University of Stavanger

**FACULTY OF SCIENCE AND TECHNOLOGY**

# MASTER'S THESIS

| | |
|---|---|
| Study program/Specialization:<br><br>Petroleum Engineering,<br>Drilling Technology | Spring Semester, 2019<br><br>Open |
| Author:<br><br>Trine Knutsen | Trine Knutsen<br>……………………………………<br>(signature of author) |

Faculty Supervisor: Kjell Kåre Fjelde

External Supervisors: Egil Thorstensen (Aker BP), Kjetil Vadset (Aker BP)

Title of master`s thesis:

**A Novel Approach to Qualifying Bismuth as a Barrier Material**

Credits: 30

Key words:
- P&A
- Bismuth
- Thermite
- Technology Qualification
- NORSOK D-010
- Aker BP
- BiSN

Total Pages: 63

Stavanger, 12/06/2019

Title page for Master's Thesis
Faculty of Science and Technology

# A Novel Approach to Qualifying Bismuth as a Barrier Material

*Trine Knutsen*
*University of Stavanger*
*Spring 2019*

# Abstract

The barrier material conventionally used for permanent P&A is cement. Since two barriers are a requirement to properly isolate potentially flowing formations, the reliability of the barriers could be enhanced by introducing a second barrier material. Application of two distinct barrier materials with differing sealing and failure mechanisms will promote a higher level of independence between the barriers.

Qualification of bismuth as a barrier material provides operators with an alternative to cement. Bismuth is a metal with such unique characteristics making it tailor-made for P&A applications. For instance, the required plug length is significantly reduced compared to the current length requirements for cement plugs. Thereby, costs are reduced. This thesis defines why bismuth is such a suitable barrier material for permanent P&A, in addition to addressing risk related issues.

Aker BP has together with BiSN initiated a verification process to verify bismuth as a barrier material inside cased hole. BiSN is utilizing thermite technology to melt a bismuth based alloy downhole, creating a fully impermeable metal-to-metal sealing plug after solidification.

The verification process presented in this thesis targets a bismuth plug sealing inside a 20" casing, without having to retrieve the 13 3/8" casing. Full scale testing was performed with various learnings to optimize the final design parameters, before conducting a field installation. The field installation, thoroughly described step by step in this thesis, was performed to verify the bismuth plug in an offshore well. This is the worlds first bismuth P&A barrier plug ever installed, and by far the largest considering its geometry.

Based on the results presented in this thesis, a proposed EAC-table for a bismuth plug has been produced to describe the function, necessary requirements and verification for future bismuth plugs.

# Acknowledgements

First and foremost, I would like to thank my supervisors in Aker BP, Kjetil Vadset and Egil Thorstensen, for providing me with this interesting case and including me in their work. Allowing me to take part in this project early, particularly towards the field installation, is very much appreciated. Your support and guidance in addition to countless meetings and discussions throughout the semester are highly valued.

Further, I would like to give a special thanks to Martin Straume, in addition to Laurent Delabroy and the whole Valhall DP P&A-team for their guidance, encouragement and sharing of expertise. By being a part of the P&A-team in Aker BP, I have earned valuable experience and received opportunities which I am grateful for.

Thank you to Michael Price in BiSN for providing me with helpful information and taking the time to answer an endless amount of questions during this semester.

Finally, thank you to my supervisor at the University of Stavanger, Kjell Kåre Fjelde, for your encouragement, assistance and thorough feedback.

# Table of Contents

**Abstract** **i**

**Acknowledgements** **ii**

**Table of Contents** **iv**

**List of Figures** **v**

**List of Tables** **vi**

**Abbreviations** **vii**

**1 Introduction** **1**
1.1 Background and Purpose of Thesis . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 1

**2 Plug & Abandonment** **3**
2.1 P&A in Short . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 3
2.2 Methods and Related Challenges . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 4
2.2.1 P&A of a Fictitious well . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 4

**3 Well Barriers and Barrier Requirements** **8**
3.1 Regulations and Guidelines . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 8
3.2 NORSOK D-010 . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 8
3.2.1 Well Barrier Requirements . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 9
3.2.2 Verification of Well Barriers . . . . . . . . . . . . . . . . . . . . . . . . . . . . 10
3.2.3 Well Barrier Element Acceptance Criteria . . . . . . . . . . . . . . . . . . . . . 11
3.3 Cement . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 11
3.4 UK Guidelines on Qualification of Materials . . . . . . . . . . . . . . . . . . . . . . . 12
3.4.1 Functional Requirements of Permanent Barriers . . . . . . . . . . . . . . . . . . 13
3.4.2 Potential Failure Modes . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 13

**4 Evolution of Barrier Length Requirements** **15**
4.1 Length Requirements for Cement Plugs . . . . . . . . . . . . . . . . . . . . . . . . . . 15

**5 Bismuth as a WBE for Permanent P&A** **17**
5.1 What is Bismuth? . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 17
5.1.1 Why is Bismuth Suitable for P&A? . . . . . . . . . . . . . . . . . . . . . . . . . 18

5.2 Function and Applications . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 21
5.3 Design, Construction and Selection . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 21
5.3.1 Bismuth Alloy . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 21
5.3.2 Thermite Heater . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 23

**6 Full Scale Testing of Bismuth as a WBE** **25**
6.1 13 3/8” x 20” Test Program . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 26
6.1.1 Test Vessel Description . . . . . . . . . . . . . . . . . . . . . . . . . . . . 26
6.1.2 Testing and Test Requirements . . . . . . . . . . . . . . . . . . . . . . . . 29
6.1.3 Risks and Challenges . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 30
6.1.4 Design factors . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 31
6.1.5 Final Design Parameters . . . . . . . . . . . . . . . . . . . . . . . . . . . . 37

**7 Field Verification on Valhall DP** **39**
7.1 Valhall . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 39
7.1.1 Seal 2 . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 41
7.2 Installation of a Bismuth Plug . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 42
7.2.1 A-30: Candidate Well Pre-rig Status . . . . . . . . . . . . . . . . . . . . . 43
7.2.2 Operational Steps . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 44
7.2.3 Verification of Installed Bismuth Plug . . . . . . . . . . . . . . . . . . . . . 54

**8 Defining critical risk related issues** **55**
8.1 Failure Modes of a Bismuth Plug . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 55
8.2 Failure Mechanisms and Root Causes . . . . . . . . . . . . . . . . . . . . . . . . . . . 55
8.2.1 Pre-Installation/Design Phase . . . . . . . . . . . . . . . . . . . . . . . . . 56
8.2.2 Operational Phase . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 57
8.2.3 Post-Placement Phase . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 58

**9 Conclusion** **59**
9.1 Summary of Qualification Process . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 59
9.2 Proposed EAC-Table for a Bismuth Plug . . . . . . . . . . . . . . . . . . . . . . . . . 60
9.3 Recommendations for Future Work . . . . . . . . . . . . . . . . . . . . . . . . . . . . 61

**Bibliography** **62**

# List of Figures


1.1 Roadmap for new P&A technologies . . . 1

2.1 Permanent P&A of a fictitious well . . . 5

3.1 Well barrier requirement and example . . . 10
3.2 Qualification process for new technology . . . 13

5.1 Bismuth plug length/diameter ratio vs pressure capability . . . 22
5.2 Thermite heater burning . . . 24

6.1 Cross section and saw cut section of full scale bismuth plug . . . 25
6.2 Test vessel . . . 27
6.3 Setup for heater removal and thermocouple locations . . . 28
6.4 Test vessel bubble traps . . . 30
6.5 Cross section of bismuth plug using BiSN-95 . . . 32
6.6 Top of bismuth plug . . . 32
6.7 Temperature gradient during test . . . 33
6.8 Final tool design and dimensions . . . 34
6.9 Heater-burn through . . . 35
6.10 Heater bottom modification . . . 35
6.11 Potential leak paths in silt lines along interface between alloy and casing . . . 36
6.12 Test vessel when heater is pulled . . . 38

7.1 Valhall location . . . 39
7.2 Valhall platform arrangement and permeable zones . . . 40
7.3 Valhall DP Seal 2 . . . 41
7.4 Pre-rig status of candidate well . . . 43
7.5 Stepwise operational well status schematics . . . 45
7.6 Leaking bridge plug with gauge hanger . . . 46
7.7 Special designed underreamer (before and after) . . . 47
7.8 Tornar tool (magnet and junk basket) . . . 48
7.9 Downhole camera . . . 49
7.10 Downhole camera: Top of sand . . . 50
7.11 Bismuth plug assembly . . . 51
7.12 Temperature monitoring above bismuth plug . . . 52
7.13 Downhole camera: Section milled window . . . 53
7.14 Downhole camera: Bismuth plug . . . 53

# List of Tables


3.1 NORSOK D-010 EAC table description . . . . . 11

4.1 Evolution of barrier length requirements . . . . . 15

9.1 Proposed EAC-table for a bismuth plug . . . . . 60

# Abbreviations

| | |
|---|---|
| BOP | Blow Out Preventer |
| CFD | Computational Fluid Dynamics |
| CRA | Corrosion Resistant Alloy |
| DP | Drilling Platform |
| DPZ | Distinct Permeable Zone |
| EAC | Element Acceptance Criteria |
| FEA | Finite Element Analysis |
| HPHT | High Pressure High Temperature |
| HSE | Health, Safety and Environment |
| ID | Inner Diameter |
| ISW | Inhibited Seawater |
| LME | Liquid Metal Embrittlement |
| NCS | Norwegian Continental Shelf |
| OD | Outer Diameter |
| OGTC | Oil & Gas Technology Centre |
| OHGP | Open Hole Gravel Pack |
| PAF | Plug and Abandonment Forum |
| PSA | Petroleum Safety Authority |
| P&A | Plug & Abandonment |
| PWC | Perforate, Wash and Cement |
| RKB | Rotary Kelly Bushing |
| SCP | Sustained Casing Pressure |
| SG | Specific Gravity |
| TOC | Top of Cement |
| WBE | Well Barrier Element |
| WBM | Water Based Mud |
| WL | Wireline |

# Chapter 1

# Introduction

## 1.1 Background and Purpose of Thesis

Plug and Abandonment (P&A) of wells is known as a time consuming and expensive operation. Thus, making P&A more cost-effective is a shared goal for the industry, and there is a need for developing new technologies for P&A. In 2015 the *Roadmap for New P&A Technologies*, shown in Fig. 1.1, was presented by Martin Straume at the annual Norwegian Plug and Abandonment Forum (PAF). This roadmap highlights focus areas and future technologies required to optimize and reduce costs in P&A in the subsequent years [Straume, 2015]. One of the focus areas includes finding alternatives to cement, which is conventionally used for well barrier plugs.

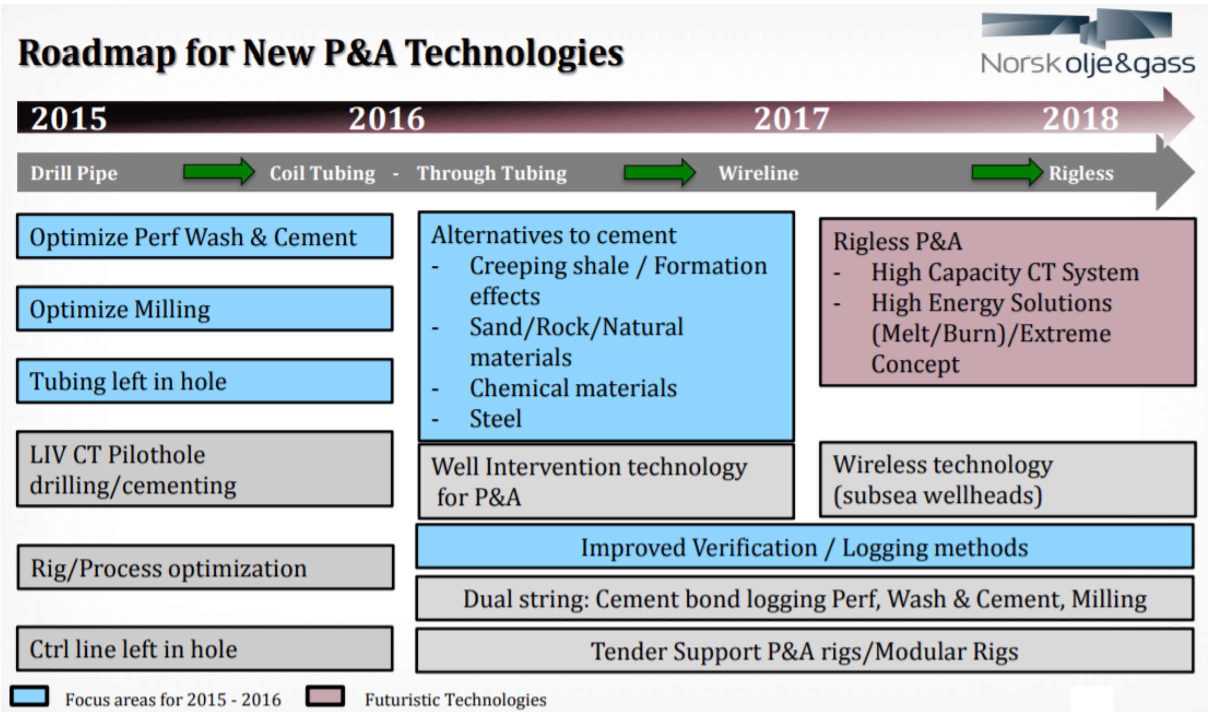



**Figure 1.1:** Roadmap for New P&A Technologies presented in 2015. [Straume, 2015]

Simultaneously, in addition to cost savings, the industry has been looking at ways to develop new non-cementitious alternative barrier materials in order to promote a higher level of independence between individual well barriers. This independence is one of the requirements set by the Norwegian Petroleum Safety Authority (PSA). Placing both primary and secondary barriers using the same material is weakening this independence. Hence, applying two distinct well barrier materials with differing failure and sealing mechanisms for primary and secondary barriers is likely to enhance the reliability of the barriers preventing unwanted flow of hydrocarbons.

Bismuth is introduced as an alternative barrier material to cement. In liquid form, bismuth can flow like water, and in solid form, it is practically impermeable, and resistant to corrosion. Moreover, and this is an important property for P&A applications, it also expands upon solidification [Carragher and Fulks, 2018b]. Consequently, when placing a barrier plug consisting exclusively of impermeable metal, the barrier length can be significantly reduced compared to cement plugs. As the barrier plug is shortened, the time frame of the preparatory work (e.g. milling) needed in advance of an installation is cut down, and costs are reduced.

Bismuth plugs are installed by melting a bismuth-based alloy in-situ downhole, using thermite to generate heat. The company BiSN Oil Tools has developed a proprietary method to burn thermite in a controlled and safe manner. This process is used to melt the bismuth alloy downhole and then let it solidify to form a pressure-sealing plug [Carragher and Fulks, 2018a].

