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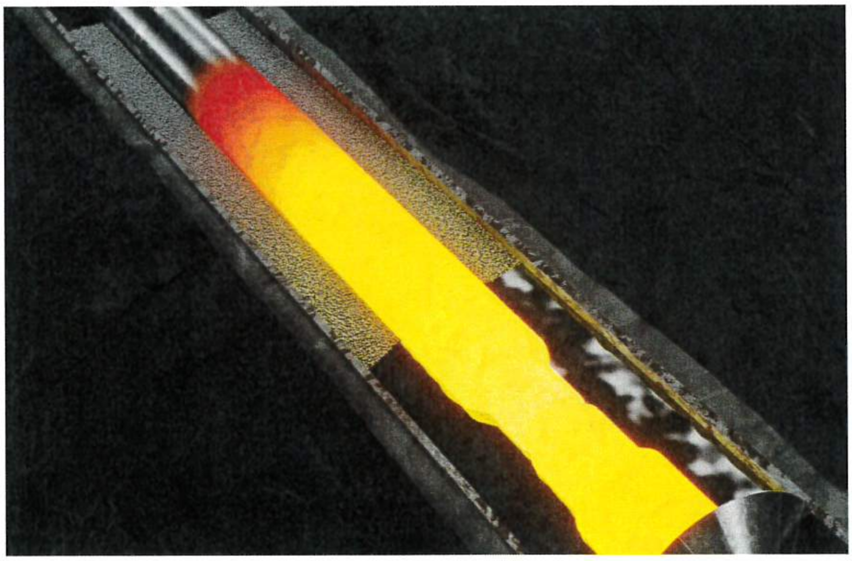
Reflekt

PETROLEUMSTILSYNET

# Knowledge acquisition on Bismuth alloy for PP&A applications




Reflekt AS
Innovasjons Park
Prof. Olav Hanssens vei 7a
4021 Stavanger

Tel. No. 92406767 (Graeme)
Tel. No. 95050040 (Mike)
Email: post@reflekt.as


| Prepared by: | Verified by: | Client approval |
|---|---|---|
| Mike Pollard | Graeme Dick | Nina Ringøen |
| MG Pollard | Graeme Dick | Nina Ringøen |

# Innholdsfortegnelse

# 1 Introduction

Reflekt has been requested by the Petroleum Safety Authority (PSA) to review current knowledge on Bismuth alloy applications for permanent plug and abandonment (PP&A) and the processes being used to qualify Bismuth alloy as a well barrier material.

The purpose of this report is knowledge acquisition. The main intention is to give a status on where the industry is and where the industry is going with respect to development, testing and use of Bismuth alloy as a well barrier material for offshore wells in Norway. Reflekt has not been asked to, nor intends to provide any opinion on the different technologies and the suitability of Bismuth alloy as a well barrier material. The descriptions of the suppliers' technologies in this report should not be interpreted as any view on the technology or the quality of the ongoing qualification processes.

In Norway there are strict requirements in regulations and standards for verification of barriers that are put in place for PP&A. These include assurance that there will be no leakage of hydrocarbon to the environment once the well has been abandoned, which is an important factor for the industry reputation. The conventional way of plugging wells is using Portland cement, and the industry has long experience with cement for drilling & well applications, including PP&A.

There is a drive in the petroleum industry to investigate new technology to reduce the cost of PP&A and improve the effectiveness of the well barriers installed. One of the technologies currently being pursued is the use of Bismuth alloys as a well barrier material. Bismuth alloy can be deployed using wireline/electric line and is therefore feasible without use of a drilling rig. Another advantage is the impermeability of some Bismuth alloys to hydrocarbons.

PP&A of wells can be complicated, and several barriers must be installed to isolate intervals with flow potential to seabed or surface. A key factor in the design is the reservoir and overburden characteristics of each individual well. In some wells, the space available to place primary and secondary barriers can be limited and conventional technologies may be difficult to apply. Bismuth alloy has the potential for shorter plug lengths compared with conventional cement plugs, provided that applicable requirements can be fulfilled.

At this time, Bismuth alloy has been qualified and used by one Operator on the NCS as a well barrier material in wells with low differential pressure and low ambient temperature.

The following companies have provided knowledge and input to this report; Aker BP, Total Energies, BiSn, Interwell, ISOL8 and Wellstrøm. SWIPA (Subsurface Well Integrity and Plug & Abandonment, a consortium of SINTEF, NORCE, NTNU. IFE and UiS, has also contributed.

Reflekt would like to thank all the people that took time to participate in the review. Publicly available information that has been referred to is included as references in section 11 of this report.

# 2 History of Bismuth alloy

Bismuth is an element that expands by about 3% as it solidifies from a molten state. The solid material is, however, brittle. Alloys of Bismuth, for example 58% Bismuth (Bi) and 42% tin (Sn) also expand on solidification and form a ductile structure that can be suitable as a well barrier material. Bismuth alloys are eutectic and melt/solidify at a relatively low temperature. Some

Bismuth alloys are impermeable to oil and gas and have a high corrosion resistance. The Bismuth alloy in liquid form has a viscosity similar to water and flows into any available spaces in the well and annuli. The high density ensures the liquid settles at the bottom of the solidified mass. These characteristics have led to Bismuth alloys being identified as a possible solution for the isolation of oil and gas in wells.

Potential applications include water shut-off, reduction or prevention of sustained casing annulus pressure (SCP) and for the use as a plug to isolate oil and gas in the reservoir or in hydrocarbon bearing formations in the overburden.

