l on the rig). The drilling and pumping of 144 m^3 mud caused a thin layer of barite/cuttings to be formed around the well as shown in Figure 2. 80% of the material settled out within a radius of 30 m from the wellhead.

3 THE PHYSICS INVOLVED

There are four main issues involved when flow of gas or water develops into a problem:

- Shallow sand zones in deep water, slightly pressurized;
- Pore pressure, slightly higher than normal;
- A weakness in the formation or the cement, linking the sand zone to the surface;
- Frequent kicks.

3.1 Shallow sands in deep water

Water depth causes the fracture gradient to become much lower relative to onshore gradient as shown in Figure 3.

Shallow flows are difficult to stop because of the narrow margin between pore pressure and fracture pressure.

3.2 Pore pressure in shallow sands

Shallow zones which cause problems are slightly overpressured, marginally greater pressure than a sea water column, i. e. in the 1.08–1.13 kg/l range.

The shallow zones are pressurized either by induced fractures, induced storage, geopressured sands, or transmission of pressure through cement channels. Geopressured sands are the most frequent cause of high pressure, and can orginate from several different mechanisms including the following:

- loading by rapid sedimentation
  - sand collapse
  - gas charging
  - salt tectonics.

From this list, rapid sedimentation is the most likely cause as indicated in Figure 4.

One method suggested for predicting SWF potential is as follows [4]:

Calculate the shallowest sedimentation rate by seismic correlation to the shallowest available offset paleo data. If the shallow sedimentation rate is higher than 500 ft per million years at the planned drilling site treat the sands below the seal as pressurized.

Geopressurized sands have a low vertical stress and an acordingly high porosity [5]. As shown in Figure 5, such uncompacted sands are exposed to erosion.

Cavities/washouts as large as 70" in diameter have been observed. If such cavities are not filled with cement, the stress created in the laterally unsupported casing can exceed the buckling strength and result in buckling.

3.3 Paths to surface

One can distinguish between three different paths to the surface:

- through the wellbore,
- through cement behind the casing,
- through weakness in the sediments.

The pathway through the wellbore is the obvious and common one, leading to hole erosion as discussed above. The two others

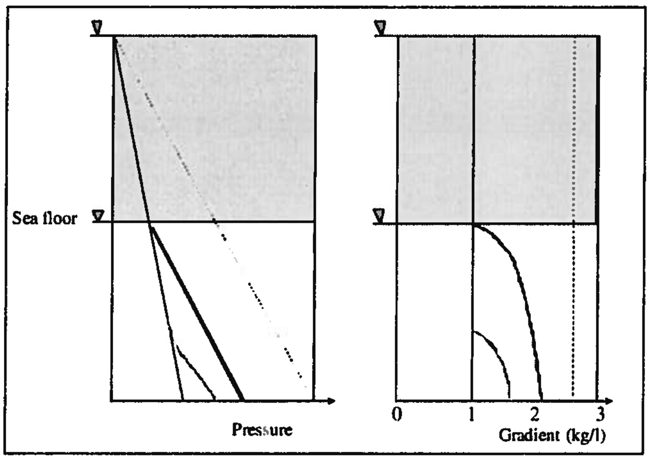

Fig. 3 Onshore (dotted) and offshore overburden gradients. Seawater causes the overburden/fracture gradient to start with a low value at sea bottom level due to the low overburden of seawater.

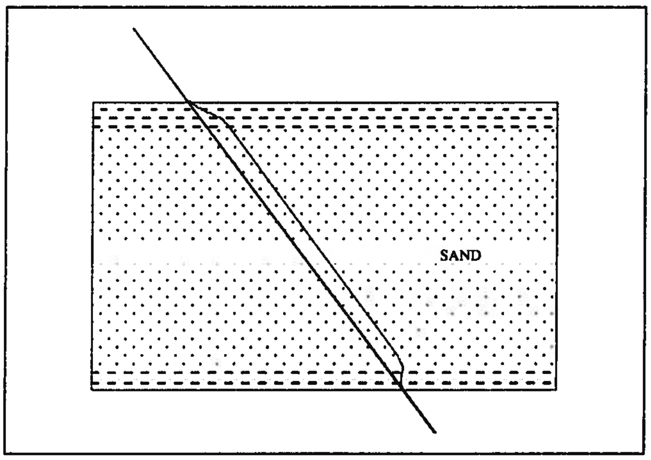

Fig. 4 Rapid sedimentation of shale cause a sand zone to be pressurized/trapped inside the shale.