Before implementing a bismuth plug as a barrier element during P&A operations, both the bismuth material and barrier design need to undergo a verification process. Qualifying and documenting necessary requirements and standards when developing new well barrier materials is considered an industry responsibility. To qualify bismuth as a barrier material for permanent P&A, Aker BP initiated a verification process in 2017. In cooperation with BiSN, Aker BP has completed an extensive verification process including both full scale yard-testing and field verification of the bismuth plug inside a 20" casing. Full scale testing was performed to evaluate design parameters such as the bismuth based alloy, thermite mixture, thermite heater/vessel and choice of well fluid. In September 2018 a bismuth plug was installed on the Valhall Drilling Platform (DP) to verify the bismuth plug in a real offshore well.

The objective of this thesis is to describe bismuth as a barrier element for permanent P&A and share the experiences and learnings obtained from the full scale testing and field installation in the verification process; evaluation of design parameters in the full scale test program will be described, and the field installation and verification will be thoroughly presented step by step. Furthermore, a NORSOK D-010-like proposed barrier Element Acceptance Criteria (EAC) table for the bismuth plug has been created for future applications.

During my master studies, I was part of the Aker BP P&A team, dwhich allowed me to be exposed to, and involved in the planning of the offshore installation of the bismuth plug. I was also offshore acting as P&A-engineer overseeing the successful installation of what is, to date, the largest P&A bismuth plug installation in the world.

# Chapter 2

# Plug & Abandonment

## 2.1 P&A in Short

Abandonment of a wellbore implies isolating all inflow sources by establishing well barriers. P&A can be categorized as temporary or permanent. Temporary P&A means the well will be re-entered, and the well barriers shall be designed for the planned abandonment period [NORSOK, 2013]. On the contrary, permanent P&A covers abandonment of a wellbore where the time perspective is eternal, and the well will not be operated or entered again [NORSOK, 2013].

Before abandoning a well permanently, the impermeable formation located above the reservoir shall be restored to prevent unwanted fluid flow from the reservoir, meaning an impermeable well barrier will be installed within the depth interval of the impermeable formation. In this thesis, the impermeable formation is referred to as a seal. To ensure the reservoir is properly abandoned, two well barriers are installed. The primary well barrier is the first barrier isolating and preventing fluid flow from the reservoir, while the secondary barrier is a back-up to the primary barrier [NORSOK, 2013]. In addition to the producing reservoir zone, potential reservoirs along the wellbore need to be isolated in the same way [NORSOK, 2013]. Requirements for the well barriers are described in chapter 3.

UK Oil & Gas divides the operational sequence of permanent P&A into 3 phases. Phase 1 is ”Reservoir Abandonment”, covering only abandonment of the reservoir. Phase 2, ”Intermediate Abandonment”, includes abandonment of any additional zones or formations with flow potential. This phase often requires operations like casing retrieval or milling of casings to ensure the seals are properly restored. Finally, Phase 3 ”Wellhead and Conductor Removal” starts after no additional plugging is required. After the third phase, no additional abandonment activities are needed [Oil & Gas UK, 2015a]. Phase 2 (”Intermediate Abandonment”) is the most time-consuming phase. The time it takes to complete Phase 2 is dependent on the number of permeable and potential reservoir zones where seals need to be restored, in addition to the complexity of the well. The complexity of a well in phase 2 is affected by Sustained Casing Pressure (SCP), restricted access to casing due to subsidence, shallow gas, well inclination, and insufficient cement bonding outside casing [Oil & Gas UK, 2015a].

## 2.2 Methods and Related Challenges

P&A is a time consuming and expensive activity without any resulting profits. Therefore it is beneficial to make the operations productive and cost-effective. A well can be abandoned using different approaches and methods to install the different barriers. The aim is to establish well barriers sealing both vertically and horizontally [NORSOK, 2013]. To ensure the barrier is sealing horizontally, access to the outermost casing is needed to verify if there is circumferential bonding behind the casing to the sealing formation. Furthermore, the barriers should be set as deep as possible in the sealing formation. If a barrier is set too shallow, the formation strength will at some point become too weak to withstand the maximum anticipated pressure, resulting in a fractured formation and risk of leakage. The minimum setting depth of a barrier can be referred to as *critical depth*. At critical depth, the formation strength is equal to or larger than the expected eternal pressure from below [BP, 2013]. Each permeable zone with flow potential has its own defined critical depth, based on formation strength of the seal, and pore pressure and fluid in the permeable formation.

### 2.2.1 P&A of a Fictitious well

A fictitious well, illustrated in Fig. 2.1, will be used to demonstrate some of the methods used to install and establish permanent P&A well barriers. The example is developed based on work experience gained at Aker BP. Fig. 2.1 illustrates the well after all seals are restored and P&A of the well is completed. This well has its wellhead on a platform, and consists of a 30” conductor, 20” surface casing, 13 3/8” intermediate casing, 9 5/8” production casing, and a 5” production liner. The conductor is driven downhole, without being cemented in place. Both 20” casing and 13 3/8” casing are cemented to surface, while the Top of Cement (TOC) of the 9 5/8” casing is far below seabed. The cemented liner is perforated and the production packer is set just above the liner hanger.

This well has two potential sources of inflow in addition to the producing reservoir. All three are here referred to as a Distinct Permeable Zone (DPZ), identified as DPZ 1, 2 and 3, with correlating seals 1, 2 and 3. The producing reservoir is the lowermost zone, DPZ 3. As noted from the well schematic, all barrier plugs are installed below its critical depth, meaning all three seals are restored respectively with two barriers. In addition, a single barrier will be set in the top of a well, called an ”open hole to surface plug”. The ”open hole to surface plug” are set to seal and prevent flow to surface after casings are retrieved [NORSOK, 2013]. In seals 1-3, where two barriers are needed, an extra long cement plug will be set as a combined cement plug to establish both primary and secondary barriers and simultaneously save time.

Some preparatory work has been done before the seals are restored. In this case, the preparatory work includes killing the well, installing a bridge plug in the bottom of the tubing and cutting the tubing above the production packer using wireline (WL), and pulling the tubing by using a rig. From this point, all work will be performed through a rig.

Restoring seal 3 will be a part of Phase 1, defined by UK Oil & Gas. Seals 1 and 2, and the open hole to surface plug will be a part of Phase 2 in the abandonment operation. After all barriers are set, the well will be ready for Phase 3, where the wellhead, conductor and 20" surface casing are removed.

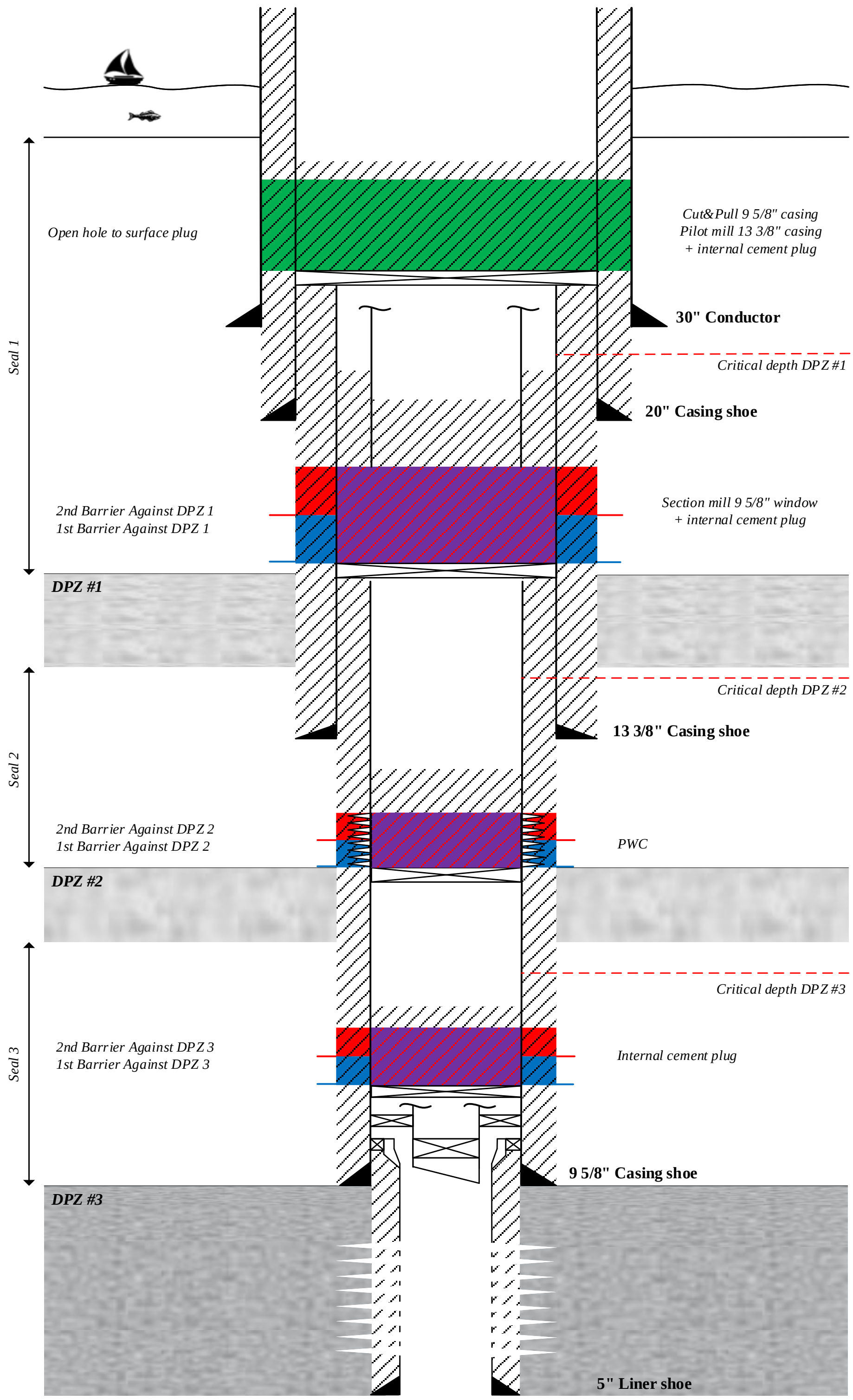



**Figure 2.1:** Permanent P&A of a fictitious well. Blue = primary barrier, red = secondary barrier, purple = combined primary and secondary, green = open hole to surface plug.

**Seal 3: Internal cement plug**

First, the 9 5/8" casing is cleaned out and logged to evaluate the bonding behind the 9 5/8" casing across seal 3. A clean-out run is performed before running the log to remove possible debris from the casing wall, thereby optimizing results from the log. Logging results showed sufficient length of circumferential bonding from cement for two barriers behind the casing. Thereafter, the seal is restored by installing a bridge plug (as a fundament for the cement) and pumping cement. To verify the integrity of the internal cement plug, it is tagged and pressure tested after the cement has set.

Challenges:

- Restricted or limited access to the well due to wellbore deformation or collapse (above critical depth)
- Contamination of cement

**Seal 2: Perforate, Wash & Cement**

The log of the 9 5/8" casing does not show sufficient circumferential bonding within seal 2. Then, the method "Perforate, Wash and Cement" (PWC) will be used to restore seal 2. This method includes perforating the casing, washing behind the perforations, and finally pumping cement downhole and out through the perforations to establish a cross-sectional barrier. This can be performed using a swab-cup tool or a jetting tool. If using the swab-cup tool, the perforations will act as nozzles when washing and cementing the annulus. The jetting tool has nozzles on the tool itself. To verify the annular cement bond after the PWC job, the internal cement can be drilled out, followed by re-logging of the 9 5/8" casing. Circumferential cement bonding is confirmed by the second log, and a new internal cement plug is placed inside the 9 5/8" casing to restore the seal. Finally, the cement plug is tagged and pressure tested to verify its integrity.

Challenges:

- Gas influx when perforating (possible pressurized gas trapped behind casing)
- Losses when perforating if mud weight is too high
- Contamination of cement
- Reliability of logging result (possible effect from perforations)
- Time consuming to drill out cement

**Seal 1: Section Milling**

Today's technology does not enable logging through two casings. Therefore, to verify the cement bond behind the 13 3/8" casing, the 9 5/8" casing has to be removed. When a casing is cemented in place, cutting and retrieving the casing is difficult and time-consuming. Then, since the TOC of the 9 5/8" casing is above the desired setting depth of the seal 1 barrier, a window in the 9 5/8" casing is made instead of removing the entire casing down to the bottom of the seal. The window in the 9 5/8" casing is made by section milling. The 13 3/8" casing in the section milled window is then logged to evaluate the annular bonding. With sufficient length of circumferential bonding behind the 13 3/8" casing, verified by the log, an internal cement plug is placed in the section milled window. An inflatable packer is set as a base for the internal cement plug. Setting an inflatable packer in the bottom of the window, instead of a 9 5/8" bridge plug, isolates the cement slurry and eliminates the risk of the slurry being affected by possible gas migration up through the poor 9 5/8” casing cement. The plug is finally verified as a barrier by tagging and pressure testing.

Challenges:
- Time consuming operation
- Swarf handling (Health, Safety and Environment (HSE) risk)
- Swarf packoff (birds-nesting)
- Risk of losses
- Possible damage to Blow-Out-Preventer (BOP) from swarf
- Correct mud/fluid properties during milling
- Sufficient hole cleaning
- Wear on mill (extra time changing knives)
- Skimming casing (worn knives causing incomplete removal of casing)

**Open Hole to Surface Plug: Cut & Pull and Pilot Milling**
Finally, the open hole to surface plug needs to be set. The TOC of this plug is set just below the seabed. To be able to log the 20” casing, both 9 5/8” and 13 3/8” casings need to be removed. Since TOC of the 9 5/8” casing is below the desired setting depth for this cement plug, the 9 5/8” casing is cut and retrieved in one piece. The 13 3/8” casing is cemented to surface, making it difficult and very time-consuming to cut and pull the casing. Thus, the 13 3/8” casing is pilot milled, meaning it is milled from the top of the casing. After pilot milling is completed, the 20” casing cement is verified through logging. Since the 30” conductor is driven downhole, it is not logged. There is a shale formation barrier on the outside of the conductor, created when the conductor was driven. A bridge plug is set in the 20” casing to act as a base for the following internal cement plug.

Cut & pull challenges:
- Time consuming if casing is stuck (need for additional cuts)
- Reliability of log (correct TOC and indications of settled barite behind the 9 5/8” casing)
- Casing stuck in cement patches or mud particles settled in annulus behind the 9 5/8” casing
- Need for safety cut and/or additional cuts
- Use of casing jack if casing is stuck
- Jarring and effects from jarring (if casing is stuck)

Pilot milling challenges:
- Time consuming operation
- Swarf handling (HSE risk)
- Swarf packoff (birds-nesting)
- Possible damage to BOP from swarf
- Correct fluid properties while milling
- Sufficient hole cleaning
- Wear on mill
- Skimming casing (worn mill causing incomplete removal of casing)

# Chapter 3

# Well Barriers and Barrier Requirements

## 3.1 Regulations and Guidelines

Oil and gas activities on the Norwegian Continental Shelf (NCS) are audited by the PSA. The PSA is the regulator, providing regulations for both onshore and offshore work on the NCS [PSA Norway, 2019a]. The main regulations are Framework HSE, Management, Facilities, Activities, Technical and Operational regulations, and Working environment regulations. Each regulation has guidelines, and the guidelines refer to recognized standards. NORSOK D-010 is an example of a recognized standard used in drilling and well operations.