The use of Bismuth alloys for plugging wells was first considered in the 1930s and patents were issued for the concept. Technology limitations precluded their use at that time. Further patents were issued in the 1960s however it was not until the early 2000s that practical concepts were developed. Initially the application was in shutting off hydrocarbon or water production, for example for remediation of Sustained Casing Pressure, and the first Bismuth alloy plugs were run for this purpose in a gas field in Canada. Bismuth alloy plugs are deployed worldwide for different applications and have recently been used as barriers in the PP&A for the shallow zones of wells on the Valhall DP platform in Norway.

There are several consortiums in Norway that are working on optimisation of PP&A including reduction in costs and assurance of robustness of well barriers. Development of Bismuth alloy technology is a focus area for these consortiums. Research on Bismuth alloy properties and characteristics is also ongoing and is being financed by the industry and through State funding.

## 3 Relevant regulations, standards, and guidelines for PP&A

The following regulations, standards and industry guidelines are relevant for the use of Bismuth alloy plugs as barriers for PP&A in Norway. These are essential references for technology qualification, testing and field trials:

Norwegian regulations

- Facilities regulation §9 Qualification and use of new technology and new methods
- Facilities regulation §48 Well Barriers
- Activity regulation §88 Securing Wells

Industry standards and guidelines

- NORSOK D-010, "Well integrity in drilling and well operations", Revision 5, 2021
- Offshore Energy UK, Guidelines for Use of Barrier Materials in Well Decommissioning, 2022
- DNVGL-RP-A203, "Technology Qualification," Edition 2019-09 - Amended 2021-09

Any other standard applied for technology qualification should be equivalent to the Offshore Energy UK or DNV-RP-A203 standards.

## 4 Methodology for report

Reflekt has reviewed publicly available information on Bismuth plug technology and has carried out interviews with key people in the companies/institutions that are currently actively working in this area. The interviews were informal, and each participant was given the opportunity to tell their story, including the status of their work, ongoing qualification processes, and their experience to date.

The key factors covered in the interviews were:

- Technology qualification process
- Laboratory testing
- Simulation and modelling
- Field trails
- Technology threats
- Risk Management
- Barrier verification
- Ambitions for the technology

The requirements for an acceptable barrier for PP&A in a well in Norway are covered by NORSOK D-010, ref. 1. At present NORSOK D-010 table C55 – Alternative barrier materials states the requirements relevant for a well barrier including a Bismuth alloy plug.
A new EAC table shall be developed in cases where an EAC table does not exist for a specific WBE well barrier element for new use of the technology.

Since the purpose of the review is knowledge acquisition then Reflekt has tried to document factual information and avoid expressing any views on the technologies and how these are being progressed. Each company/institution was given the opportunity to comment on the sections in this report relevant to them.

## 5 Bismuth Alloy Technologies and Suppliers

The Bismuth alloy is run into the well in a solid form, either cast on the running tool or deployed as beads (pellets). Heat is applied to melt the alloy from either a pyrotechnic source or by electrical heating. The pyrotechnic source is normally thermite, typically a mixture of iron oxide and aluminium, although bismuth oxides can be used and here the reaction product provides the Bismuth alloy. The potential to supply sufficient energy to melt the Bismuth alloy electrically has been made possible due to technology developments in downhole heaters and electrical wireline cables.

As the Bismuth alloy solidifies the expansion generates radial forces that push the Bismuth alloy against the steel casing/tubing wall. This expansion and the friction forces between the Bismuth alloy and the steel provide mechanical retention and a seal at the alloy/steel interface. Bismuth alloy does not bond to steel however the equivalent shear bond strength from the expansion and friction can be significantly higher than for a cement bond. It is noted that Bismuth alloys that do bond with steel casing/tubing are under development. It is also noted that alternative alloys that contract on solidification however bond to steel, are also being investigated for different applications in wells.

There were three distinct technologies for Bismuth alloy plugs that were covered in this review:

- Bismuth alloy melted by thermite in a controlled reaction – BiSn/ISOL8
- Bismuth alloy melted by an electric heater – Wellstrøm
- Bismuth alloy generated through a thermite reaction that also melts the casing/tubing – Interwell

Each technology has features that may be appropriate for any particular application being considered. The companies all have ongoing technology qualification processes that include assessment of technology threats, and all are using third parties for facilitation and verification of the qualification process. The companies all have ambitions to develop and qualify their technologies for application for higher temperature environments, for example in PP&A of reservoir sections.

## 5.1 BiSn

BiSn supplies the Wel-lok system where Bismuth alloy is deployed as an integral part of the running tool and thermite is used to melt the alloy in place, see figure 1. BiSn has several different applications and has carried out over 400 deployments worldwide and of these 50% were for PP&A. The BiSn system was used by Aker BP for the Seal 1 and Seal 2 barriers on the wells on Valhall DP. Aker BP and BiSn have cooperated closely in the development of these barriers.

