Permanent Abandonment of a North Sea Well Using Unconsolidated Well-Plugging Material

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Summary

The traditional plug-and-abandonment (P&A) method of exploration wells in the North Sea is to set a series of cement plugs to isolate the pressurized zones from each other and from surface. This paper describes a North Sea P&A field case. In this case, an alternative method was used with a Bingham-plastic unconsolidated plugging material with high solids concentrations. This alternative method addresses well-integrity issues such as those caused by shrinking of cement or gas migration during setting, fracturing after setting, or long-term degradation by exposure to heat and chemical substances in the well.

The gas-tight well-barrier element described here does not set up after placement and does not shrink. Furthermore, it cannot fracture even when shear forces exceed its strength. When this happens, the material floats and shear forces are reduced below yield strength, causing the plug to reshape. Because this is a purely mechanical process, the transition between solid and fluid phase is repeatedly reversible (in principle, an infinite number of times).

The plug is thermodynamically stable because its sealing property is decided by the solids particle-size distribution (PSD) and bound water only. The closely packed particles and absence of free water mean that the entire column is kept homogeneous and no internal redistribution of particles may occur. Hence, the permanent gas-tight barrier will prevent influx through the wellbore.

In the field case, a successful implementation of the technology was obtained. The field case shows how the fast and efficient placement of the plug contributes to overall cost reduction. The paper explains how the well-barrier element complies with Norwegian requirements for permanent P&A; these requirements also apply to the UK sector (*NORSOK D-010* 2004; Oil and Gas UK 2009). Operational procedures are also presented in some detail.

Introduction

Permanent abandonment of offshore exploration wells represents a significant part of the drilling cost. Normally, these operations are conducted with cement [see for example, Liversidge et al. (2006) and Nelson and Guillot (2006)]. A series of cement plugs is placed to isolate the pressurized zones from each other and from surface. In some cases, as on the Kristin high-pressure/high-temperature field in the Norwegian Sea (Saasen et al. 2004), a concentrated sand slurry (Svindland 2004) was applied for temporary abandonment. In this case, the slurry was used to plug back the openhole reservoir section of a well that was to be completed by a different rig at a later stage of the field development. By eliminating time-consuming drillout of cured cement, it was estimated that up to 7 days of rig time was saved, representing a significant cost reduction for the operator.

The operation described in this paper is different from the temporary abandonment jobs described previously. Use of the concentrated-sand-slurry method reduced the cost of permanently abandoning Exploration Well 25/8-17, "Jetta," in the North Sea. In addition to cost and time savings, other factors influencing the choice of method were health, safety, and environment benefits and reduced operational risk. The well was drilled with the semisubmersible drilling rig *Bredford Dolphin*. The deck space on the rig is limited, and the equipment rigup was, therefore, a challenge. However, as will be shown, the operation with the concentrated sand slurry was successful, and the material will act effectively for plugging pressurized formations during abandonment operations. Norwegian requirements are to use two independent barriers in addition to a shallow plug. The unconsolidated sand plug requires a foundation; it cannot be placed on top of a liquid. The material is also not suitable as a foundation for a kick-off plug or behind structural (weight-/load-bearing) casing because of its relatively low shear strength.

Theoretical Considerations

Permeability. Darcy's law states that the flow velocity of an incompressible fluid through a homogeneous, porous mass is proportional to the net pressure gradient and inversely proportional to the viscosity of the flowing medium. The pressure drop as a function of the velocity (v) is shown in Eq. 1. Here, use of consistent units is assumed.

$$\frac{\Delta P}{\Delta L}=\frac{\mu}{k}v \cdot \qquad (1)$$

For flow through a packed sand bed, the flow can be calculated using the semiempirical Blake-Kozeny equation [see, for example, Bird et al. (1960)]. This equation is presented as Eq. 2. The factor 150 is an empirically adjusted factor that also includes the geometrical terms arising from treating flow around spheres.

$$\frac{\Delta P}{\Delta L}=\frac{150\mu}{d_p^2}\frac{(1-\varepsilon)^2}{\varepsilon^2}v \cdot \qquad (2)$$

In this equation, d_p is the sand-particle diameter and ε is the bed nonsolid fraction. The Blake-Kozeny equation can be rewritten as the Darcy equation when the permeability k is rewritten as shown here:

$$k=\frac{\varepsilon^2}{(1-\varepsilon)^2}\frac{d_p^2}{150}. \qquad (3)$$

The sand-slurry system described in the present paper consists of a mixture of particles with a wide PSD. The larger particles alone would leave a fairly permeable matrix. The volume between the large particles is filled with smaller particles, and the volume between these smaller particles is reduced by adding even smaller particles, and so on, down to micron-sized particles. Therefore, micron-sized particles will define the maximum permeability of the system. The sand-slurry-system permeability is reduced further by the presence of particles both larger and smaller than d_p. The permeability dependency on the particle size in a homogeneous sand pack, calculated from Eq. 3, is shown in **Fig. 1** for porosities ε = 0.20, 0.25, 0.30, and 0.35.