There are mainly three sections in the regulations referring to well barriers: [PSA Norway, 2019a]

Management: Section 5 ”Barriers”

Facilities: Section 48 ”Well Barriers”

Activities: Section 85 ”Well Barriers”

The main message from these regulations concerning permanent P&A is the demand for independent barriers and their longevity. The well barriers shall have sufficient independence. In other words, the secondary barrier must not be affected by a damaged or defective primary barrier. The barriers need to keep their verified integrity throughout the entire period, in this case eternity [PSA Norway, 2019a].

## 3.2 NORSOK D-010

To ensure the regulations set by the PSA are met during well operations, the NORSOK D-010 standard *”Well integrity in drilling and well operations”* was formed by the Norwegian petroleum industry [PSA Norway, 2019b, NORSOK, 2013]. Here, well integrity is defined as *”application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids* *throughout the life cycle of a well"* [NORSOK, 2013]. Operating companies, together with other interest organizations (e.g. "Norsk Olje og Gass"), are continuously working to develop and improve NORSOK D-010, and the current edition is revision 4.

### 3.2.1 Well Barrier Requirements

Section 4.2.3 in NORSOK D-010 covers the general requirements for well barriers. If a well enters a formation containing hydrocarbons or a formation with flow potential, NORSOK D-010 requires having two well barriers in place. NORSOK D-010 defines a well barrier as an *"envelope of one or several well barrier elements preventing fluids from flowing unintentionally from the formation into the wellbore, into another formation or to the external environment"*. The general requirements for a well barrier are to: [NORSOK, 2013]

- *Withstand the maximum differential pressure and temperature it may become exposed to (taking into account depletion or injection regimes in adjacent wells)*
- *Be pressure tested, function tested or verified by other methods*
- *Ensure that no single failure of a well barrier or Well Barrier Element (WBE) can lead to uncontrolled flow of wellbore fluids or gases to the external environment*
- *Re-establish a lost well barrier or establish another alternative well barrier*
- *Operate competently and withstand the environment for which it may be exposed to over time*
- *Determine the physical position/location and integrity status at all times when such monitoring is possible*
- *Be independent of each other and avoid having common WBE to the extent possible*

If not specified otherwise, NORSOK D-010 requires leak rates of zero for all well barriers. However, acceptance criteria should be established to justify effects from media compressibility, air entrapment, volume, and temperature effects [NORSOK, 2013].

**Barrier Requirements for Permanent P&A**

As previously cited from NORSOK D-010, a well barrier may consist of numerous WBEs. As illustrated in Fig. 3.1 (a), both internal and external WBEs shall not allow fluid flow vertically nor horizontally [NORSOK, 2013]. WBEs frequently used to form a barrier for permanent P&A are casing cement, creeping formation, casing and cement plugs [NORSOK, 2013]. An example of typical WBEs forming a well barrier are shown in Fig. 3.1 (b). Here the WBEs are casing cement, casing and a cement plug, in addition to in-situ formation on the outside with sufficient strength. All permanent well barriers need to be set in a sealing impermeable formation where the in-situ formation strength is able to withstand maximum anticipated pressure. Furthermore, since the wells will not be re-entered after P&A, well barriers shall be designed for eternity [NORSOK, 2013].

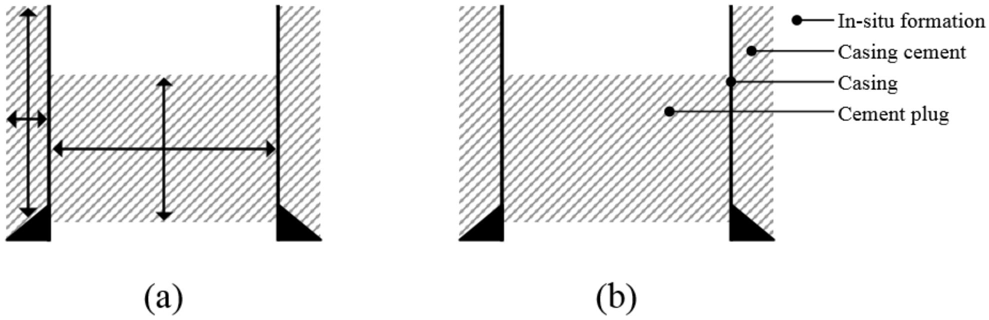



**Figure 3.1:** (a) NORSOK D-010 requires all WBEs sealing both horizontally and vertically. (b) Example of collaboration of WBEs to form a permanent well barrier.

Section 9.5 in NORSOK D-010 covers permanent abandonment, and states that the essential qualities of a WBE should be: [NORSOK, 2013]

- *Provide long term integrity (eternal perspective)*
- *Impermeable*
- *Non-shrinking*
- *Able to withstand mechanical loads/impact*
- *Resistant to chemicals/substances ($H_2S$, $CO_2$ and hydrocarbons)*
- *Ensure bonding to steel*
- *Not harmful to the steel tubulars integrity*

Additional concerns that should be evaluated and accounted for regarding placement and design of a WBE are; *downhole placement techniques, minimum volumes required to mix a homogeneous slurry, surface volume control, contamination of fluids, shrinkage of cement or plugging material and WBE degradation over time* [NORSOK, 2013].

### 3.2.2 Verification of Well Barriers

All barriers and WBEs requires verification. To verify if a well barrier is able to withstand maximum differential pressure, the barrier is pressure tested. Preferably, the pressure test should be performed by applying pressure in the flow direction. If not able to apply pressure in the desirable direction, NORSOK D-10 allows pressure testing from the opposite direction if the barrier is sealing in both directions [NORSOK, 2013]. As an example, after a cement plug is set, its ability to withstand differential pressure is verified by applying pressure above the plug, even though the flow potential is in the opposite direction.

According to NORSOK D-010, if not able to perform a pressure test, other specified methods shall be used for verifying the well barrier [NORSOK, 2013]. However, NORSOK D-010 does not refer to any verification methods as an alternative to pressure testing.

Placement and location of a downhole barrier can be verified through tagging if the barrier is set inside a casing. The external barrier, normally casing cement, is verified through logging or displacement calulations [NORSOK, 2013].

### 3.2.3 Well Barrier Element Acceptance Criteria

Chapter 15 in NORSOK D-010 consists of several well barrier EAC-tables. The general table description from NORSOK D-010 are shown in Table 3.1. Each WBE has its own table describing technical and operational requirements concerning the WBE. The main features are description, function, design construction and selection, initial test and verification, use, monitoring and common WBE [NORSOK, 2013].

| Features | Acceptance Criteria | See |
|---|---|---|
| **A. Description** | This is a description of the WBE | |
| **B. Function** | This describes the main function of the WBE | |
| **C. Design (capacity, rating and function), construction and selection** | For WBE that are constructed in the field (e.g. drilling fluid, cement), this should describe:<br>a) design criteria, such as maximal load conditions that the WBE shall withstand and other functional requirements for the period that the WBE will be used,<br>b) construction requirements for the WBE or its sub-components, and will in most cases consist of references to normative standards.<br>For WBEs that are pre-manufactured (production packer, DHSV), the focus should be on selection parameters for choosing the right equipment and proper field installation | Name of specific references |
| **D. Initial test and verification** | This describes the methodology for verifying the WBE being ready for use and being accepted as a part of a well barrier | |
| **E. Use** | This describes proper use of the WBE in order for it to maintain its function during execution of activities and operations | |
| **F. Monitoring (regular surveillance, testing and verification)** | This describes the methods for verifying that the WBE continues to be intact and fulfills the design criteria | |
| **G. Common WBE** | This describes additional criteria to the above when the element is a common WBE | |

**Table 3.1:** NORSOK D-010 EAC table description [NORSOK, 2013]

## 3.3 Cement

The most commonly used well barrier element for permanent P&A barriers is cement. Cement is used both externally (casing cement) and internally (cement plug). For well cementing, Portland cement is used. Its low cost and durability makes the cement suitable for P&A well barriers [Khalifeh et al., 2013]. Also, the cement can be modified using additives to help achieve desired properties or meet chemical and physical standards [PetroWiki, 2019]. The permeability is not equal to zero, as desired, but relatively low. Portland cement is hydraulic cement, meaning compressive strength is developed relatively quick when cement is set, even under water [Nelson and Guillot, 2006]. Portland cement slurry is easy to pump, and it is easy to predict when the slurry is establishing strength [Nelson and Guillot, 2006, PetroWiki, 2019].

However, when conventional cement (without the addition of expanding agents) sets and builds compressive strength, it will start to shrink. Micro-annuli can be formed between the cement and the formation or casing wall during cement-shrinkage, potentially allowing fluid or gas migration. If micro-annuli have been formed, the cement can lose its sealing capacity [Nelson and Guillot, 2006].

Additional concerns affecting the cement quality and sealing capacity are corrosive environments, High Pressure High Temperature (HPHT) environments, tectonic stresses, and gas migration during setting of cement [Khalifeh et al., 2013]. Chemical substances (e.g. $CO_2$, $H_2S$ and hydrocarbons) cause chemical reactions in the set cement affecting the mechanical features [Vrålstad et al., 2016]. Variations in the well temperature can cause cracks in the cement and debonding with the casing due to casing expansion and contraction when the temperature varies [Vrålstad et al., 2015]. Tectonic stresses can damage the integrity of the cement by causing cracks and establishing fluid flow paths. Finally, gas migration or gas influx into a cement slurry during setting can lead to a permeable cement [Khalifeh et al., 2013].

Going through the list of essential qualities for a permanent barrier for P&A in section 3.2.1, it can be questionable whether conventional cement are fulfilling the requirements set for materials towards permanent abandonment (in particular towards being impermeable and non-shrinking).

## 3.4 UK Guidelines on Qualification of Materials

NORSOK D-010 mainly refers to cement as barrier material when discussing and demonstrating permanent P&A well barriers. UK Oil & Gas have identified several potential barrier materials as an alternative to cement: Grouts (non-setting), thermosetting/thermoplastic/elastomeric polymers and composites, formation, gels, glass, metals, and modified in-situ materials. In order to use new unconventional barrier materials, a verification process needs to take place. UK Oil & Gas has developed *"Guidelines on Qualification of Materials for the Abandonment of Wells"* to help qualify new barrier materials [Oil & Gas UK, 2015b].

The process of qualifying a new barrier material, according to UK Oil & Gas, is shown in Fig. 3.2 [Oil & Gas UK, 2015b].

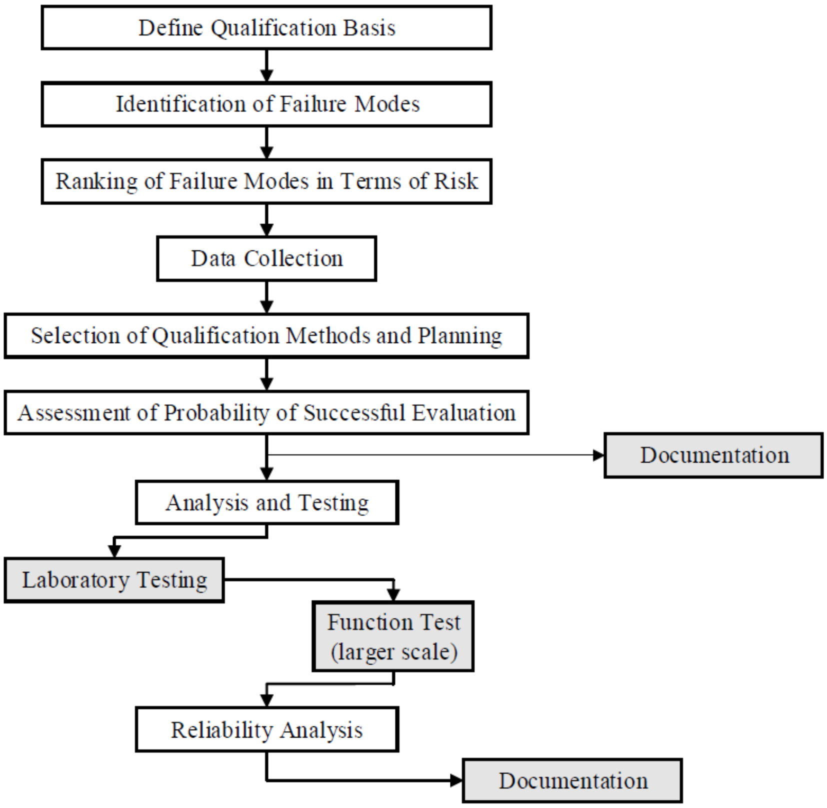



**Figure 3.2:** Qualification process for new technology [Oil & Gas UK, 2015b].

### 3.4.1 Functional Requirements of Permanent Barriers

UK Oil & Gas separates the functional requirements of permanent barriers into six main requirements [Oil & Gas UK, 2015b]:

1. Sealing - Material has low permeability and sufficient length in wellbore
2. Position - Barrier should maintain its position, not allowing movement (lateral or vertical)
3. Placeability - Be able to verify successful placement of barrier
4. Durability - Barrier materials should not degrade with an eternal perspective
5. Removal options and "reparability" concepts - Able to remove barrier if the barrier is leaking
6. Absence of environmental harm - Barrier material not being harmful to environment

### 3.4.2 Potential Failure Modes

A fundamental part of qualifying a new barrier material is understanding how and why the material may fail. Three possible failure modes for a barrier material are: shift in barrier position, barrier leakage through the bulk material, or barrier leakage around the bulk material [Oil & Gas UK, 2015b].

**Shift in Barrier Position**

The objective of a barrier is to restore a seal at a set position. If the position of the barrier is shifted, vertically or laterally, it may lose its function as a well barrier. A barrier material is kept at its set position through bonding with the casing, either chemically or by surface friction [Oil & Gas UK, 2015b].

**Barrier Leakage Through the Bulk Material**

Leakage through the bulk material of a barrier is a consequence of permeability and porosity in the barrier material. In a case of dissimilar fluid concentrations above and below a barrier material, the difference will cause fluids diffusing through the barrier. Other driving forces generating fluid flow through pores in the barrier material are pressure differences above and below the barrier or buoyancy effects [Oil & Gas UK, 2015b].

**Barrier Leakage Around the Bulk Material**

The failure mode including leakage around the bulk material of a barrier involves cracking in material, debonding (micro-annulus) and dissolution. There can be several mechanisms leading to failure of the outer sealing capacity of the material [Oil & Gas UK, 2015b].