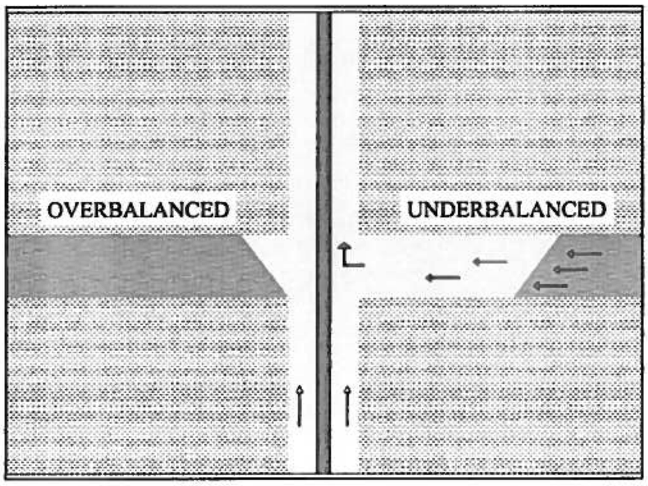

Fig. 5 Sand erosion in shallow sands. An overbalanced drilling situation is shownto the left and underbalanced to the right. After Alberty [5].

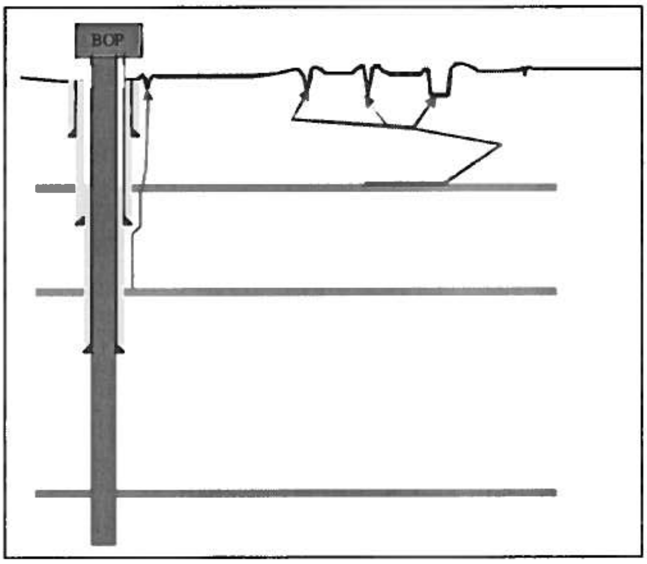

Fig. 6 Flow of gas or water to surface through leaking path ways.

are more complex and need some elaboration.

Flow through cement and/or behind the casing. As the slurry begins to hydrate, it changes from a true fluid, via a soft gel-like material and finally to a solid, hard material. While the cement is in a liquid state, the hydrostatic pressure of the cement column is higher than the pore pressure of the gas bearing formation. As soon as the cement column is either self supported or supported by the wall by means of the slurry's gel strength, the column can no longer transmit hydrostatic pressure. From this point on the hydrostatic pressure of the remaining water in the porous/permeable cement matrix must balance the sand pore pressure. However, sometimes the cement pore pressure decreases below the gas pressure while the slurry is still weak enough to let gas penetrate through it [6, 7]. The cement pore pressure is now a function of the cement free pore water. If the water volume in this stiff, self contained or hanging matrix is reduced the pressure will immediately decrease. Any water loss before the matrix is selfsupported has no influence on the hydrostatic pressure because the slurry is a flowing liquid at that time. However, initial water loss will both lead to a quicker increase of the slurry yield point and influence the quality of the filter against the sedimentary formation. The quality of the filter against the sedimentary formation is important, because when the selfsupport state has been reached, the intrinsic water has normally a much lower viscosity than the slurry itself and should preferrably be kept inside the lsurry to avoid pressure reduction.