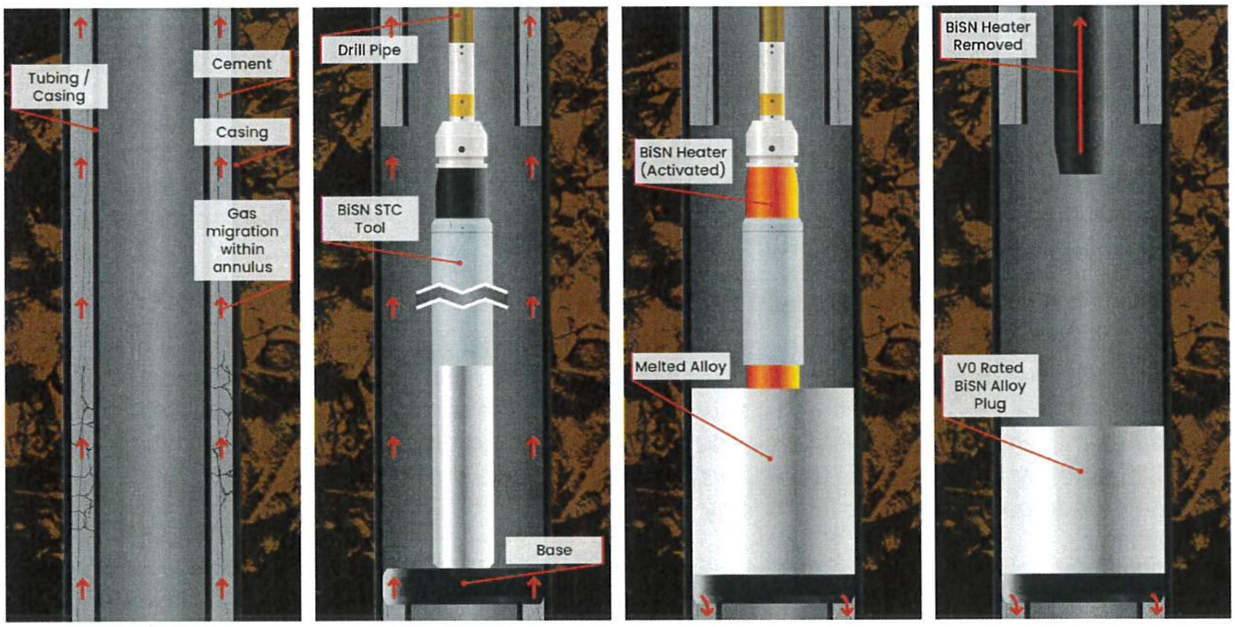



Figure 1 The stages in running and setting a Bismuth alloy plug

BiSn offers a range of Bismuth alloys with varying characteristics, in particular melting point. A particular focus area is Bismuth alloys that can be used for reservoir isolation and can therefore withstand a higher downhole temperature. BiSn has developed additives to the thermite that control the exothermic reaction, and hence the temperatures generated in the heater.

BiSn is working with Aker BP on the application of Bismuth alloy using beads/pellets instead of the alloy cast on the tool. This reduces the dimensions of the running tool significantly, in particular the weight and consequential handling challenges.

BiSn has a close cooperation with Aker BP on the technology development and qualification of bismuth alloy plugs for the Valhall DP wells. DNV was involved in the qualification process for the Bismuth alloy plugs for these applications. Failure mode assessment is part of the qualification process.

BiSn has carried out laboratory and full-scale testing on the mechanical integrity of the alloy plug by application of pressure above and below. Leak tests are also carried out to verify the integrity of the alloy plug. Laboratory testing is also used to verify corrosion resistance.

BiSn uses Queens University for finite element modeling and simulation of thermal processes. The modelling together with the laboratory tests and trials full scale trials are used to determine when the thermite heater should be extracted from the molten alloy in the well.

As part of the technology qualification process a field trial of 2 years on the Valhall DP well A30 was carried out to test the deployment and long-term integrity of the Bismuth alloy plug.

## 5.2 Interwell

Interwell uses thermite to generate sufficient heat to melt the local casing/tubing, see figure 2. Temperatures generated by the thermite reaction can reach 3700 C. The resulting molten mass segregates and then solidifies to form a barrier in the well. Bismuth oxide is used in the thermite and the resulting reaction yields Bismuth metal as a product. The thermite also contains other components that combine with the Bismuth to form the alloy for the lower part of the plug in the well. The solidified material consists of Bismuth alloy, steel, and residue from the annulus.

Interwell has deployed this technology in wells in Canada to reduce/prevent leaking gas in annuli, ref 2.

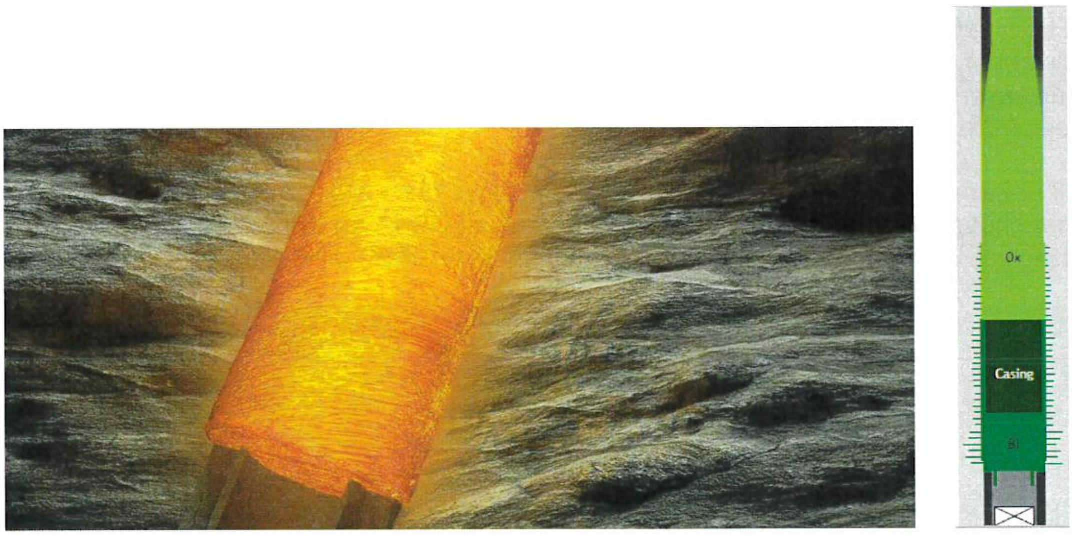



Figure 2 Thermite exothermic reaction and resulting plug, ref. 2

Interwell has established a technology qualification process based on DNV-RP-A203 for their technology and is working with several external organisations, including SINTEF, on the technology development. DNV is involved in the third-party review process and has been involved since 2003. Interwell is also working with other companies and institutions on the thermite development.