Cracks in the material can be formed as a consequences of internal or external stresses exceeding strength limits of the barrier material or bond between the material and the casing. Another form of cracks are ”stress corrosion cracks”, which is initiated if a material set in tension is affected by corrosion. Corrosion of the material will remove mass, and cracks will be initiated [Oil & Gas UK, 2015b].

Debonding and formation of micro-annulus between the casing and the barrier material can occur if the material shrinks, which is a known effect during solidification of cement and most metals. Debonding is also a possibility if a material creeps, meaning it loses its strength and deforms after experiencing loads over time, often called delayed strain. Compressive stresses are reduced when a material creeps, meaning barrier materials bonding with casing through expansion can experience shift in its position and lose its sealing capacity [Oil & Gas UK, 2015b].

Dissolution of the material can lead to defected material properties and loss of barrier integrity. Barrier materials can degrade and corrode through chemical reactions with external substances (e.g, $CO_2$, $H_2S$ or hydrocarbons) or reactions internally in the material. If the material undergoes dissolution through reactions with an external substance, the rate is controlled by diffusion or fluid flow [Oil & Gas UK, 2015b].

Finally, leakage on the outside of the bulk material inside a casing can occur if flow paths or channels are left on the casing wall due to improper displacement or insufficient cleaning of setting area [Oil & Gas UK, 2015b].

# Chapter 4

# Evolution of Barrier Length Requirements

## 4.1 Length Requirements for Cement Plugs

In 1967 the first regulations in Norway covering permanent P&A of wells were published, but specific requirements for barrier lengths and positioning was not discussed until 1975, when *"Regulations for drilling for petroleum in Norwegian internal waters"* was published [Samad, 2017]. The only barrier material reviewed then, as now, was cement. The minimum length for a single barrier cement plug was 30 m in open hole. More conservative length requirements was presented in 1981 where the minimum length increased to 50 m [Samad, 2017]. When the first edition of NORSOK D-010 was published in 1997, no specific length requirements for cement plugs were stated [Samad, 2017]. In 2013, the 4th edition of NORSOK D-010 was published, requiring the length of a single barrier in an open hole cement plug for permanent P&A to be 100 m [NORSOK, 2013].

Despite the considerable development in technology concerning P&A and well construction, the length requirements have become more conservative throughout the years. Table 4.1 lists an overview of how the cement length requirements of a single barrier have developed for an open hole plug, a cased hole plug and an open hole to surface plug.

| | Regulations for drilling for petroleum in Norwegian internal waters | Regulations for drilling etc. for petroleum in Norwegian internal waters | NORSOK D-010 Rev. 4 |
|---|---|---|---|
| | 1975 | 1981 | 2013 |
| Open hole plug | 30 m | 50 m | 100 m |
| Cased hole plug | mechanical foundation + 15 m cement<br>OR<br>30 m cement above and below casing shoe | mechanical foundation + 20 m cement<br>OR<br>50 m cement above and below casing shoe | mechanical foundation + 50 m cement<br>OR<br>100 m cement |
| Open hole to surface plug | 150 ft (=45.72 m) | 100 m | mechanical foundation + 50 m cement<br>OR<br>100 m cement |

**Table 4.1:** Evolution of length requirement for a single barrier cement plug [Sæth, 2018]

Today's cement plug length requirements are equal for any well conditions. A deep set plug for a HPHT well and a shallow plug sealing a permeable zone with a hydrostatic pore pressure has the same requirements. With varying flow potentials, it could be questioned whether the same requirements should apply for all well conditions and pore pressures.

In 2015, Godøy et al. published the SPE-paper *"Well Integrity Support by Extended Cement Evaluation - Numerical Modeling of Primary Cement Jobs"* where a methodology for evaluating required cement lengths in various well conditions were presented. A numerical leakage model was developed where leakage rates were based on effective permeability and use of Darcys law [Godoy et al., 2015]. Godøy et al.'s methodology was the background for Christer Sæth's master thesis. Sæth's thesis *"A Risk Based Approach for Calculating Barrier Lengths"* evaluated cement barrier lengths for shallow and hydrostatic pressured zones through Simeo WellCem leakage calculator [Sæth, 2018]. Relevant assumptions were made, and leakage criteria were set by building a reference case and performing simulations of leakage across a deep set single barrier in a well on Valhall DP, fulfilling NORSOK D-010 requirements. Seal 2 in the Valhall field, described in Sæth's thesis, is the sealing cap rock for a hydrostatic pressured zone with a minor flow potential. Simulations showed that only 13 m cement could be sufficient as one barrier for an internal cement plug, while NORSOK D-010 requires 50 m [Sæth, 2018].

Another leakage calculator, presented by [Moeinikia et al., 2017], considers three different leak paths when evaluating leakage rates from cement barriers. The leak paths considered are: leakage through bulk cement, leakage through cracks in the cement, and leakage through micro-annuli.

Determining a sufficient length for a cement plug is challenging considering the cement not being impermeable, in addition to the various factors potentially affecting cement quality, as described in section 3.3. On the contrary, an impermeable and expandable bismuth plug would possibly require a remarkable reduction in barrier length, while withstanding the same pressure differentials. The following chapter will address why bismuth is suitable for P&A , and why bismuth plugs will require a reduced barrier length.

# Chapter 5

# Bismuth as a WBE for Permanent P&A

## 5.1 What is Bismuth?

Bismuth is a metal labelled ”Bi” in the periodic table of elements. The metal has a crystalline structure. A remarkable trait is its low melting temperature and expansion upon solidification. In addition, both electrical and thermal conductivity is noteworthy low compared to other metals [Stoll, 2017].

In SPE 191469, [Carragher and Fulks, 2018a] lists the unique features of bismuth:

- *Melting point = 273 °C (Relatively low melting point compared to other metals)*
- *When in liquid form (melted) it has a viscosity very similar to water*
- *Very dense with a Specific Gravity (SG) of 10*
- *Non-corrosive and not affected by $H_2S$ or $CO_2$*
- *Upon solidification it expands approximately 3% (similar to how water expands to ice)*
- *Non-toxic*
- *It is an eutectic metal that goes from a liquid to solid state almost instantaneously when it cools below its melting point, bypassing the gel phase*

When setting a bismuth plug, the bismuth is run in hole in solid state together with a thermite heater. The heater is activated when at setting depth to melt the bismuth, and thereafter pulled out of the melted bismuth. Finally, the bismuth re-solidifies and creates a seal through its expansion. The thermite heater is further described in section 5.3.2.

However, pure bismuth will not be deployed as a barrier element, but rather a bismuth-based alloy. Pure bismuth melts at 273 °C, and its eutectic characteristic causes it to solidify instantly when the temperature drops below its melting temperature. Hence, there is a risk of not achieving the wanted placement and position of the bismuth prior to solidification. The melting temperature of pure bismuth is therefore not suitable for all well environments. To lower the melting temperature, bismuth can be combined with other metals to generate a bismuth-based alloy. Bismuth-based alloys and their melting temperature can be regulated to fit various well environments, depending on alloying elements and their quantity. Nevertheless, the melting temperature still needs to be above the temperature at the setting depth in the well to prevent uncontrolled melting of the alloy [Carragher and Fulks, 2018a]. Except the melting temperature, the bismuth-based alloys are designed to retain the unique qualities of pure bismuth (low viscosity, high density, expansion upon solidification, etc.). In this thesis, whenever referring to a bismuth plug, it is not pure bismuth, but a bismuth-based alloy. The bismuth alloy and its characteristics will be further discussed in section 5.3.1.

### 5.1.1 Why is Bismuth Suitable for P&A?

Bismuth has several qualities making it a suitable sealing material for permanent P&A. Firstly, the metal is impermeable, eliminating any chance of leakage through the plug. When melted downhole, the bismuth can easily displace well fluids with its high density and intrude the smallest pores and indents with a viscosity similar to water, not requiring pumping or pressure applied from surface. The melted bismuth forms to the shape of the casing, making it independent of the geometry and possible deformations in the setting area. Further, the extensive expansion of the bismuth during solidification creates the sealing mechanism of the material, and holds the bismuth in place through surface friction. Since it solidifies in the top and bottom first, the bismuth is forced to expand radially. The ability to expand upon solidification is one of the most important arguments for considering bismuth as a barrier element. Regarding long term integrity, being non-corrosive and not affected by neither $H_2S$ nor $CO_2$ are valuable characteristics towards use in permanent P&A applications.

**NORSOK D-010 Barrier Requirements**

As listed in section 3.2.1, NORSOK D-010 has several requirements for well barriers, both in general and specifically for permanent P&A. BiSN has carried out work towards qualifying bismuth, including lab and mechanical testing, analysis and simulation, setting of small-scale and full-scale plugs, and testing of subsystems and full systems [Underwood, 2019]. This section covers how the bismuth plug qualifies as a barrier element with respect to each of the requirements set by NORSOK D-010, listed in section 3.2.1.

General Well Barrier Requirements:

**(1)** *"Withstand the maximum differential pressure and temperature it may become exposed to (taking into account depletion or injection regimes in adjacent wells)"*

Before setting a bismuth plug, it will be designed and tested specifically towards its application in regards to expected differential pressure and temperature. Therefore will all bismuth plugs have a distinctive design suited for its setting environment [Underwood, 2019].

**(2)** *"Be pressure tested, function tested or verified by other methods"*

Testing performed by BiSN has shown bismuth plugs withstand the same pressure differential whether pressured from above or below. Therefore, the integrity of the plug may be verified using conventional pressure testing from above [Underwood, 2019]. Tagging may be performed to verify the position of the plug.

**(3)** *"Ensure that no single failure of a well barrier or WBE can lead to uncontrolled flow of wellbore"*
This requirement may not be valid for the bismuth as this requirement applies to the well barrier strategy for the entire wellbore, and not just to a single WBE [Underwood, 2019].

**(4)** *"Re-establish a lost well barrier or establish another alternative well barrier"*
Just like cement, bismuth plugs can be drilled out using conventional milling tools [Underwood, 2019].

**(5)** *"Operate competently and withstand the environment for which it may be exposed to over time"*
A bismuth based alloy has the ability to withstand any environment it may be exposed to over time by being corrosion resistant and not affected by $CO_2$ or $H_2S$ [Underwood, 2019]. For further explanation, see requirement (5) under "Permanent P&A Well Barrier Requirements".

**(6)** *"Determine the physical position/location and integrity status at all times when such monitoring is possible"*
As mentioned, physical position/location can be verified through tagging the bismuth plug. Integrity status of the plug can be verified by a pressure test [Underwood, 2019].

**(7)** *"Be independent of each other and avoid having common WBEs to the extent possible"*
The bismuth plug itself is independent of other WBEs. Nevertheless, the integrity of the resulting well barrier is dependent on the elements in which the bismuth is set. The most likely scenario is to set the bismuth plug inside a cemented casing. The casing and cement must maintain their integrity for the final barrier to be viable. If a bridge plug is set to act as a base for the bismuth, it is not relied upon to contribute to the sealing capacity of the bismuth plug [Underwood, 2019].

Permanent P&A Well Barrier Requirements:
**(1)** *"Provide long term integrity (eternal perspective)"*
Two known concerns regarding the long term integrity of the bismuth alloy are creep and corrosion, mentioned in section 3.4.2 as mechanisms potentially leading to leakage around the bulk material. Pure bismuth is a non corrosive metal. However, for bismuth alloys used in well applications, the industry is currently performing accelerated long term integrity testing to prove the corrosion characteristics. This is further explained when discussing requirement (5) "Resistant to chemicals/substances ($H_2S$, $CO_2$ and hydrocarbons)" below. BiSN conducts creep testing to characterize thresholds at downhole temperatures. Stress calculations and Finite Element Analysis (FEA) are conducted to verify that stress levels in the plugs are lower than the bismuth plug's maximum stress level. Lastly, the studies currently ongoing are also examining ageing of the material at low and elevated temperatures. All this work is ongoing, but the performance of BiSN's bismuth plugs already installed in actual wells indicates the material strength and design parameters are sufficient to withstand actual plug stress levels [Underwood, 2019].

**(2)** *"Impermeable"*
As the material of the plug is a pure metallic alloy, it is impermeable to liquids and gases at the molecular level. As such, BiSN has not deemed it necessary to test permeability of the base material itself [Underwood, 2019].

**(3)** *"Non-shrinking"*
In contrast to cement, which is the current baseline material for P&A, bismuth alloy expands upon solidification. Expansion is not caused by fluid absorption, but due to a liquid-to-solid phase change, in which the bismuth alloy transforms from an amorphous to crystalline atomic structure [Underwood, 2019].

**(4)** *"Able to withstand mechanical loads/impact"*
Impact, described as a sudden mechanical load exposed to the set plug, is normally a concern for components subjected to tensile stress. However, the stress state of a bismuth plug is compression against the casing wall/formation once set due to the expansion characteristics of the bismuth alloy. Its volumetric expansion enables the plug to be exposed to and withstand differential pressure/axial compressive forces [Underwood, 2019].

**(5)** *"Resistant to chemicals/substances ($H_2S$, $CO_2$ and hydrocarbons)"*
Pure bismuth is a non-corrosive metal not affected by chemical substances like $H_2S$ and $CO_2$. However, studies are performed to prove the bismuth alloy has the same characteristics. BiSN, the Oil & Gas Technology Centre (OGTC) and BP are performing corrosion studies. Per date, two corrosion test studies have been performed on bismuth. In addition, a third test is due for completion at the end of 2019. In the test studies completed, the bismuth alloy was set in an environment consisting of an acidic brine solution with $CO_2$ and $H_2S$. Both tests showed similar corrosion resistance to *Inconel 718*, which is a corrosion-resistant material. Also, 14-to-28 day immersion tests, measuring damage caused by corrosive environments, revealed low long-term corrosion rates. Rates were found to be less than 1 mil per year (mpy). A mil is about 0.001", or 1/40 of a millimeter. The current testing includes immersion tests run for 12 months, but results are not available yet. As for galvanic corrosion, occurring if two dissimilar metals are set in a corrosive electrolyte, there was an interaction with normal casing steels, meaning it was more than zero. Compared to normal casing steels, galvanic interaction was less when coupling bismuth alloy with Corrosion Resistant Alloys (CRAs), and even lower for nickel alloys such as Inconel 718. However, the measured weight loss of the bismuth alloy when interacting with casing steels were lower than the already-low numbers in the tests where the bismuth was not coupled with steel [Underwood, 2019]. These are the current results provided by BiSN as corrosion studies are still ongoing.

**(6)** *"Ensure bonding to steel"*
Bismuth is not chemically bonded to the casing to provide a seal and maintain its position. Instead, its sealing capacity and resistance to axial movement are relying on the expansion of the bismuth. In lab and workshop testing, BiSN has demonstrated many hundreds of times that the radial expansion of the bismuth and resulting friction forces are sufficient to create a seal and resist the axial force created by differential pressure [Underwood, 2019].