The chemical product of water and cement has a lower volume than its original components [8]. The stiff matrix will start to shrink, but the accumulated strength across the cement sheet resists external shrinkage at some stage. Instead the shrinkage continuous inside the matrix, and water is sucked into the pores as soon as they develop. If sufficient water is available in the slurry itself (intrinsic water), the hydrostatic pressure of the intrinsic water will be slightly reduced. If insufficient water is available within the matrix, water or gas from the surrounding will be sucked into the matrix.

The widely accepted assumption that a shear stress or yield point of 500 lb/100 ft^2 would hinder gas to migrate through the cement [9] is misleading. Gas or water enters the cement independent of its shear stress. The suction pressure may theoretically become as high as the formation pressure ($p_{pore} - 0$), while the cement shear stress can hardly reach such a high value. It is of higher importance to design a slurry were surplus water is contained within the slurry. As a result, reducing the fluid loss minimizes the decrease of cement slurry pore pressure. In shallow formations in deep water this becomes even more important where low temperature slows down the hydration process and water/gas has a larger time window to enter the slurry. From previous investigations [6, 8] it seems that the critical time window for water or gas to enter and migrate through the cement, is between initial and final set.

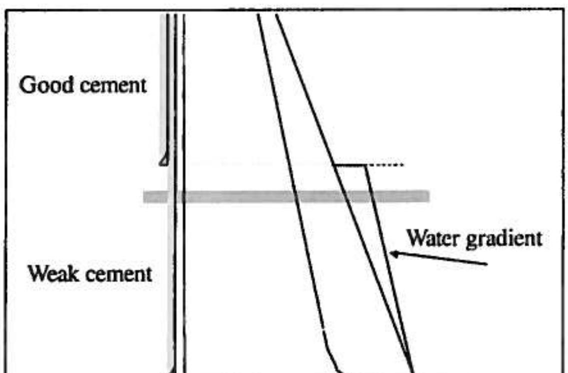

Fig. 7 Charging of shallower zones through weak cements.

Backe et al. [6] showed that there was a high probability that intrusion of gas/water creates microcracks in the cement. At a short, but overlapping time period, the matrix permeability is high and the tensile strengh is low enough for fluid to enter the cement and migrate through it vertically. The penetrating fluid has a low viscosity (viscosity of water at 20 and 5°C is approximately 1.0 and 0.5 cP respectively). Cement sheets which have been exposed to gas or water migration has been cut through and analyzed, and the matrix show evidence of micro cracks and/or micro holes.

Flow through a weakness in the formation. As indicated in Figure 6, the fluid (gas, water or mud) may flow through a weakness in the formation. The weakness may be found at any depth, and interconnected by a weak cement. The weak cement, as discussed above, may lead the flow all the way to the surface or to a shallow zone, as indicated in Figure 7. The weakness in the formation may be caused by faults or by induced fractures, interconnected by horizontal permeable sand zones. If mud mounds or hydrocarbon vents are detected, the area has a high potential of SWF or SGF [3]. Figure 8 presents a shaded image of a mud vulcano (or brine or hydrocarbon vulcano). Such subsea vulcanoes indicate extensive faulting or sands which have reached their seal capacity/fracture limits.

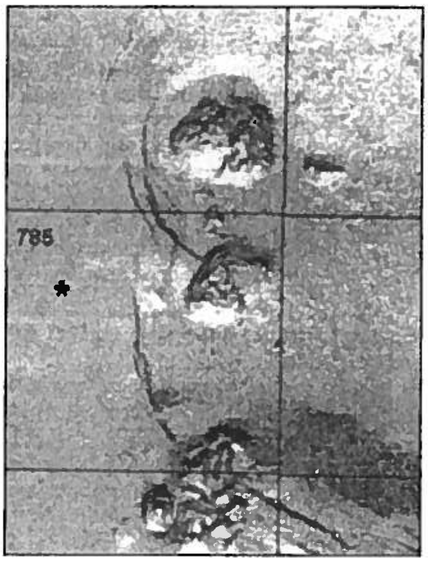

Fig. 8 Seabottom shaded monds images [3].