Much of the laboratory testing on test barriers is carried out at SINTEF in Trondheim and includes mechanical integrity and leak integrity. Laboratory testing is also used to verify corrosion resistance.

Interwell has designed and developed purpose-built small- and full-scale test equipment to test the system in relevant environments to support the technology development and qualification.

Interwell uses modelling, simulation, and data captured from scaled tests to help calibrate data collected from deployment in real wells to the extent of barrier success.

Full scale tests have been carried out on the behaviour of the molten mass produced from the thermite reaction and its segregation into the components as predicted. This is an important factor to demonstrate that an impermeable Bismuth alloy barrier has formed over the complete cross-sectional area.

## 5.3 ISOL8

Isol8 provides alloy in bead or cast forms and use their proprietary engineered thermite recipes to melt the alloy in-situ. They can use bismuth based expanding alloys (such as Bi-Sn and Bi-Ag) and can also use non-bismuth alloys. The creation of a metallurgical bond between the alloy and the casing is why isol8 are not restricted to bismuth alloys. isol8 originally received funding from the Scottish Government and RSRUK to fund their prototype alloy barrier technology.

In the isol8 high expansion tool the bismuth alloy is deployed in the form of beads within the running tool. When the beads are deposited a thermite heater is used to melt the Bismuth alloy and then extracted when the melting is complete, see figure 3. Isol8 has experience with deployment of their technology in offshore North Sea wells onshore UK, offshore Denmark and in salt cavern wells in the Netherlands. Several modifications were made to the technology as a result of this experience.

Isol8 uses proprietary flux recipes to bond their alloys to steel and hence will have significantly higher sheer-bond strengths than cement. isol8 is also working with alternative composite alloys that include steel aggregates to mitigate the long-term effects of creep.

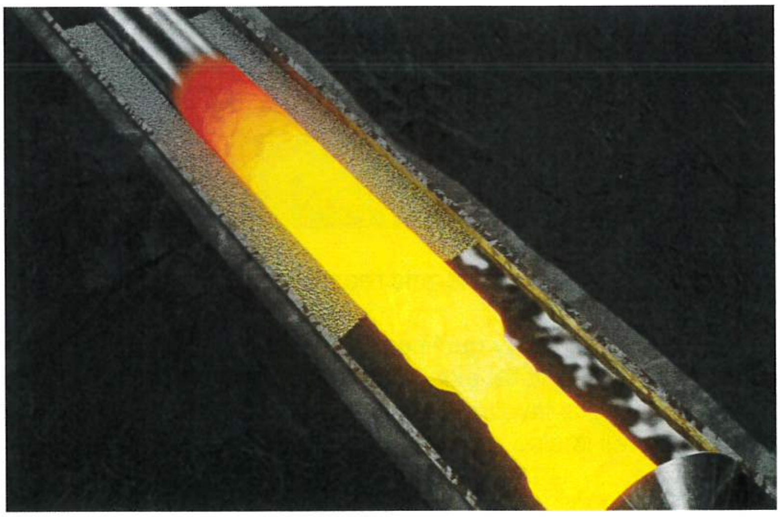


Figure 3 Thermite heater activated and melting the Bismuth alloy beads

Isol8 is carrying out a qualification process in accordance with the UKOE guidelines on barrier materials. They are following the DNV RP A203 certification process, which includes failure mode and effects analysis (FMEA).
Laboratory testing is used to verify mechanical properties and corrosion resistance.
isol8 has in-house resources for finite element modelling and multi-physics analysis of the phase change processes.

## 5.4 Wellstrøm

Wellstrøm work closely with Rawwater, who has almost 25 years' experience with Bismuth alloy applications, including the design of disposal wells for nuclear waste. Wellstrøm use their own solution, WS Bismuth, which uses a downhole electric heater to melt the Bismuth alloy, see figure 4 and 5. The tool has been designed to stringent specifications defined by TotalEnergies, the main industrial sponsor of Wellstrøm.