**(7)** *"Not harmful to the steel tubulars integrity"*
This requirement may address galvanic (discussed above in requirement 5), chemical or metallurgical attack. BiSN uses their bismuth alloy in test casings daily without any evidence of chemical attack on the casing, and thereby there is no reason to believe casings are attacked chemically by the bismuth. Regarding metallurgical attack, there is a possibility of Liquid Metal Embrittlement (LME) in the period the alloy is molten inside the casing. LME means that a ductile material, in this case the casing, experiences brittle fractures and lose its tensile ductility if subjected to specific liquid metals. To investigate whether the bismuth alloy causes LME, testing will be conducted in 2019.

## 5.2 Function and Applications

BiSN has set bismuth plugs for various oil well applications, with the possibility of sealing both inside tubing/casings and externally through casing annuli. Applications include; water shut-off and prevention of sand production in Open Hole Gravel Pack (OHGP) completions, repair of leaking packers or casings, eliminating SCP or leakage through poorly cemented casing annuli, isolating perforations in cased hole completions, tubing seals, and achieving gas tight seals across uncemented annuli between two casings.Tubing seals, isolating perforations, and sealing annuli (both cemented and uncemented) are applications for well abandonment. Bismuth can be deployed downhole using wireline, and requires no additional pumping from surface to circulate the bismuth in place when melted due to its high density and low viscosity [BiSN, 2019].

Qualification of bismuth as a barrier element will provide operators with an alternative to cement for P&A barriers. A bismuth plug can be applied as a secondary barrier, in addition to a cement plug being the primary barrier. Then, there will be two independent barriers with dissimilar sealing mechanisms. The bismuth will seal through expansion, while the cement is sealing through bonding with the casing or formation. Furthermore, the two plugs will have different failure mechanisms and failure modes. The wellbore conditions or forces causing failure of a cement plug may not cause failure of the bismuth plug, and vice verca. In addition, due to the characteristics of the bismuth, a shorter plug may be sufficient to create a sealing barrier. This way, the total length needed for sealing the formation is reduced. In addition, the amount of casing needed to be removed is reduced, and thereby also the costs.

The qualification process presented in this thesis targets a bismuth plug where the main function will be to create an impermeable metal-to-metal seal set inside a cased hole with confirmed annular bonding for permanent P&A.

## 5.3 Design, Construction and Selection

A bismuth plug is set by utilizing bismuth and thermite technology. The bismuth-based alloy is casted to the outside of a thermite heater and run into the well on electric line. When at setting depth, power is supplied to initiate the chemical reaction generating heat to melt the bismuth alloy. Varying well environments requires distinctive bismuth-based alloys and complementary thermite heater configurations to control the heat generated.

### 5.3.1 Bismuth Alloy

BiSN currently has four bismuth-based alloys in use; BiSN-95, BiSN-124, BiSN-138 and BiSN-263. The alloys are based on varying compositions of bismuth together with silver, tin or led [Underwood, 2019]. 95, 124, 138 and 263 are the corresponding melting temperature of the alloys in Celsius (°C). Melting temperature is varied to make the alloy suitable for various well applications, considering temperature in the setting area. If the temperature at setting depth is very low, its cooling effect on the bismuth alloy could cause uncontrolled solidification before achieving the correct placement across the casing. By comparison, if the downhole temperature exceeds the melting temperature of the bismuth alloy, the alloy could potentially start melting before reaching desired setting depth, and the alloy would not be able to solidify at all. In conclusion, shallow set bismuth plugs requires low melt temperature alloys, while deeper set plugs requires a higher purity of bismuth in the alloys, increasing the melting temperature.

Compared to pure bismuth, properties of a bismuth-based alloy are changed to a minor extent when adding alloying elements to lower the melting temperature. The viscosity of the alloy still remains similar to water, like pure bismuth. While pure bismuth expands 3% upon solidification, the bismuth alloys has expansion coefficients varying from 0.4%-1.4%. However, this rate of expansion will act radially and be sufficient to anchor the plug in the well and block all fluid flow. Alloy densities are slightly reduced compared to pure bismuth, but not decisively. Specific gravity of the bismuth-based alloys range from 8.6-10.5 SG, still high enough to not require any pumping or squeezing to displace well fluids and place the alloy in the sealing area. [Underwood, 2019].

The barrier plug length can be reduced considerably compared to cement barrier plugs, due to the impermeability of bismuth alloys. BiSN has performed tests to investigate the relationship between length/diameter ratio and differential pressure capability. Water was used as medium for these pressure tests. Results, presented in Fig. 5.1, proves an approximately linear relationship [Underwood, 2019]. For instance, a 2 m long bismuth plug with an outer diameter (OD) of 17.73 in (inner diameter (ID) of a 20” casing) has a length/diameter ratio of 4.2. Then, according to Fig. 5.1, the plug should be able to withstand around 2400 psi differential pressure.

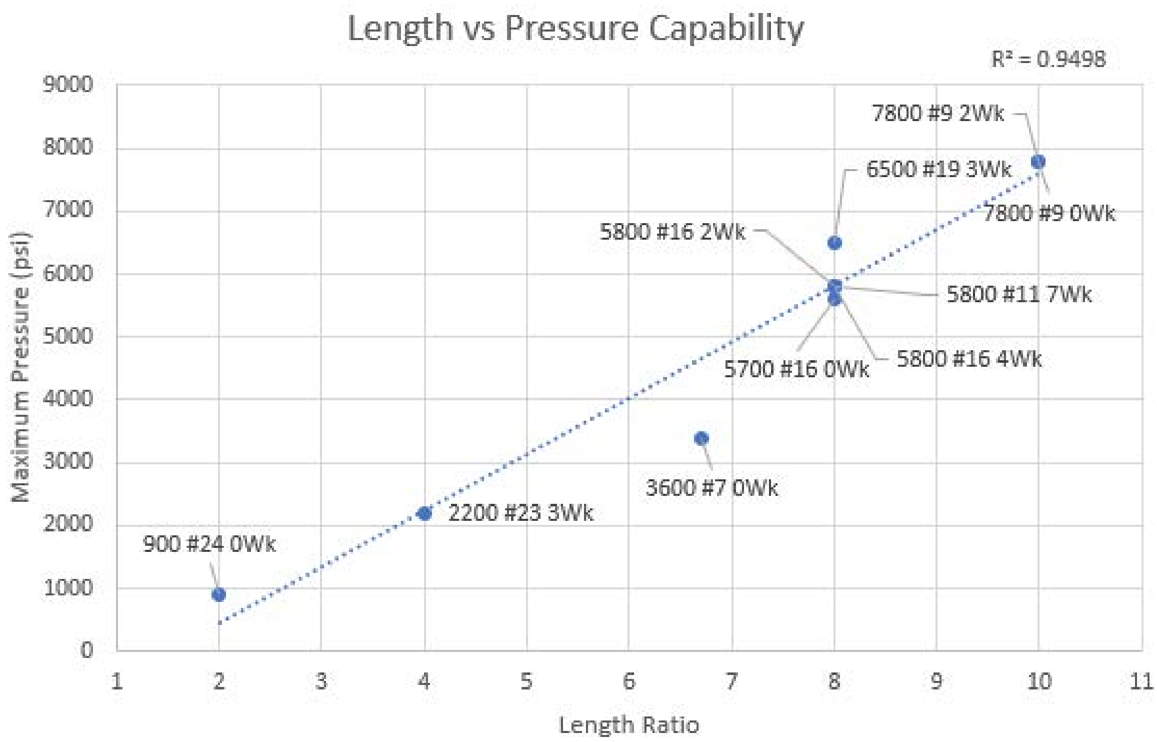



**Figure 5.1:** Length/diameter ratio vs. differential pressure capability of a bismuth plug [Underwood, 2019]

In this thesis, BiSN-138 is the alloy referred to when discussing a bismuth alloy. Testing showed BiSN-138 was preferred for P&A applications, further described in section 6.1.

### 5.3.2 Thermite Heater

To melt the bismuth downhole, a heater is required. Previously, electrical heaters have been tested for this application. Due to the extreme amount of power and energy required to melt the bismuth, it would take hours to melt a small volume of bismuth using an electric heater. Additionally, the heaters failed keeping the bismuth melted until reaching the entire sealing area and filling all voids. The setting depth would also be limited by voltage drops in the electric line [Carragher and Fulks, 2018b].

Instead of an electric heater, a thermite heater run on electric line will be used to melt the bismuth downhole. The thermite heater consists of thermite deployed inside a sealed pipe. Heat and energy is a result from an exothermic chemical reaction where the thermite burns, displayed below [Carragher, 2017].

$$
\begin{array}{lclclclcl}
\text{Iron oxide} & + & \text{Aluminium} & \longrightarrow & \text{Aluminium oxide} & + & \text{Iron} & + & \text{Heat} \\
3\,\text{FeO} & + & 2\,\text{Al} & \longrightarrow & \text{Al}_2\text{O}_3 & + & 3\,\text{Fe} & + & \Delta\text{H}
\end{array}
$$

Thermite, which is a mixture of iron oxide and aluminium, reacts to produce bi-products such as aluminium oxide, iron and heat. The chemical reaction needs to be activated, and this is done by applying heat. The temperature needed to activate the chemical reaction of the thermite, and the temperature at which it burns, is as high as 2000 °C. At this temperature, the energy output from the reaction is 10 000 kJ. However, such high temperatures are not suitable at downhole conditions, and will damage the steel casing. To control the burning temperature of the thermite, BiSN has added binding and damping agents to the thermite mixture. The binding agents secure the mixture from separating, ensuring a constant chemical composition of the thermite. The damping agents regulate the burning speed and the total heat output from the chemical reaction. After adding the binding and damping agents, the heat generated from the reaction can range from 200-800 °C, where the burning times vary from 15 seconds to 45 minutes [Carragher and Fulks, 2018b]. BiSN have developed various generations and mixtures of thermite to be able to customize the heater to each application of the bismuth plug. This way, both burning rate and energy produced can be modified and controlled. The thermite can either be provided as powder or crumbles inside the heater.

When running the thermite heater on standard electric line, the chemical reaction will be initiated by a ”starter”. The starter does not require much power, but will be activated by using 240 V and 60 mA for 15 seconds. Once the starter is activated, it provides heat to initiate the chemical reaction in the thermite heater. The power requirements of the starter is not more than as required when setting bridge plugs or perforating using wireline [Carragher and Fulks, 2018b].

The burning reaction of the thermite is similar to a burning candle, as it will burn from the top and down. Fig. 5.2 (a) to (c) illustrates how the thermite mixture burns from the top and down inside the heater. The first illustration Fig. 5.2 (a) shows the thermite heater before the chemical reaction is initiated, while

(b) demonstrates how the thermite burns. Black indicates unburned thermite while red indicates burning thermite generating heat. Fig. 5.2 (c) illustrates the thermite heater after burning is complete. As a result, the bismuth alloy in the top will melt first and flow down on the outside of the heater when the thermite is burning. Finally, when the thermite burn has reached the bottom of the heater, all of the alloy will be melted and located around the bottom of the heater [Carragher and Fulks, 2018b]. If the temperature generated by the thermite is too high, it can result in a burn-through of the heater, as illustrated in Fig. 5.2 (d). During a heater burn-through, the thermite will leak through its container and prevent the burning process from moving towards the bottom of the heater. Consequently, a burn-through causes an incomplete burning of the thermite, resulting in a deficient melting of the bismuth. Only the thermite down to the point of burn-through will act as expected. To reduce the risk of a burn-through, the heater is coated.

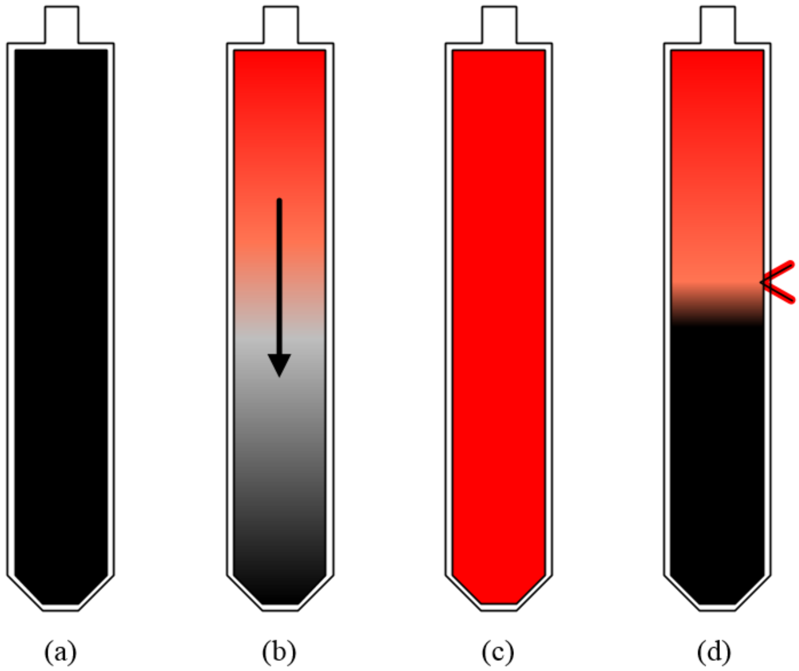



**Figure 5.2:** Thermite burning process inside heater. (a) Thermite placed inside its container before burning reaction is initiated. (b) The chemical reaction is initiated, and the thermite burns and generates heat from the top and down. (c) After thermite burn is complete. (d) In case of a burn-through, the thermite burn is stopped at the point of burn-through.

# Chapter 6

# Full Scale Testing of Bismuth as a WBE

Aker BP and BiSN collaborated to develop and qualify a tool capable of setting a permanent and gas-tight barrier plug, consisting solely of bismuth alloy, for permanent P&A. This qualification process targets a plug inside a 20” casing, deployed through a 13 3/8” casing. Fig. 6.1 (a) shows the full cross section of the plug where the 13 3/8” casing is still present, while (b) shows a saw cut section of the final 20” plug where 13 3/8” is removed prior to setting the plug. The proposed length for the bismuth plug was 2 m, which according to BiSN’s length/diameter assessment (Fig. 5.1) should be able to withstand approximately 2400 psi pressure differential. BiSN has previously performed plenty small-scale tests and function testing of their bismuth alloys and thermite heaters, but not towards qualification for permanent P&A. An extensive test program, described in section 6.1, was established to produce and validate the design for deployment of a metal-to-metal seal, where testing was performed at BiSN’s locations in Houston. The material presented in this chapter is based on reference from [Price and Elizondo, 2018], unless stated otherwise.