3.4 Kicks

The mud density must be low to avoid breaking down the weak formation. As a result of this the swabbing problem is amplified. The shallow hole size is large, much cuttings are produced, and in loose formations the hole may produce cavings/sand which altogether may lead to significant mud density increase. Bottoms up or sweep pills becomes necessary to clean the well to keep well pressure down. When the well pressure is low, only a small
reduction is necessary in order to swab in a kick from the formation. Kicks are monitored through video cameras installed on the wellhead (traverse) or on ROV. Twice a stand, drilling is stopped and the well is observed for at least 15 minutes.

4 SOLUTIONS

Solutions to SWF/SGF can be divided into two groups: procedural solutions and cement slurry design.

4.1 Procedures

Operations in deep water does not allow the upper part of the well to be shut in. Therefore the first two well sections are drilled riserless. According to Alberty [5] the main solutions to drill through shallow sands:

Drill with seawater down to the sand, kill, and then drill to 20" casing setting depth with weighted mud. This procedure is also recommended by IADC. The method presented below is a summary of the IADC recommended procedure for drilling in deep waters [4]. The method focuses on safety/gathering of informaton about potential problems: Try first to avoid SWF sands. Then

1. drive/drill first casing as deep as possible;
2. then use pilot hole; better hole cleaning at minimum flow rate and minimum wash out/erosion;
3. sweep pill every stand (some operators every 45 feet); reduce cuttings load and quantify hole volume;
4. apply LWD (logging while drilling (γ, R, PWD); Find casing shoe point; minimize sand penetration;
5. store kill mud: (ρ_{pore} + 0.025 kg/l) $\leq \rho_{kill}$ $\leq$ (ρ_{frac} – 0.035 kg/l);
6. after penetrating sand, circulate clean and flow check (ROV/sonar at well outlet + at up to 100 m (300 ft) radius)
   – if decreasing flow: just ventilate, then kill pill
   – If increasing: dynamic kill, then kill pill
7. casing shoe as close as possible to sand zone; max. formation strength;
8. run and cement casing with best practice;
9. to drill further without BOP, SWF must now be controlled with heavy mud returning to sea floor. This will control SWF/hole erosion. But it will be a logistic problem.

Since the cement is such a hot topic here, here are some comment on cementing procedures.

Cementing techniques for shallow sand intervals. To minimize the problems stated above (migration of gas/water through cement) the displacement of the mud and handling of the well during WOC (wait on cement) must be optimized.

Gas migration along micro annulus between the cement sheet and the formation is partly a question of how well the operation was performed. Obtain good wall cleaning and mud displacement to obtain good binding and cement quality. After WOC avoid changes in temperature and hydrostatic pressure to avoid mechanical stresses transmitted from the casing to the cement sheet [10]. Since the external shrinkage of cement slurries are negligible, the slurry itself does not create stresses that may lead to microcracks and microannulus.

Due to pipe flow profile, there will be a long mixing zone when cement is displacing mud; the longer the mixing zone the sharper the flow profile. Therefore a flat flow profile is aspired. Lowering the mud viscosity will increase its mobility and reduce channeling/fingering effects. A maximum flow rate flattens the flow profile and improves sweeping. Use centralizers/scrapers and reciprocate/rotate casing if possible during displacement to avoid fingering and unobtainable »shadow« volumes.

Mechanical seal in the annulus. Gas or water migration behind the casing is such a serious problem that extra procedural precautions have to be taken. One precaution is to place a mechanical seal in the annulus. A concepts that have been tested and are applied in the GoM4 is exemplified in Figure 9.

The 20" casing is run and cemented across the sand zone with standard housing with a casing packer above the zone. Flow from the sand zone is now controlled as the packer provides mechanical seal in addition to cement. The packer must, however, hold a minimal pressure until the cement sets up. If the packer does not hold (rupture or does not inflate), the cement sheet is the only barrier against flow.