As long as the slurry is static and is in its state as a particle-to-particle-bond gel, it will at minimum exert a hydrostatic head equal

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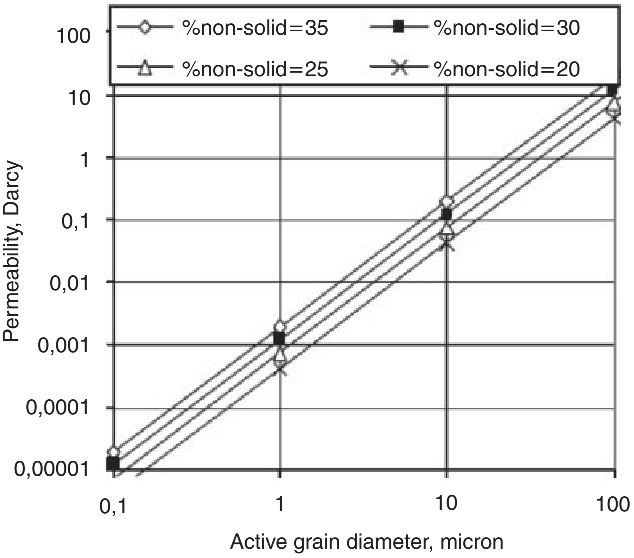

Fig. 1—Permeability as function of the sand-grain size for different porosities.

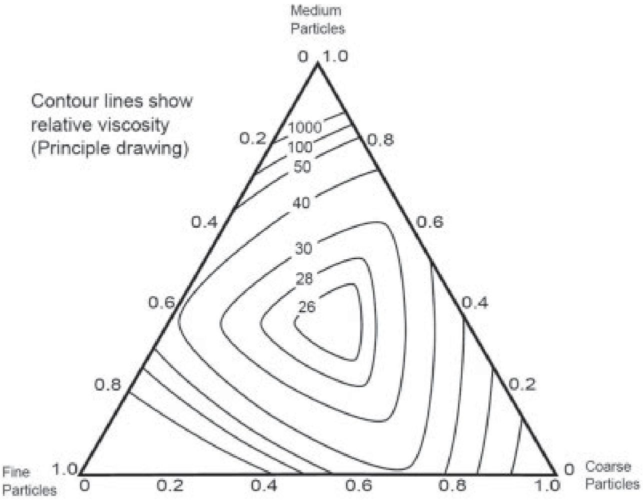

Fig. 2—The Farris effect. Principle drawing of viscosity as a function of particle-size fraction for a trimodal system. The illustration is based on data from Barnes et al. (1989) and shows the relative viscosity for a slurry with 65% solids by volume.

to water or brine phase. It is important to note, however, that this pressure gradient is not the pressure control gradient of the plug. This is because the liquid gradient will only be "seen" by fluid entering into the pore space of the slurry. Because the particles that control permeability are of submicron size, the resulting permeability is less than 1 md. The presence of larger, impermeable particles further reduces the permeability from this theoretical value deduced from Blake-Kozeny [see for instance MacDonald et al. (1991)]. With such a low permeability, the migration rate through the plug is on the order of cm/yr and volumetric rate becomes negligible because of the very low effective porosity of the slurry.

If the fluid volume migrating into the porous medium were to flow at a higher rate than mentioned in the preceding paragraph, it would have to mobilize the entire column. In this case, the pressure gradient has to overcome the yield stress bonding the slurry to the casing and formation in addition to the weight of the entire slurry. This would in turn make the slurry behave like a fluid, and it exerts the gradient of 2.15 SG (17.9 lbm/gal) on the fluid source below.

Note also that even if the hydrostatic head should exceed formation-fracture gradients, this will not cause loss into the formation because the particles bridge off at the fracture mouth and this prevents any fracture propagation.