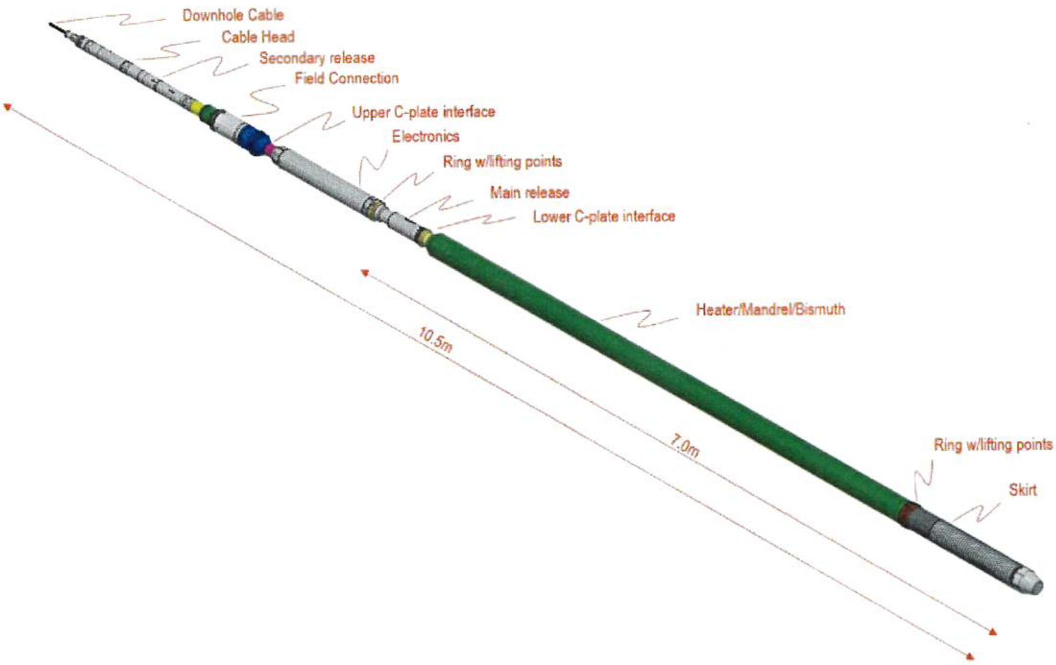



Figure 4 Wellstrøm running tool

Figure 5 The Bismuth alloy cast on the Wellstrøm running tool

The Bismuth alloy is melted around a central mandrel that is then left in the well as part of the plug, see figure 6. This gives the possibility for logging the Bismuth alloy in the annulus behind the mandrel, see middle diagram in figure 6. The electrical technology has been developed together with TotalEnergies and Aarbakke Innovation. The heater has thermal sensors installed to measure the temperature changes and provide information on when the heater should be extracted. Wellstrøm uses ribs in the running tool to provide a shoulder that then enhances the radial forces that secure the plug and provide mechanical and leak integrity. Hydraulic pressure is applied from the surface when Bismuth alloy is in a molten state to press the alloy into the cavities in the annulus and formation.

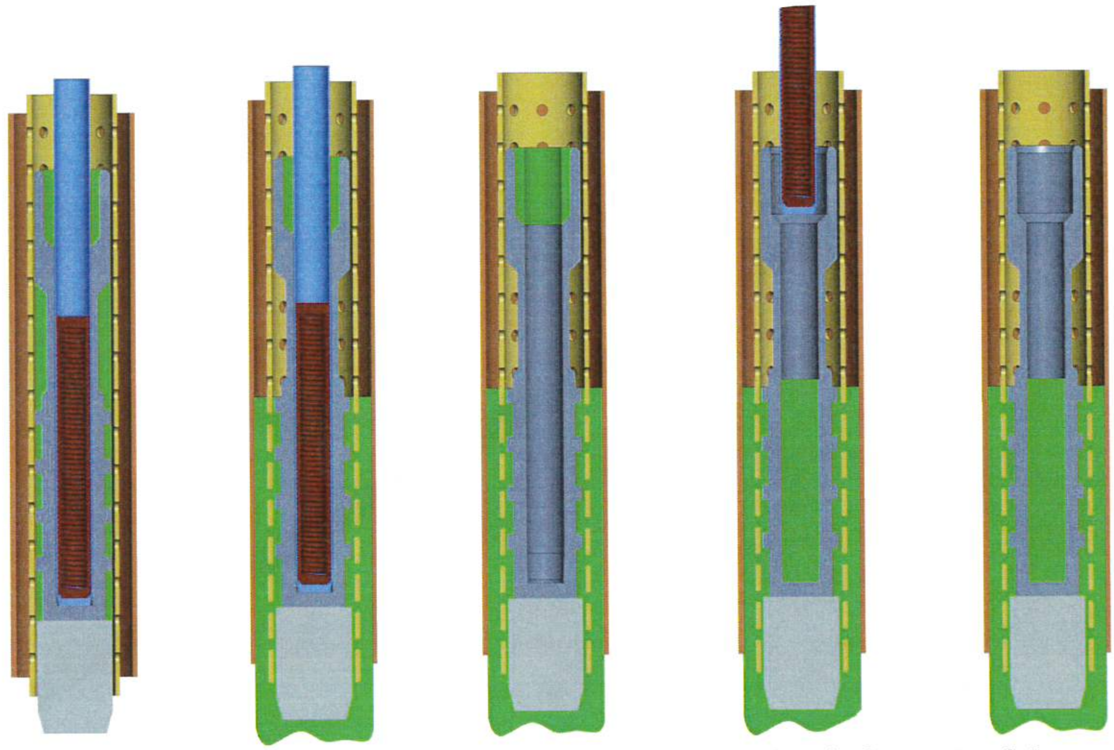


Figure 6 The 5 stages for the Wellstrøm Bismuth alloy plug deployment, ref. 3

The dark grey represents the mandrel, the green represents the Bismuth and the dark red represents the electric heater.

Wellstrøm has also investigated the possibility of setting the Bismuth alloy plugs in a drilling mud environment and has carried out tests and pilot to demonstrate that this is feasible.

Wellstrøm has established a qualification process that is being applied for different Bismuth alloys. Astrimar are involved in the assessment of the reliability of the systems and Bureau Veritas is used for third party verification of the qualification process. FMECA is carried out for verification of system reliability.

Wellstrøm has established laboratory, full-scale and pilot testing processes for the optimization of the electrical heating. The laboratory testing is an important factor in the prediction of the radial forces generated to secure the plug mechanical integrity and to verify corrosion resistance.

Laboratory testing is also important in demonstrating the potential for setting the Bismuth alloy plugs in drilling mud and with leaking gas.
Wellstrøm uses CFD modelling and testing for the thermal processes and the thermal modelling is to ensure heating is performed carefully and peak temperatures are minimized, ref. 3.

With the support of TotalEnergies, Wellstrøm has carried out field trials at the NORCE Ullrigg test facility that included testing the alloy plugs for mechanical and leak integrity, Figure 7 shows a cross section of a Bismuth alloy plug set in the casing annuli sealing fractures in the cement. The plug met the sealing performance requirements set by TotalEnergies for its intended application in the Danish North Sea.