Drill with liner into problem zone. Drilling with liner or with casing has not yet been applied but in conjunction with lost circulation in subsiding formations, but so far not within SWF/SGF drilling. As soon as the losses starts, the casing is withdrawn some feet and cement is pumped immediately. The problematic formation is thus quickly sealed off. There are two different ways to achieve this:

a) Full Rotary Drilling of Liner [11]: This solution implies that the bit is rotated from the surface. The liner/hanger system must be rotated together with the bit, and must take a lot of torque. Parts of BHA are abandoned when cementing into the loss zone. This part of the BHA must be drillable.
b) Sliding liner [12]: Drill normally down towards the problem zone. Just before entering the problem zone the equipment is changed to DRILL-IN-LINER BHA. Drill a few meters into the problem zone, until losses occurr. The liner is set and cemented. The mud can now be adjusted and it is possible to resume

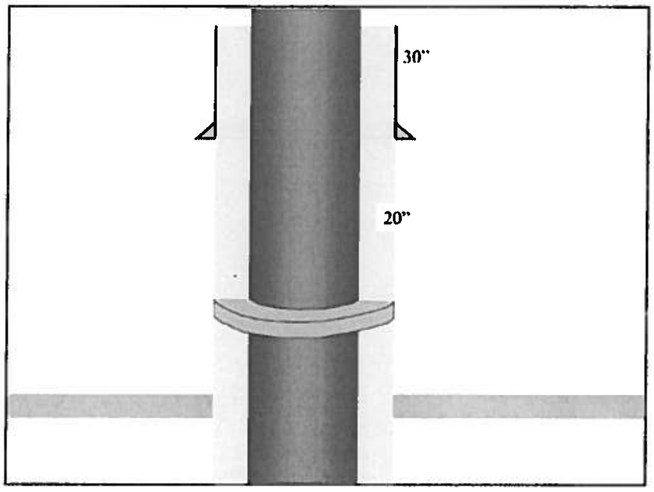

Fig. 9 Casing packer for stopping gas/water migration through/along the cement. After IADC [4].

drilling including an external core bit and an inner standard bit, both driven by a motor in the liner.

4.2 Cement slurries

The problems when designing a cement slurry for shallow formations in deep water are:

- low surrounding temperature leads to low hydration rate and long transition time;
- low fracture gradient. Neat cement slurry has a density of 1.92 kg/l and needs an extender to bring it down to 1.3 kg/l. ECD control requires very low pump rate;
- SWF/SGF through cement due to cement slurry behaviour.

There are several solutions to combat water or gas migration through a hydrating cement slurry. In general these solutions are the following, alone or in combination:

- short hydration transition time/right angle set;
- low free water (to avoid channeling and intrinsic segregation);
- low API water loss (< 10 ml/30 min);
- lead cement should set later than the high quality tail cement across sand interval (to maintain hydrostatic pressure during hydration);
- expansion during hydration or high compressibility (to neutralize suction pressure);
- rheology of lead cement > spacer > tail slurry (to optimize displacement).

A list of commercial products called "Anti-gas migration agents" is updated and published annually [13]. One of the products that has become very popular is foamed cement, usually in the form of nitrogen (N2), and offered by all the major cement service companies. Since the slurry now is compressive, most of the pressure will be maintained during the transition time and thus prevent suction of water or gas into the slurry. Several of these products are discussed in the literature [10, 14, 15].

5 CONCLUSION

SWF/SGF is a serious problem related to drilling in deep waters. Water or gas starts to flow either through the borehole, through the cemented annulus or through weaknesses in the formation, leading to sand production, accompanied by buckling and collapse of the casing due to loss of structural support. The two most important and direct causes of flow are:

1) Too low mud pressure to control the sand zone's pore pressure during drilling.
2) Too low pressure in the cement column during hydration of the slurry.

The obvious solutions have been to neutralize the two causes;

1) Increase the hydrostatic pressure up to kill mud density when a overpressured sand is encountered.
2) Neutralize the pressure reduction in the cement by creating a compressible slurry (which expands when pressure is reduced).

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