Gas-Tight Slurries. The gas tightness of the material is documented using the Intertek JVS 1000 test. This test system is the recommended test for gas-tight cement slurries used in the Norwegian sector of the North Sea. For a detailed description, see Jamth et al. (1995). The slurry is placed in a 4-in. inside-diameter, approximately 1.7-m long test pipe inside an annulus, which is gradually heated to 160°C during 4 hours according to API SPEC 10B. With a 1,000-psi system pressure applied, a differential nitrogen pressure is applied at the inlet of the pipe and a computerized sensor system records pressure, temperature, and in and out flow of nitrogen for the duration of the test.

The tests show that the material remains gas tight for a differential pressure exceeding the hydrostatic gradient of the slurry. The total pressure control gradient of the plug is the sum of the hydrostatic gradient of the slurry and a constant. The constant is an expression of the yield stress between the material and the inner wall of the test apparatus (Saasen et al. 2004). By tilting the apparatus, the hydrostatic head is reduced while the yield stress remains constant, enabling quantification of the yield strength of the material in the actual geometry. The test can be repeated indefinitely and demonstrates the self-healing properties of the plug.

Pumpability. The concentrated sand slurry is made pumpable by carefully designing the PSD to make the smaller particles fit into the free space between the larger particles, according to optimal-packing principles. The particle concentration of the material is approximately 75% by volume. Excessive amounts of water or other liquids must not be added to the mixture because the interparticle distances in the slurry would become too large and thus generate space for the larger particles to segregate. If this were to occur, it would hinder the interfilling by smaller particles.

A typical maximum sand concentration for randomly configured sand slurries is 50–55% by volume. At this concentration, the large particles will have direct particle-to-particle contact making the slurry solid-like and completely nonpumpable. Andreasen and Andersen (1930) and Farris (1968) quantified the effects of controlling viscosity by adding solids in large fractions. An example of the pumpability of a trimodal suspension is illustrated in **Fig. 2.**

Shown in Fig. 2 are contour lines for the viscosity relative to the fluid fraction's viscosity. The viscosity of multimodal suspensions will have a minimum for a relatively high concentration of the larger particles. The presence of too much fines will also create too high a viscosity. For a more detailed explanation of the theory and applications of such complex slurries, a consultation with introductory textbooks on rheology such as Barnes et al. (1989) is recommended.

Godøy et al. (2004) evaluated the slurry viscosity, finding that it behaves like a Bingham fluid with a yield stress and a plastic viscosity. They found that it is possible to vary the yield stress and plastic viscosity significantly by varying the PSD of the slurry and still keeping the porosity constant.

Well Integrity and Government Regulations. The operator is the only responsible body for ensuring the well is secured. Obviously, simply following recommended guidelines or industry best practices does not waive this responsibility. The Petroleum Safety Authorities is the governmental body overseeing the industry on the Norwegian Continental Shelf. In short, for any well to be abandoned requires the well owner to submit a detailed P&A program describing the methods applied. The program also includes a description of acceptance criteria for each well-barrier element. For details on the recommended well-integrity guidelines, consult the Norsok Standard (*NORSOK D-010* 2004).

Responsible well-integrity management is not only a requirement. It can also give companies willing and able to implement new technology a competitive advantage. Securing wells with long-term integrity in mind greatly reduces future costs and risk of impact on reputation. The consequences of an incident are so serious that trial and error is not an option when being innovative. The sand-slurry material has been thoroughly tested and qualified by the service provider in cooperation with research institutions and the industry through laboratory and field or pilot testing during the last 10 years.