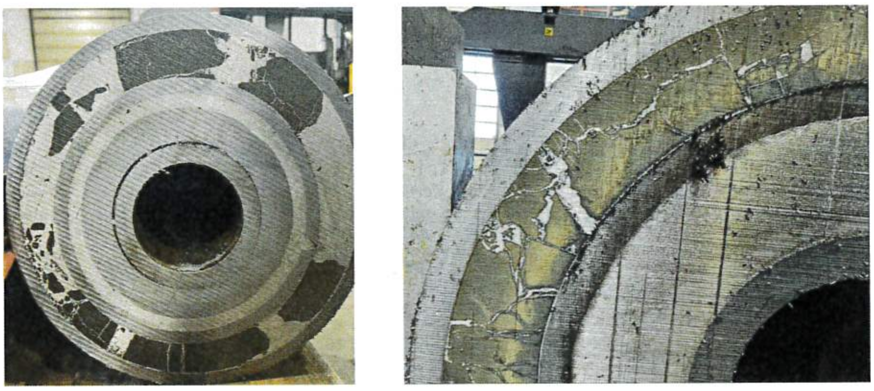


Figure 7 Full-scale demonstration pilot, January 2023, ref. 4

## 6 Operator Involvement

There are several operators around the world that have used Bismuth alloy for shutting off hydrocarbons including in PP&A applications. The suppliers are responsible for qualification of their technologies, including qualification of the barrier material. It is the operator in Norway that is ultimately responsible for assuring that the Bismuth alloy plug is qualified as an acceptable well barrier for PP&A.

It is also the operator's responsibility to verify the barrier in accordance with NORSOK D-010 and ensure the qualification process meets the requirements in the Facilities Regulations. The qualification or testing shall demonstrate that applicable requirements in the regulations can be fulfilled, e.g., securing of wells for eternity and verification according to best practises and accepted standards and norms.

It is essential that there is close cooperation between the operator and the supplier on PP&A applications. Each field and well has its own unique features and can have significantly different challenges to an acceptable PP&A. This means that any technology that has been through the supplier's own qualification process will need to be qualified for the specific application by the operator. In some cases, the supplier's qualification process and actual experience may result in a relatively simple application to a specific case. In other cases, a significant amount of work may be required.

### 6.1 Aker BP

Aker BP recognised challenges for the PP&A of the Valhall DP wells, including multiple zones to be isolated and the potential for gas to surface in the annulus between the conductor and the surface casing. In one of the zones there was a limited vertical distance to establish primary and secondary barriers, hence conventional cement barriers were difficult to install and verify.

Figure 8 Installing a Bismuth alloy plug on Valhall DP

Aker BP decided to progress actively the use of Bismuth alloy plugs for PP&A and established a cooperation agreement with BiSn. The focus was the Seal 1 (environmental plug) and Seal 2 (shallowest zone with potential for hydrocarbon flow) barriers where the ambient temperature at these depths was between 30° C and 40° C and there were tried and tested Bismuth alloys suitable for these temperatures. The proposed plugs in the 'Seal 1' application would be 30" in diameter and required over 10 tons of Bismuth alloy. The 'Seal 1' barrier is set within the conductor hence sealing the entire well bore. A key factor for Aker BP was the assurance of clean casing where the alloy plug was deployed, and special tools were developed for this purpose. Bismuth alloy plugs were set and verified for 'Seal 1' barriers in 30 wells and for 'Seal 2' barriers in5 wells. In the 'Seal 2' barrier the Bismuth plug was the primary barrier, and a cement plug was the secondary barrier. Aker BP emphasized the advantages (in their view) of using a combination of Bismuth alloy and cement in a PP&A application, with the different materials characteristics complementing each other, ref. 5.

Aker BP worked closely with BiSn to qualify the technology for the Valhall DP application. Technical authorities in Aker BP were closely involved in the technology development process. As part of this process eight full scale tests were carried out for the 'Seal 1' and 'Seal 2' applications.

A field trial was set up in the A30 well on Valhall DP and the well was monitored for close to two years, and the Bismuth alloy plug was then drilled out.

Aker BP is currently working with BiSn on PP&A on the Hod wells and in particular the use of Bismuth alloy beads/pellets instead of casting the alloy on the running tool, see figure 9.

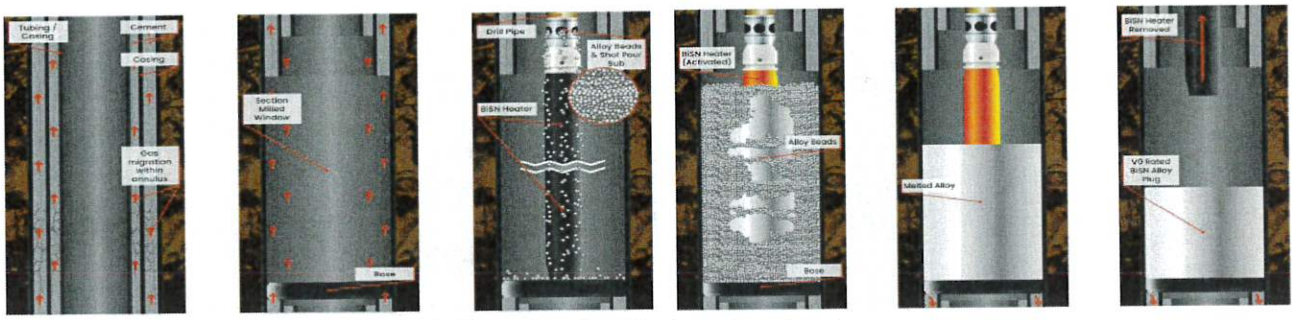



Figure 9 Bismuth alloy deployed as beads

Aker BP is following the development of Bismuth alloy technology with a view to PP&A of the deeper sections where the temperatures are higher and is following progress from all suppliers.