(a) (b)

**Figure 6.1:** (a) Full cross section of plug when 13 3/8”x20” annulus is accessed by drilling holes in the 13 3/8” casing. (b) Saw cut section of final 20” bismuth plug deployed through a section milled interval in 13 3/8” casing (gouges along lengths are a result of torch cutting the 20” vessel open to retrieve plug). [Price and Elizondo, 2018]

## 6.1 13 3/8” x 20” Test Program

The extensive test program was initiated towards qualifying bismuth as a well barrier element inside a 20” casing, deployed through a 13 3/8” casing, referred to as a 13 3/8”x20” bismuth plug. The goal was to create a barrier element only consisting of bismuth alloy, meaning the thermite heater would be removed. Initially, the main objective was to establish a rig-less solution for setting the bismuth plug, and a rig based solution was set as a contingency.

No comparable testing had formerly been performed up to this point. Thus, several design parameters needed to be examined, as well as their compatibility and interactions. Design parameters included the bismuth alloy, the thermite mixture, the heater design, and the well fluid.

Through full-scale yard testing, the system design was tested and evaluated over eleven full-scale tests. The requirement was to achieve two repetitive successful tests, fulfilling all test objectives. Lastly, as a part of the qualification testing, the bismuth plug would be installed in a well for field verification and monitoring, further described in chapter 7.

### 6.1.1 Test Vessel Description

The test vessel consists of a 13 3/8” casing deployed inside a 20” casing, illustrated in Fig. 6.2. Casings are fitted with end plates and welded with the heater inside to create a pressure vessel. Pressure can be regulated and recorded both above and below the bismuth plug in the vessel during firing and pressure testing. To record temperature, a thermocouple array is installed on the outer wall of the 20” casing in the setting depth of the plug, illustrated in Fig. 6.3 (a). To allow elevation and removal of the heater, the test vessel was modified to some extent, displayed in Fig. 6.3 (b). An extension tube was installed on top of the vessel, enabling elevation of heater. Top of the heater was fit with a wireline cable head connection, and wireline was run through a packoff and two sheave wheels.

The 13 3/8” casing was not cemented in place, but sand was placed to act as a base for the bismuth alloy in the wellbore and the annulus. Primarily, the 13 3/8” casing was set concentrically inside the 20” casing. However, to simulate a worst case scenario, the 13 3/8” casing was positioned eccentrically, with a 0.5” offset between casings on the near side. Firing heater in eccentric configuration showed no noticeable effects on the plug formation with this tool design and these well parameters.

As the installation of a bismuth plug primarily was considered for a rig-less solution, access to the 13 3/8”x20” annulus was obtained through drilling holes in the casing. Holes were drilled over a 0.6 m (2 ft) interval. For the final tests, section milling a window in the 13 3/8” casing was preferred, as focus was shifted towards a rig-based solution. Against the end of the testing period, when approaching a potential field-installation, it became evident that a jack-up rig would be present at the offshore location, and the installation would be a rig based solution. Section milling was then preferred to enable a proper clean-out of the 20” casing wall in order to eliminate potential leak paths.

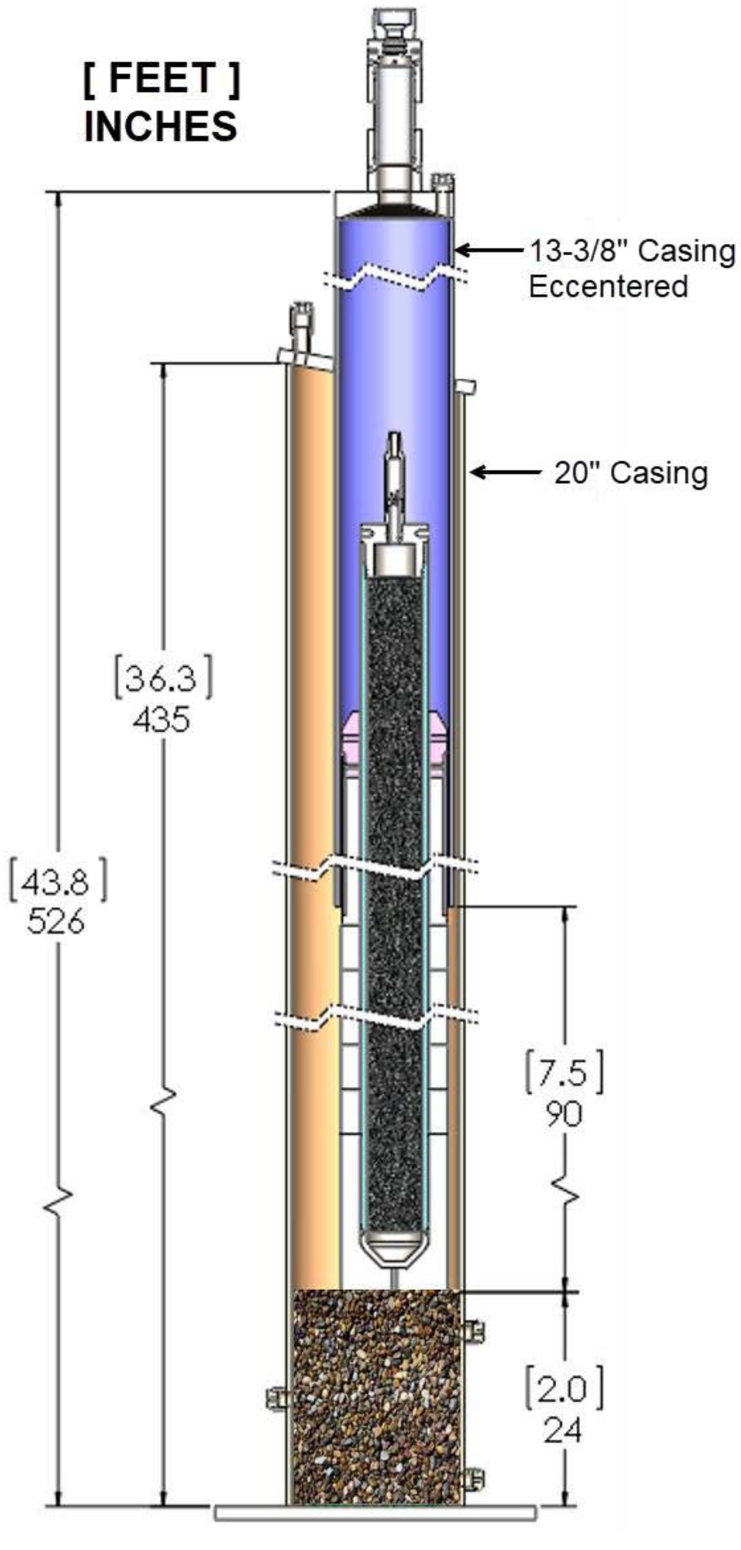
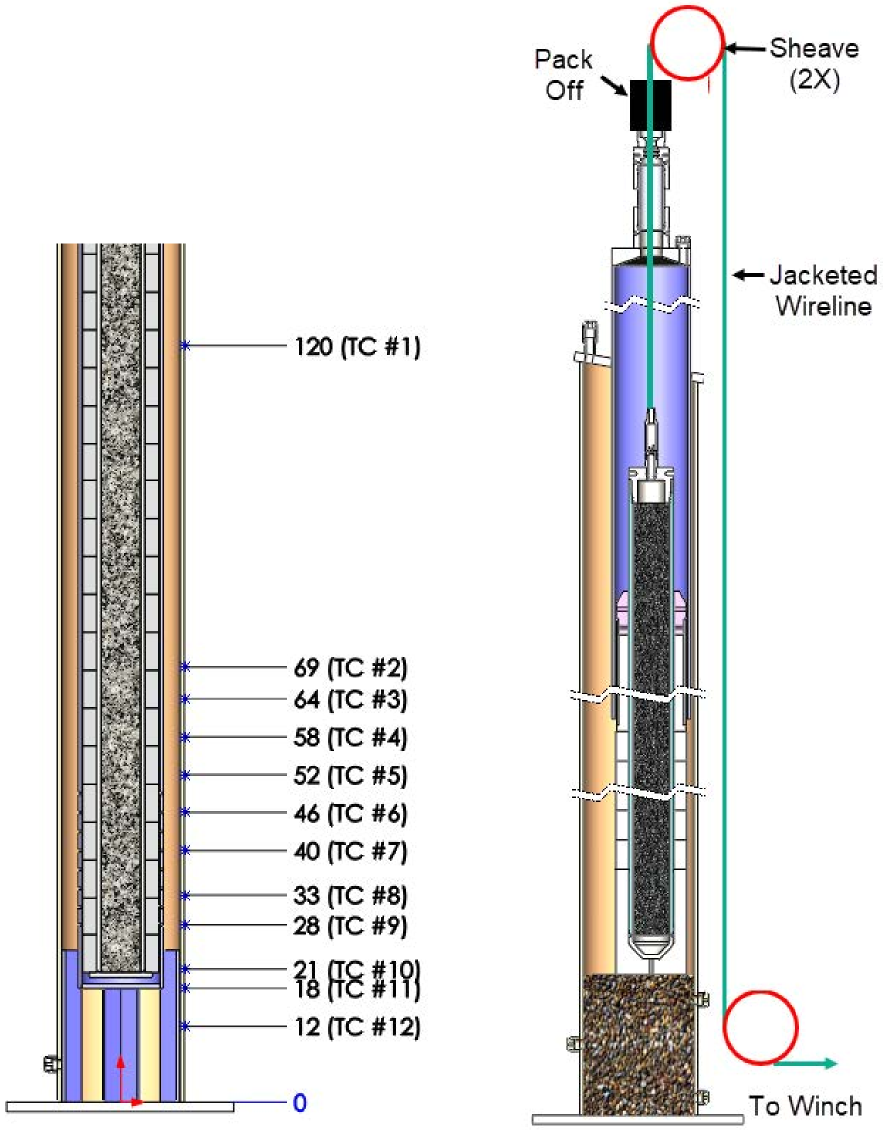



**Figure 6.2:** Test vessel setup. Thermite heater deployed with bismuth (white) set on top of a sand-foundation. Heater is positioned inside 13 3/8" casing, placed eccentric inside 20" casing. [Price and Elizondo, 2018]

The pressure in the test vessel was set to 600 psi to replicate hydrostatic pressure at setting depth in the well elected for field verification of the bismuth plug.




(a) (b)

**Figure 6.3:** (a) Thermocouple locations, installed outside the 20” casing (distance from bottom in inches) (b) Vessel setup for heater removal using wireline [Price and Elizondo, 2018]

Other test parameters:

| | |
|---|---|
| Inner Casing | 13 3/8” OD, 72 lb/ft (12.35” ID), 80 ksi yield strength |
| Outer Casing | 20” OD, 133 lb/ft (18.73” ID), 80ksi min yield strength |
| Deviation from vertical | 0 degrees |
| Ambient temperature | 30 °C (approximately) |

### 6.1.2 Testing and Test Requirements

Sealing capacity and integrity of the bismuth were verified through pressure tests. The two sides of the plug were hydraulically isolated from one another, where one side was pressurized to reach desired pressure differential, while pressure was monitored on both sides. To begin with, a low pressure differential was held across the plug. If no communication was observed across the plug, the pressure differential was elevated, and another hold period performed. This procedure was repeated until the seal failed and enabled communication across the plug, or until the seal passed the test, meaning the plug successfully held the target differential pressure. Nevertheless, after achieving successful tests in the final design, pressure was applied until leakage was observed. As mentioned in section 3.2.2, when pressure testing well barriers to verify their integrity, differential pressure should be applied in the potential flow direction. Yet, NORSOK D-010 allows pressure testing in the opposite direction if the barrier is sealing in both directions. Aker BP's and BiSN's test program includes application of differential pressure and pressure testing on both sides of the sealing plug to verify that the plug has a sealing capacity in both directions.

Initially, the plugs were pressure tested to 1000 psi. Differential pressure was applied above and below, using water as test medium (hydro test). Acceptance criteria was $<1\%$ pressure loss over a fifteen-minute interval. For the second test, a gas test was implemented. Nitrogen ($N_2$) was used as test medium to apply pressure from below. The acceptance criteria for gas testing was no bubbles for 12 hours. Halfway through the test program, the objective differential pressure set for verification of the bismuth plug was lowered from 1000 psi to 500 psi. 1000 psi was initially the preferred test pressure. However, the selected candidate well for the field application had a maximum 500 psi test pressure, restricted by test pressure of outer casing. Hence, remaining tests were run to 500 psi. Another amendment implemented to the test program was ageing tests. Vessel and bismuth plug were left to sit for a period, 4 weeks at most, before performing a re-test.

First, gas tests were performed using nitrogen or helium. When using helium, a helium sniffer was set up to measure any presence above normal atmospheric content. Helium was early found unsuitable as a test medium since nitrogen is the industry accepted standard gas medium, and it is therefore difficult to relate results of a helium test to external audiences. When gas testing with nitrogen, gas leakage was initially recognized through visual observations of bubbles on camera, in addition to vessel pressure monitoring. The gas test monitoring was eventually improved by installing a bubble catcher on top of the vessel, shown by the green pointers in Fig. 6.4. If bubbles of nitrogen surfaced, they would be trapped inside the bubble catcher and accumulated. Furthermore, slopes were implemented in the top of the vessel, illustrated in Fig. 6.4, as flat edges and shelves could prevent bubbles from reaching the bubble catcher. As a result, the risk of potentially missing bubbles was eliminated, enabling a more reasonable assessment of leakage rate. In final tests, only nitrogen-gas tests were preferred as they were the deciding factor for approval of the test result. The final gas tests were held and checked for bubbles for 12 hours, and re-testing was performed after 9 days. Lastly, the plug was pressurized to failure, also with gas.

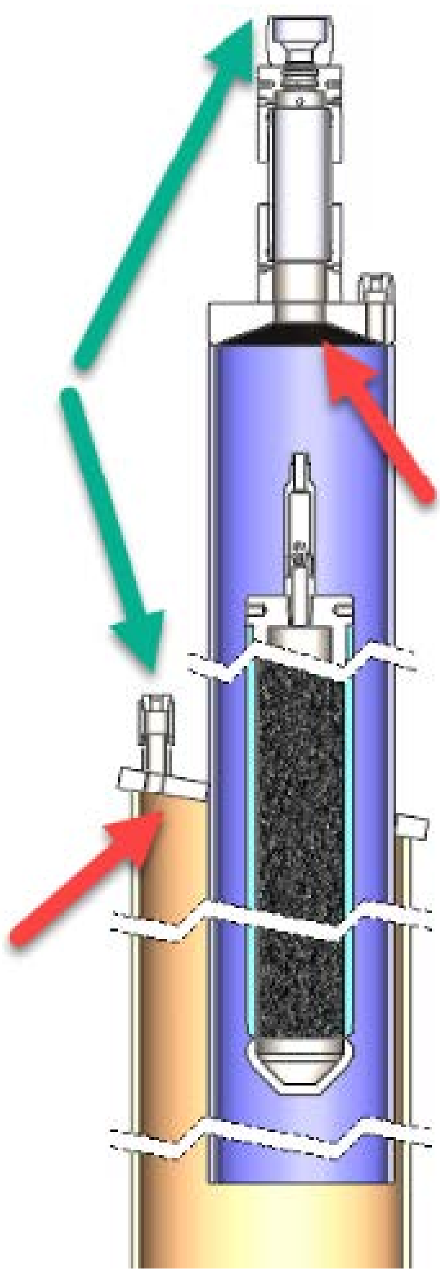


**Figure 6.4:** Test vessel bubble traps. Green = bubble catcher locations. Red = sloped edges. [Price and Elizondo, 2018]

### 6.1.3 Risks and Challenges

Project risks and challenges primarily included removal of the heater and the size of the sealing plug, both being new and first-time actions never done before. Removal of the thermite heater was a new requirement set by Aker BP towards installation of bismuth alloy plugs. Up until now, BiSN had never removed the thermite heater in field installations. The objective of heater removal is to leave a plug consisting solely of bismuth alloy, eliminating potential leak paths along the heater. Removal of heater added complexity to test setup and execution, and simultaneously requiring great precision at the time of removal. If pulling out too soon, there is a risk of not melting the entire volume of bismuth deployed downhole. On the other hand, if pulling out too late, there is a risk of not being able to recover the heater at all. If the alloy has already solidified, the heater will be stuck. Limited research had previously been performed towards heater removal. Only a few tests conducted with a 7" casing had attempted heater removal.