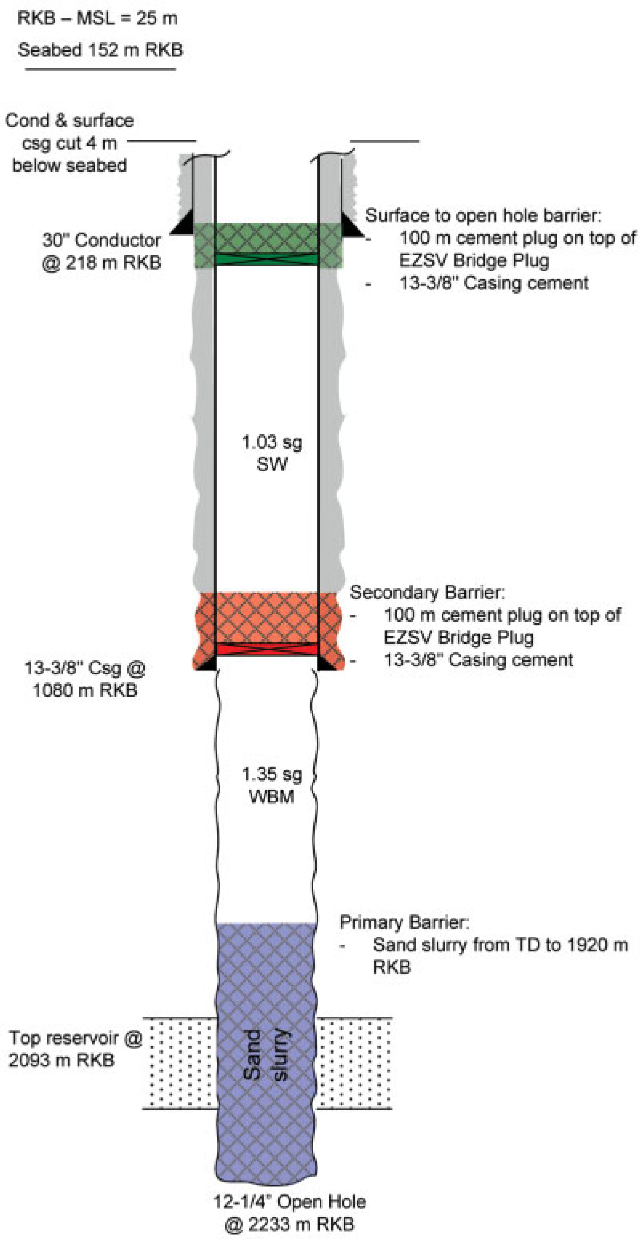

Fig. 3—Well-abandonment schematic.

All jobs performed have shown that when the material has been placed successfully in the well, performance has been as expected.

On two occasions during early field trials for other operators, the material bridged off before reaching its intended position in the well. These incidents have led to a thorough revision of operational procedures. Although the unconsolidated material may be removed simply by circulating it out of the well, it is obviously important to mitigate the risk of unsuccessful placement, thus avoiding time loss. Successful placement is dependent on keeping the material homogeneous during the time of placement. This is accomplished by avoiding contamination during transport, storage, and pumping. If excessive fluid is introduced into the slurry, the individual grains may redistribute internally and cause segregation, making it impossible to pump.

25/8-17 Jetta, Operational Description

The objective of the operation was to place a 290-m-long concentrated sand plug as a permanent primary barrier in the 8½-in. openhole section of the vertical Exploration Well Jetta from total depth (TD) at 2211 m reference Kelly bushing (RKB) to 173 m above top of the reservoir at 1920 m RKB, as shown in **Fig. 3.** Originally, the well was drilled to 2233 m measured depth. However, fill was tagged with 5 tons at 2211 m measured depth.

Fig. 4—Normal well returns before sand-slurry appears.

Open-ended 5-in. drillpipe was run in hole, tagged bottom, and picked up 1 m. The slurry was then pumped down the pipe and up the annulus from TD at 550 L/min (3.5 bbl/min). A total volume of 30.5 m^3 of the sand slurry was pumped with exactly the same volume of mud returned from the well. The slurry was displaced with water-based drilling fluid just like when placing a balanced plug, again observing full returns. The drillstring was then pulled out of the sand plug from TD to above the planned top of plug with practically no overpull. Closed-end displacement was pumped at every 100-m interval while tripping out. The whole pumping operation was performed without any delays, and formation losses were not observed.

Verification and documentation of the top of sand slurry (TOS) differs from when using cement, which is normally verified after curing by tagging with a predetermined weight on the drillpipe. This is not possible with the unconsolidated-sand-slurry plug because its shear strength is not sufficient to allow verification by tagging. Therefore, verification is performed by mud circulation while observing returns over the shakers. A full annulus volume is first circulated with the string placed above initial theoretical top of pumped-sand-slurry column and thereafter at the final TOS. Absence of sand-slurry returns during the first circulation and full return flow are evidence that the slurry has effectively displaced drilling fluid from TD and upward. Presence of sand in a second circulation with the drillpipe positioned at the planned height, 5 to 10 m below the theoretical top of sand proves that the material has reached its intended height, TOS. In this well, the plug was dressed off according to plan at 1920 m RKB, with a significant amount of sand appearing at the shakers after exactly one annulus volume had been pumped. The pictures in **Figs. 4 and 5** show how the return flows are easily distinguishable from each other.

Fig. 5—Sand-slurry returns while dressing off at 1920 m RKB.