Aker BP has also been actively sharing their experience with Bismuth alloy technology for PP&A.

## 6.2 TotalEnergies

The initial interest in Bismuth alloy was in the Mærsk Oil organisation in Denmark from ca. 2016 and the first application was intended for the Tyra field to repair leaking packers with a BiSn Wel-lok system, however delays to the testing program meant that the opportunity for an offshore trial was missed for that campaign. TotalEnergies later financed further testing for the BiSn Wel-Lok system in 2018 and two attempts with the ISOL8 system in onshore gas wells operated by Third Energy Yorkshire, UK in 2021, plus also a further onshore trial in an onshore salt producing well operated by Nobian near Enschede in The Netherlands in 2022.

TotalEnergies is now working closely with Wellstrøm, to develop electrical heating of the alloy downhole. TotalEnergies is also closely involved in the technology qualification and the specific threats and risks associated with their wells and intends to qualify the technology to DNV RP A-203, and OEUK requirements.

TotalEnergies is still following the development of all the Bismuth alloy technologies developed by all the major vendors and reviewing the potential for their wells. They are working towards the possibility of using Bismuth technology for a PP&A campaign in Denmark in 2023 and beyond, and have set targets for PP&A technology, performance, and verification. TotalEnergies is focused on learning and experience transfer and is actively involved in PP&A Forums and in papers and articles on their experience including at SPE conferences.

# 7 Ongoing Research

The focus on the future requirements for PP&A has led to research funding for new technologies including Bismuth alloys. Research is ongoing in investigation into different alloy compositions and characteristics.

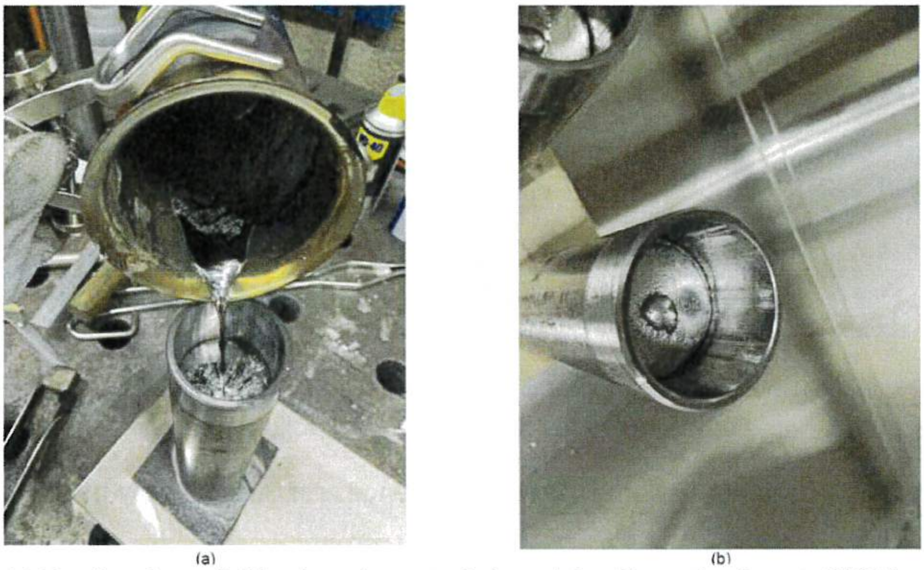



Figure 10 Testing the solidification characteristics of the Bismuth alloy at SWIPA, ref. 6

SWIPA is funded from Research Council Norway and industry. SWIPA has two PhD students and a post-doctorate working full time on research into Bismuth alloys for PP&A applications.

SWIPA is investigating the radial and axial forces generated during the solidification process and creep which may affect the integrity of any Bismuth alloy plug. An important factor in this work is the mechanical bonding between the Bismuth alloy and the steel casing/tubing and the effect of any contaminants. SWIPA is carrying out tests on the mechanical integrity of the plug and the leak integrity. This includes verification of the solidification process with a continuous gas stream through the plug as it solidifies.

Creep, and other aging-effects, is an important focus area for SWIPA, and work is ongoing to understand the behaviour of the Bismuth alloy plug in a long-term perspective. While most of the research work at SWIPA is associated with PP&A, the potential for other applications, e.g., water and gas shut-off and other well integrity applications are recognised.

## 8 Technology Threats

Qualification of bismuth alloy as a well barrier material needs to be viewed in an 'eternity' perspective, and threats associated with the technology and its application need to be assessed in this context. The following threats were discussed as part of the review.

- **Plug length:** The potential for possible leakage paths around the well barrier element through the formation. This is particularly important since the Bismuth alloy plug length often used (1-2 meters) is less than a conventional cement plug length (30 – 50 meters), ref 1.

- **Corrosion:** Bismuth alloy has a high corrosion resistance however tests are required to ensure the alloy can withstand specific corrosion factors for each application, e.g., $CO_2$, $H_2S$, pH

- **Creep:** Metal alloys are subjected to creep over time as the internal structure of the alloy changes. Metal alloys with a low melt/solidification temperature can be subjected to creep at the ambient temperature in a well. Assurance has to be provided that creep will not affect the integrity of the barrier over time.

- **Stress relaxation:** Stress relaxation in the plug and the casing/tubing can affect the forces that hold the plug mechanically in place. Assurance has to be provided that stress relaxation will not affect the integrity of the barrier over time.

- **Contamination:** Contamination of the plug may lead to micro-annuli that could provide a leak path through the plug. The acceptable level of contamination needs to be assessed in the technology development process.