Furthermore, to this point, all bismuth plugs set through casing by BiSN had been on a considerably smaller scale, typically up to 7" diameter. Scaling is a complex matter with regards to the process of setting a bismuth alloy plug, thus comprehensive testing was required to optimize the tool design. Incomplete melting of bismuth alloy and thermite heater burn-through were two concerns towards optimizing the tool, in addition to the matter of finding correct alloy and thermite mixture, to create a 20" sealing plug.

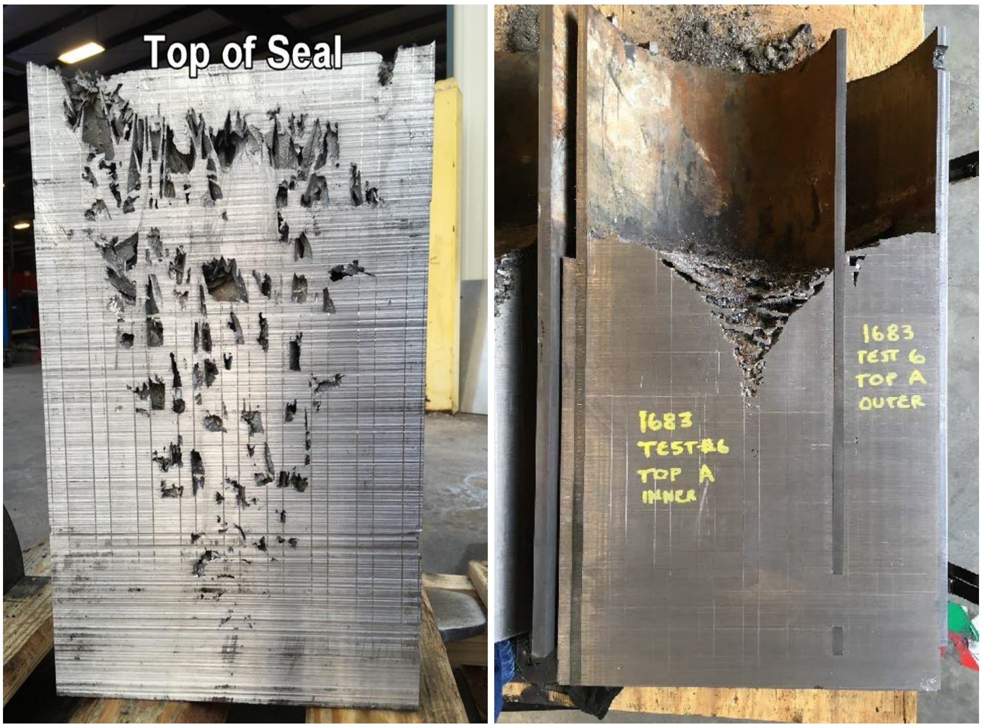
Another challenge, and another "first", was the relatively low setting temperature desired for the 13 3/8"x20" bismuth plug. At the setting depth the 13 3/8"x20" bismuth plug is aimed for, the temperature is approximately 30 °C. Ambient temperature in Houston is generally around 30 °C, hence the ambition of testing as close to well-conditions as possible was not difficult to achieve. All previous plugs set by BiSN have been set at higher temperatures. Temperature has a considerable effect on the design, especially towards choice of bismuth alloy and thermite mixture. In this case, the setting temperature of 30 °C was a new concern considering its cooling effect on the bismuth. Nevertheless, although the ambient temperature is representative for a well, the air conductivity differs from formation conductivity. This should be kept in mind considering cool down and solidification of the melted bismuth.

### 6.1.4 Design factors

The essential factors considered towards the tool design was the bismuth alloy, the thermite selection, the vessel for the thermite (referred to as the "heater"), and finally the choice of well fluid. These elements cannot be selected independently as they all work together in constructing a successful seal.

**Bismuth Alloy**
Alloy selection is the primary element to be considered, as only the bismuth alloy constitutes the barrier. Due to its low melting point, BiSN-95 was the initial candidate alloy for this application.

Pressure testing of the bismuth plugs was followed by dissection and inspection of the plug. When using BiSN-95 alloy, no evident leak paths were found, but notable voids were discovered at top of the plug. Fig. 6.5 shows two examples where voids were created in the upper sections in plug when using the BiSN-95 alloy. These voids formed an inverted cone pattern from the top of the plug. As cooling rate was lowered, as an effect of fluid selection, the conical void in the top of the plug was less-pronounced, seen in Fig. 6.5 (b). Yet, due to the voids detected in top of the solidified alloy, the quantity of alloy was increased. The justification of alloy increase was enabling the length of the seal without voids to meet intended original length of a full sealing plug. Eventually, the BiSN-95 alloy was found unsuitable for P&A applications as research concluded the alloy has insufficient expansion.




(a) (b)

**Figure 6.5:** Inspecting cross section of the bismuth plug when using BiSN-95. Both pictures are only showing top of the final bismuth plug. (a) Top section (top 38%) of the bismuth plug when set in fresh water. (b) Top section of the bismuth plug when set in water-based mud. [Price and Elizondo, 2018]

Finding BiSN-95 incompatible for P&A resulted in a switch to the BiSN-138 alloy. BiSN-138 has improved expansion performance compared to BiSN-95, since it has a higher concentration of bismuth in the alloy mixture. Furthermore, a considerable difference was observed from the BiSN-95 plug when inspecting the BiSN-138 plug. When using the BiSN-138 alloy, no voids were found within the solidified alloy. In contrast to BiSN-95, the final test using BiSN-138 showed the plug's center "bulged out", shown in Fig. 6.6. The expansion bulge is most likely a result of alloy expansion in the core of the plug after it had already solidified at the surface, since the core would have been the last to solidify by the nature of heat transfer.


(a) (b)

**Figure 6.6:** Inspection of the top of the final bismuth plug. (a) Top of the bismuth plug seen from above. (b) Demonstration of the top of the bismuth plug bulging out [Price and Elizondo, 2018]

As previously mentioned, the bismuth alloy would most likely solidify in the top and bottom first. Hence, expansion will be forced to act radially. This statement is justified when studying temperature measurements along the setting depth of the plug. Fig. 6.7 presents temperature readings over an 8 hour interval from the thermocouples outside the 20" casing during one of the tests. The temperature gradient plot indicates bismuth is first solidifying in the top and bottom, and thereby forcing radial expansion.


**Figure 6.7:** Temperature gradient during creation of a bismuth plug. Color plot are displaying temperature measurements over an 8 hour interval at different depths (distance from bottom in inches on the far/near side of the eccentric casing). Temperature decreases first in the top and bottom, causing the bismuth alloy to solidify here first. [Price and Elizondo, 2018]

One test included adding pea gravel (simulating cement and swarf) in the bottom of the vessel to investigate possible effects on the seal. As the bismuth alloy has a high density, the prediction was that the gravel would float to the top of the plug. Tests showed that the pea gravel had floated to top of the alloy, just as predicted, and was located in the top few inches of the alloy without impeding the seal. Additionally, another test showed considerable amount of pipe scale and other debris that was contained in the vessel, all of which floated to the top of the plug. Hence, the risk of debris or swarf affecting the seal may be disregarded.

The bismuth was originally deployed in the form of alloy rings on the outside of the heater. However, when more alloy was added to compensate for the volume that was originally displaced by the heater and increasing the plug length, the ability to melt all of the alloy became a challenge. Thus, the best solution was found to be a combination of alloy rings and casting the alloy directly onto the heater. Fig. 6.8 illustrates final tool design and shows how the bismuth is distributed around the thermite heater. Bismuth was casted directly onto the heater in the top and bottom sections, while the intermediate section contained bismuth alloy rings slid over the heater.

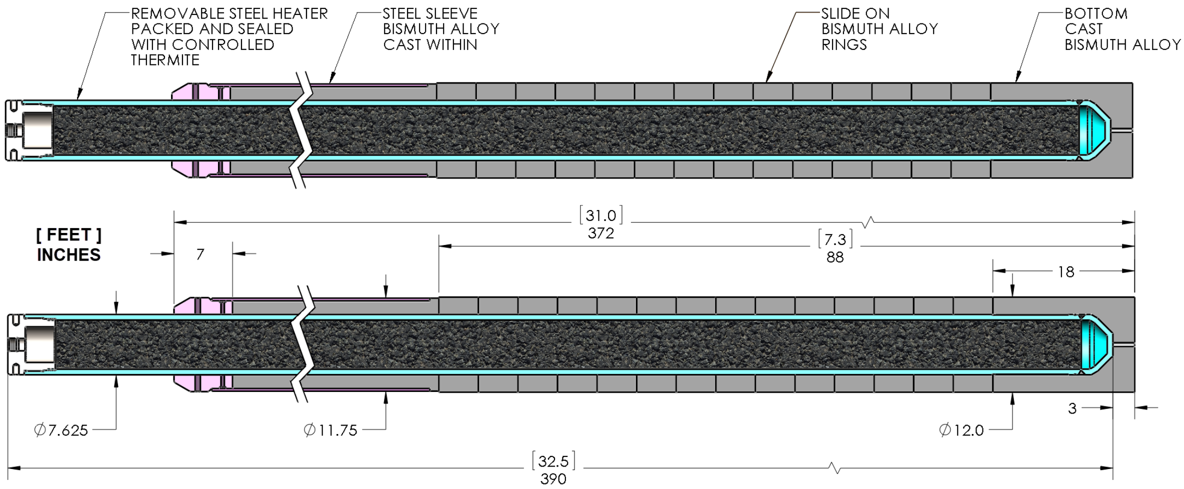



**Figure 6.8:** Final design and dimensions of the thermite heater and bismuth alloy. Bismuth casted directly on heater in top and bottom sections, while slid on as alloy rings in middle section. [Price and Elizondo, 2018]

**Thermite Selection**

Thermite selection is complex and critical. Heat generated from the burning thermite mixture should be sufficient to fully melt bismuth alloy while simultaneously avoiding burning through the heater. Considering bismuth alloys have varying melting temperatures, thermite mixtures need to be modified accordingly. BiSN has developed different generations and mixtures of thermite to adjust heat output and burning rate. As mentioned, if the generated temperature is too high there is a risk of burning through the heater. In case of a burn-through, alloy and well fluid are able to rush into the heater and prematurely extinguish the burn, leaving bismuth alloy unmelted. Similarly, there is a risk of not melting the entire alloy if burning rate is too fast, since not enough heat is generated.

Modification of other design parameters, such as bismuth alloy and well fluid, required re-evaluation and further testing to select an appropriate thermite mixture for the 13 3/8"x20" plug. When switching to 138 alloy, a simultaneous switch was made to the thermite selection in order to provide additional heat. However, this pushed the energy balance further than intended, resulting in burn-throughs. An example of a burn-through is shown in Fig. 6.9. A complete melting of the bismuth was difficult to obtain. Several generations and mixtures of thermite were considered during the test program. Finally the initial thermite used for the initial test with BiSN-95 was proved efficient for this design, resolving burn-throughs while melting all bismuth alloy.

The burning rate was observed by monitoring temperatures recorded by thermocouples outside the 20" casing. Temperature recordings also gave an early indication of a potential burn-through if temperatures did not rise above the melting temperature of the alloy in the lower section. Similarly, a successful burn of thermite was recognized when recording temperatures above the melting temperature of the alloy.

Further details concerning BiSN's thermite mixtures are not described in this thesis due to confidentiality and intellectual properties.


**Figure 6.9:** Heater burn-through resulting from burning a thermite mixture generating excessive temperatures. [Price and Elizondo, 2018]

**Heater design**

The heater containing the thermite mixture is a 7 5/8" OD casing, 52.8 lb/ft. The initial length of the heater was 3.65 m (12 ft), but the final tool design required elongating the heater to 9.9 m (32.5 ft).

After experiencing burn-through, a ceramic coating was introduced to the inside of the heater as a protective barrier for burn-through protection. This coating was not included in the initial test as the development of the coating was relatively new and still being qualified for smaller heaters. Further testing revealed that a single layer of coating on the inside of the heater was not sufficient to prevent burn-through. Hence, enhanced double coating was implemented for further burn-through mitigation. As a result of this test program, coating is now the standard for all BiSN's heaters.

Subsequently, the bottom of the heater was changed from a flat end cap to a bevelled cap to improve heat transfer below the heater and reduce the risk of alloy freezing prematurely. Changes to the heater bottom are illustrated in Fig. 6.10. Modifying the bottom of the heater removed the base for the alloy rings, requiring the alloy base to be cast directly onto the bottom of the heater.

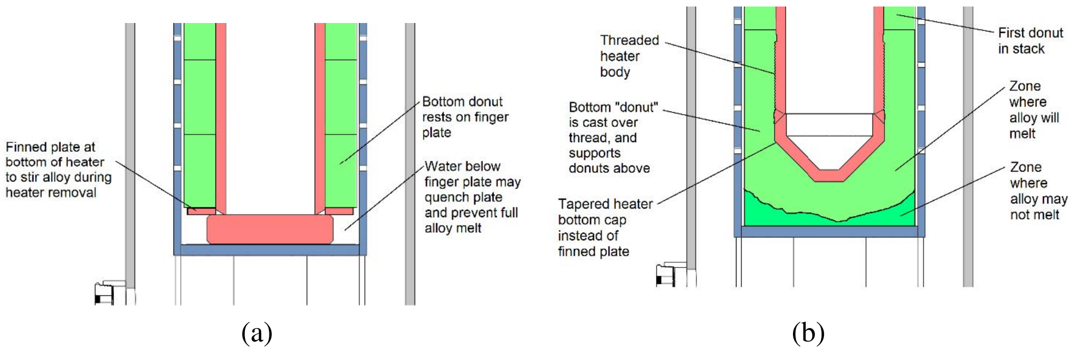



**Figure 6.10:** Modification of heater bottom to improve tool design. (a) Previous heater bottom with a flat end cap. (b) Modified rounded heater bottom. [Price and Elizondo, 2018]

To improve the efficiency of transferring heat to the alloy, preventing unsuccessful melting of alloy and heat loss to the surrounding fluid, a steel sleeve was introduced to the heater design. Now, the steel sleeve was covering the top part of the heater, requiring alloy to be cast directly onto the heater in this section. The final heater design is illustrated in Fig. 6.8.

