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

Arlid Saasen, SPE, Det norske oljeselskap ASA and the University of Stavanger; Sturla Wold, SPE, Bjørn Thore Ribesøn, SPE, Tu Nhat Tran, SPE, Det norske oljeselskap ASA; Arve Huse,* SPE, AGR Petroleum A/S; and Vidar Rygg, SPE, Ingvar Grannes, SPE, and Alf Svindland, SPE, Sandband Well Plugging A/S

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).

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 a well that was to be completed by a different rig at a later stage (Svindland 2004) was applied for temporary abandonment. In this case, repeated reversibility (in principle, an infinite number of times).

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.

\[ \frac{\Delta P}{\Delta L} = \frac{\mu v}{k} \]

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.

\[ \frac{\Delta P}{\Delta L} = \frac{150 \mu (1-\varepsilon)^2}{d_p^2 \varepsilon^3} v \]

In this equation, \(d_p\) is the sand-particle diameter and \(\varepsilon\) 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:

\[ k = \frac{\varepsilon^3}{150 (1-\varepsilon)^1} d_p \]

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 \(\varepsilon = 0.20, 0.25, 0.30, \) 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...
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 inter-particle 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. 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.

**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.
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.

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 m³ 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.
Wellsite Equipment. The slurry is premixed in a fully automatic industrial facility and transported to the rig site 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 CO₂, H₂S, 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
The authors would like to thank Det norske oljeselskap, Dana Petroleum Norway, and Bridge Energy for permission to publish this paper.

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Arlid Saasen works as a technology advisor in Det norske oljeselskap ASA in Oslo. He holds a position as adjunct professor at the department of petroleum engineering at the University of Stavanger. Saasen has previously worked as specialist in fluid technology in Statoil and as researcher in Rogaland Research (now IRIS). He has a degree in fluid mechanics from the University of Oslo, Norway and a PhD in rheology from the Technical University of Denmark, Lyngby. Saasen has been a member of SPE for more than 25 years. Sturla Wold works as Wells Technology Manager in Det norske oljeselskap ASA in Trondheim. He has previous experience as a drilling engineer, a well service engineer, and a well service supervisor from ExxonMobil and Shell. Wold has also worked with subsea systems and wellheads in Vetco Gray. He holds a Master’s degree in petroleum technology from the University of Science and Technology in Trondheim. Bjørn Thore Ribesen is currently Drilling Manager at Det norske oljeselskap ASA’s Oslo office. He was previously Drilling Manager for exploration campaigns in Det norske. In Det norske’s predecessors, N Oil Energy and DNO International, Ribesen was a senior drilling engineer. He has also served in various positions for 11 years in Schlumberger. Ribesen holds a degree in offshore engineering from University of Newcastle upon Tyne, UK. Tu Nhat Tran has been working as senior drilling engineer at Det norske oljeselskap ASA since 2008. He began his career as a drilling fluids engineer working for M-I 1993–1996. Tran has previously worked as staff engineer in Statoil 1997–2008 in various disciplines including drilling, subsea, operation and early phase. He has a Master’s degree in petroleum technology from the University of Science and Technology in Trondheim. Arve Huse works as a senior drilling engineer in Lundin Norway A/S in Oslo. He was previously Drilling Advisor and Lead Drilling Engineer for the Bredford Dolphin drilling campaign in AGR Petroleum Services. Huse has also worked with completion and production technology in Norsk Hydro for 11 years. He holds an MS degree in marine engineering from the Norwegian University of Science and Technology in Trondheim. Vidar Rygg works as a project manager for Sandaband Well Plugging. He has previously been working with Wireline Logging through various positions for Baker Atlas for 15 years in Europe, Africa, Latin America, and the US. Rygg holds an MS degree in petroleum engineering from the University of Science and Technology in Trondheim. Ingvar Grannes works as an operation manager for Sandaband Well Plugging. He has previously been working with drilling and completion for various drilling contractors internationally. Grannes holds a BS degree in drilling from the University of Stavanger. Alf Svindland is a retired petroleum engineer with an MS in petroleum engineering and an MS in metallurgy from the University of Science and Technology in Trondheim (former NTH). He gained 11 years experience in reservoir, production, drilling, IT, and economy with Phillips Petroleum Company. Svindland worked 14 years as chief engineer with Fina Exploration Norway. He directed the collaborative research and development for Fina Exploration Norway. Svindland worked 10 years as a consultant. Currently, he works as a technical adviser in Sandaband Well Plugging A/S. Svindland has been an SPE member for 30 years.