- **Cleanliness of the casing/tubing:** The cleanliness of the casing/tubing the Bismuth alloy will be in contact with is important to prevent leak paths at the alloy/steel interface, e.g. debris, corrosion products, old cement etc. Methods for cleaning and standards for cleanliness need to be assessed as part of the technology development.

- **Distribution of radial and axial expansion forces:** The radial forces generated in the solidification/expansion process are a key factor in assuring the mechanical integrity of the plug. If the plug is allowed to expand axially, the radial forces will be smaller, perhaps compromising the seal to the tubular. A key factor is the plug length/diameter ratio.

- **Medium surrounding the plug:** The material in the annulus will influence the heat transfer from the heater to the surrounding formation. Water is a good conductor and will allow significant transfer of energy, cement acts more as an insulator and will prevent heat transfer. This is critical to ensure sufficient energy is applied to fully melt the Bismuth alloy.

- **Effect of temperature on casing/cement/formation in the barrier in the well:** Thermite can generate temperatures that can melt steel casing/tubing and heat up the surrounding formation. The technology development process needs to cover whether the high temperature can affect the surroundings and compromise the integrity of the barrier.

- **Effect of differences in thermal expansion coefficients between casing and bismuth alloys:** Steel and Bismuth alloy have different coefficients of expansion therefore will shrink differently when the plug cools. The technology development process needs to ensure that this difference cannot affect the integrity of the barrier.

- **Brittleness of the Bismuth alloy:** Bismuth alloys need to be tested to ensure a stable ductile plug can be formed. Some Bismuth alloys may be brittle and/or can be subjected to holes that form during solidification. These can provide a leak-path through the plug.

Reflekt's impression from the interviews is that the companies involved are aware of these threats and have included these in the technology development and qualification processes they have in place.

## 9 Risk management

There are specific hazards associated with the Bismuth alloy technologies that need to be considered in the risk management process. These include both safety and working environment hazards. The risk management processes in each company should address these hazards throughout the manufacture, transport/logistics, deployment, operation, and verification.

Thermite used for melting of the Bismuth alloy, is a pyrotechnic material that generates significant energy and a high temperature when the exothermic reaction is initiated. Precautions are required to ensure the reaction is not started before the tool is deployed. Normally the reaction is initiated with an electric current generated from the surface.

Bismuth alloy could be deployed as a cast on the running tool, and this creates challenges with material handling since the weight could be over 10 tons depending on the application. Deployment of the alloy in bead form also creates material handling risks that need to be managed.

## 10 Discussion

The technology readiness level (TRL) reached for the qualification of each technology has not been noted in this report for two reasons. Firstly, the level achieved is a dynamic process and is only relevant at the time of issue of this report. Secondly, each technology must be seen in the context of its use and its suitability for well characteristics, for example temperature, deviation, depths etc., and be qualified for this specific application.

The operators and suppliers involved in the review have established processes for technology qualification and for failure and reliability analyses and third parties are engaged to facilitate the processes and carry out independent reviews. It is the responsibility of the Operators to document the fulfilment and completion of relevant qualification processes to be able to demonstrate to the authorities as part of any consent process for PP&A.

The operators and suppliers have set up laboratory and field tests as part of the technology development process and this is also important in demonstrating that the applications will meet the required standards. The operators and suppliers are also using modern simulation and modelling techniques in the technology development and for optimization of operational parameters.

The industry considers that there is a potential for the use of Bismuth alloy technology for shutting off hydrocarbons and water, and for the PP&A of wells. Specific challenges in individual fields and wells may make conventional techniques difficult to deploy and achieve the PP&A objectives, hence other technologies need to be developed. Bismuth alloy may be a suitable alternative.

There are uncertainties with the behaviour of the bismuth alloys over time with respect to permanent plugging and the eternity perspective and further work is required in this area. There is still significant work to be done before the application of Bismuth alloy as a well barrier material for deeper wells with higher temperatures and/or differential pressures.

The development of Bismuth alloy technology for PP&A must always keep a focus on the ultimate objective of a barrier that meets the NORSOK D-010 requirements. It is the responsibility of the operator to ensure that the overall technology qualification process for the specific application meets the required standards before actual deployment.

The industry should consider developing a well barrier element acceptance criteria (EAC) table for Bismuth alloy plugs to be included in NORSOK D-010, ref. 1. The process for establishing this table should follow a similar process to the development of the EAC table for Perforate, wash, cement (PWC). Each operator that uses Bismuth alloys in well barriers must develop their own EAC for the use of Bismuth alloys until a common industry EAC is included in NORSOK D-010.

There are several ongoing technology developments associated with the development of Bismuth alloy as a well barrier material that may provide new solutions to existing problems associated with well including PP&A, for example:

- development of liquid thermite,
- use of thermite to melt casing as an alternative to section milling,
- use of thermite heaters to stimulate shale creep,
- development of Bismuth alloys that bond to steel,
- development of other metal alloys that bond to steel.

It is noted that there are several consortiums working on development of PP&A technology, there is also an active PP&A Forum where operators actively share knowledge and experience. The suppliers and operators contribute to knowledge sharing through articles, papers, and presentations at Drilling and Well conferences, e.g., SPE (Society of Petroleum Engineers) Conferences.

It is apparent from the discussions with the different suppliers that there is some reluctance to share information, each protecting what they consider to be a technological advantage, and this is understandable. Knowledge of bismuth alloy as a well barrier material is in an early stage of development compared to knowledge of the characteristics of cement, and there is much that is still uncertain. There seems to be room for more collaboration and cooperation in characterization of bismuth alloys and being more open with the results of lab testing and field trials where this is directly relevant to the qualification of the technology as a well barrier material. This then allows for verification of testing methods and results. Improved collaboration and cooperation should contribute to realizing the potential of Bismuth alloy technology in PP&A applications.

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