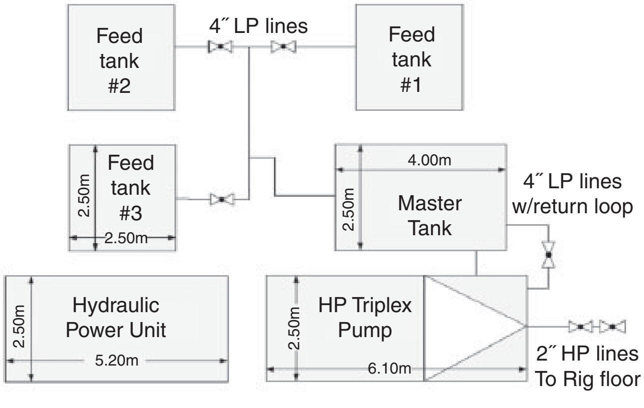

Fig. 6—Deck layout.

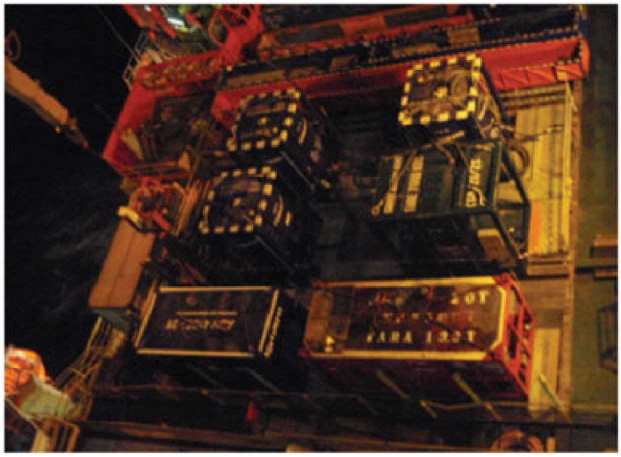

Fig. 7—Photograph of deck layout.

Wellsite Equipment. The slurry is premixed in a fully automatic industrial facility and transported to the rigsite in purpose-built tanks ready to be connected to the high-pressure pump. The tanks are equipped with built-in screw pumps and agitators powered by a dedicated hydraulic power unit. The 4-in. low-pressure loop is fully enclosed, ensuring no spill or contamination of the material when feeding the high-pressure pump. See **Fig. 6** for a schematic of the setup of the equipment. An actual photograph from the rig is presented in **Fig. 7.** The equipment was lifted onboard 3 days before the planned operation should start. Sea fastening and scaffolding were required, necessitating an extra day of preparation. The sand-slurry crew consisted of three persons, sufficient to operate all the equipment and also to perform the actual pumping operation.

Benefits of Using Concentrated Sand Slurry for P&A Operations. New technology or methods are generally not implemented unless a very specific and very current problem can be solved thereby. Well-proven technology will always be preferred because the change automatically triggers numerous tasks according to the company's internal procedures for management of change, such as new risk assessments, unfamiliar equipment, new service providers, and contractual issues. The method described in this paper, however, was considered sufficiently beneficial to justify implementation.

By not having to tag cement, the period of waiting for cement curing is eliminated. This may typically reduce rig time by 8 to 12 hours per plug. In the current operation, there was no need to change to a 300-m cement stinger. This reduced the time consumed on this particular job by an additional 7 to 8 hours.

Curing of sophisticated cement recipes involves complicated chemical processes. Contamination issues, temperature effects, and losses or seepage to the formation all affect the critical transition period before sufficient compressive strength is achieved. This effect introduces operational risks. The function of the sand-slurry material comes only from physical and mechanical properties once the slurry has been placed successfully in the wellbore. Therefore, the potential risk associated with chemical reactions, as when using cement, is eliminated. Premature curing of cement is also not an issue with sand slurry.

The material consists mostly of quartz sand and water, with a small amount of dispersant and viscosifier added to keep the material pumpable. The chemical additives do not contain environmentally hazardous components. Quartz is a thermodynamically stable mineral. Unaffected by downhole fluids such as CO_2, H_2S, and hydrocarbons, it remains stable and impermeable permanently. Being nonshrinking and able to reshape, it self-heals, eliminating any leakage through channels or microannuli, and it does not fracture.

Conclusions

Exploration Well 25/8-17 Jetta was permanently abandoned using a nonconsolidating concentrated sand plug in the reservoir interval as the primary well-barrier element. The secondary well-barrier element and a surface plug were placed inside casing, using the traditional method of a mechanical plug with cement above it. The plugging material does not undergo any chemical reactions, meaning it does not fracture, shrink, or degrade, and it is intended to be effective permanently.

The time consumption of the plugging operation was significantly less than traditional operation time for abandonment operations.

Acknowledgments

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