**Fluid**

Originally, fresh water was used as test medium. Moreover, weighted fluid was required as the primary barrier in the candidate well, prompting a change of test fluid from fresh water to 10.8 ppg water based mud (WBM). The bismuth plugs constructed using WBM provided passing results when pressure testing with water, but not with gas.

During dissection and inspection of the bismuth plugs after implementing WBM as test medium, thin vertical silt-lines of mud-solids were found present at the interface between the alloy plug and the casing, displayed in Fig. 6.11. Though not confirmed, these presented a concern as their presence may have allowed for potential leak paths. To eliminate potential leak paths, subsequent tests were run using a particle-free fluid with the same weight. Calcium chloride brine ($CaCl_2$) replaced the WBM. After switching to brine, successful gas tests were achieved.

(a) (b)

**Figure 6.11:** Silt lines observed during inspection of plug, representing potential leak paths along interface between alloy and casing. (a) Silt lines observed on outside of plug. (b) Silt lines observed on inside of casing. [Price and Elizondo, 2018]

Furthermore, presence of mud-solids along the interface between the casing and the alloy highlighted the concern for other solids or particles establishing leak paths along the interface, for instance patches of cement. Hence, the significance of a thorough cleanout of the outer casing, before installing the sealing bismuth plug, was discovered.

### 6.1.5 Final Design Parameters

An abundance of learnings were made during the extensive test program where several design factors were assessed. The final result was an optimized design towards a rig-based solution where access to 20" casing was obtained through section milling a short interval in the 13 3/8" casing. Fig. 6.12 illustrates the final arrangement of the test vessel when the heater was pulled and the bismuth seal restored. After two successful tests fulfilling the test requirements of passing a 500 psi gas test, the tool design was ready for a well application.

Summarized final design parameters:

| | |
|---|---|
| Alloy | BiSN-138 (ring stacks in middle section, cast directly to heater in top and bottom) |
| Fluid | Weighted $CaCl_2$ brine (10.8 ppg) |
| Heater | Double ceramic coating of casing ID, sleeve included, and rounded heater bottom |
| Thermite | Mixture produce enough heat to melt bismuth while heater burn-through is avoided |
| | |
| Pressure test | Nitrogen, 500 psi, held 12 hr (passed post aging test after 9 days) |
| Failure pressure | Leakage observed at 1000 psi |

Lastly, an essential learning was understanding the importance of cleaning the casing before melting the bismuth downhole. Particles like cement patches along the interface between the alloy and the outer casing constitutes a major risk towards sealing capacity as they represent potential leak paths. Hence, cleaning the casing before creating a bismuth seal became an important focal point for the following field installation in a well.

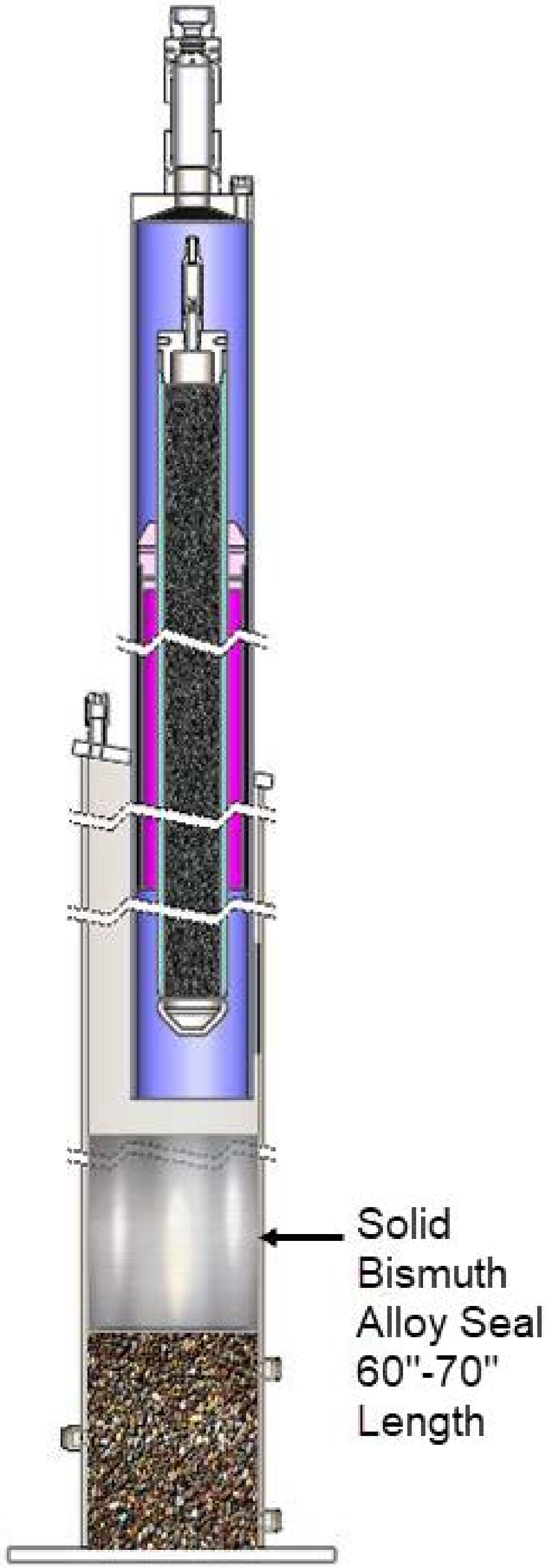



**Figure 6.12:** Test vessel after the heater is pulled from the melted bismuth. [Price and Elizondo, 2018]

# Chapter 7

# Field Verification on Valhall DP

After optimizing the tool design of the 13 3/8”x20” bismuth plug through the test program described in chapter 6, the next step in the verification process was to install the bismuth plug in a well at the Valhall field. After installation, this plug would become the largest bismuth plug ever installed in a well.

## 7.1 Valhall

Valhall, located in the southernmost part of the NCS, is an oil field discovered in 1975. Its location is shown in Fig. 7.1. Production from the chalk formation/carbonate reservoir was initiated in 1982, and the oil giant is presumed to maintain production until 2050. Today, the Valhall complex consists of six separate bridge-connected platforms; quarters platform (QP), drilling platform (DP), production and compression platform (PCP), wellhead platform (WP), injection platform (IP), and production and hotel platform (PH). Additionally, three unmanned platforms; Hod, Valhall Flank North and Valhall Flank South, are managed remotely from the Valhall field center. The arrangement of the platforms positioned on the Valhall field is illustrated in Fig. 7.2 [AkerBP, 2019, BP, 2013].


**Figure 7.1:** Valhall field location [BP, 2016]

Due to comprehensive production, without any water injection until 2004 to help maintain reservoir pressure, the reservoir has depleted and the seabed subsided by 7 m. As a result of seabed subsidence, the air gap between mean sea level and the platforms DP, QP and PCP is now below an acceptable level. Hence, these platforms need to be removed. For Valhall DP, P&A of the 30 wells drilled is required before the platform can be removed. P&A of DP wells was initiated in 2014, and the P&A campaign was projected to last for 10 years [BP, 2013]. Per date, 20 wells have been fully P&Aed as per phase 2, 6 wells still have some remaining P&A scope, and 4 wells are awaiting to be permanently abandoned.

Fig. 7.2 illustrates the complexity of the Valhall field where the reservoir overburden consists of several permeable zones with inflow potential, here referred to as DPZs. Only five DPZs are outlined in the figure, but there are in total 9 DPZs, where the 9th zone is the producing reservoir. Before abandoning the wells on Valhall DP, all DPZs need to be isolated with barriers fulfilling requirements from NORSOK D-010. However, as DPZs 2-5 are hydrostatically pressurized, seal 2 has sufficient strength to seal these DPZs. Hence, 11 barrier plugs need to be installed before abandoning a well in a safe manner: two barrier plugs in seals 9, 8, 7, 6 and 2, in addition to an open hole to surface plug.

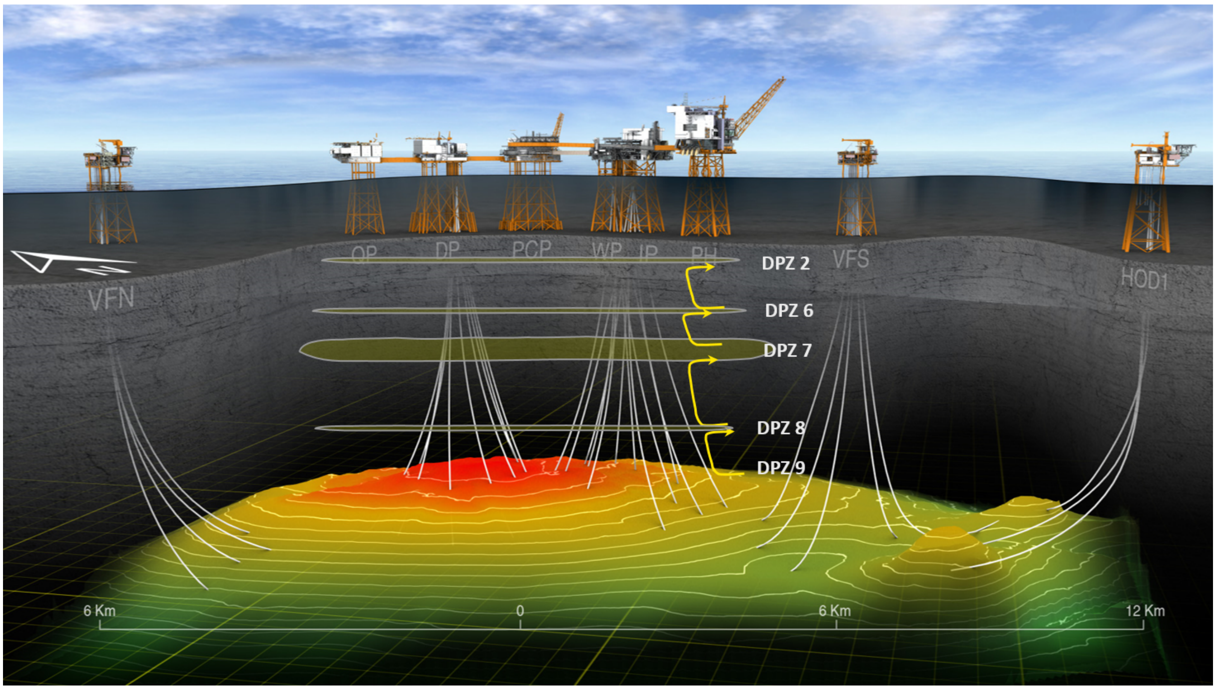



**Figure 7.2:** Valhall platform arrangement and permeable zones (DPZs) [BP, 2016].

In addition to several sources of inflow, restricted access to tubing and casings is a recurring challenge for Valhall DP wells. Seabed subsidence, as a result of compaction, has caused collapsed and deformed casings. Hence, the desired setting depth for the deeper barriers may not be attainable [BP, 2013]. Thirdly, restoring seal 2 with NORSOK D-010 qualified barriers is a challenge in all wells on Valhall DP. When studying the time consumption to place barrier plugs in all seals respectively, it becomes evident that approximately one third of the time spent on a well is used to restore seal 2. The complexity of seal 2 is further described in section 7.1.1.

### 7.1.1 Seal 2

As mentioned, it is difficult to fulfill NORSOK D-010 requirements for well barriers when restoring seal 2. Fig. 7.3 illustrates the upper part of a typical well design on Valhall DP, where the total length of seal 2 is 78 m. As 2x30 m circumferential annular casing cement is required to fulfill NORSOK D-010 requirements, circumferential bonding needs to be verified behind both the 13 3/8" casing and the 20" casing. However, since today's logging tools does not enable logging through two casings, the 13 3/8" casing must be recovered down to 20" casing shoe to enable verification of the 20" casing cement.

Many of the 13 3/8" casings on Valhall DP were properly cemented where the top of casing cement is located above mud line (seabed). Hence, milling would be required for removal of this casing. However, several of the 20" casings on Valhall DP are worn and de-rated after formerly drilling multiple sidetracks from the 20" casing shoe. Additionally, the surface casings are positioned rather close in the seal 2 area as the wells are more or less vertical to this depth. Therefore, milling the 13 3/8" casing inside the 20" casing should be avoided as it can cause additional leak paths in the current well, but also in the neighboring wells.

In spite of this, the 20" casing has been logged in some wells where the 13 3/8" casing has been cut and retrieved. In these cases, logs has proved circumferential casing cement behind the 20" casing. In addition to the track record of circumferential 20" casing cement, cement reports describing successful cementing operations of the 20" casings are used to qualify the casing cement as an external barrier without logging on Valhall DP. Consequently, utilizing bismuth to create a sealing plug inside the 20" casing, without retrieving the 13 3/8" casing, will reduce the seal 2 time consumption significantly.

Even though seal 2 on Valhall DP is a suitable future application area for the 13 3/8"x20" bismuth plug, the bismuth plug installed and described in this chapter was not set to act as a barrier in the candidate well. This bismuth plug was set exclusively towards verifying bismuth as a future barrier material. Seal 2 on Valhall DP was found convenient for verification of the bismuth plug.

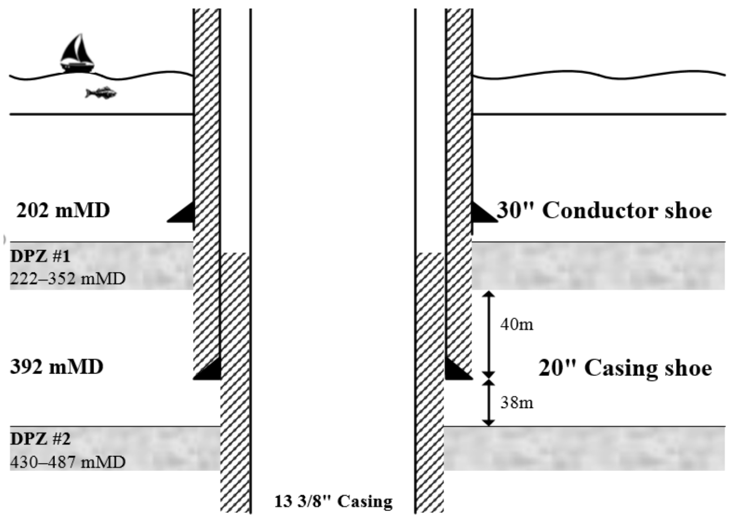



**Figure 7.3:** Illustration of a typical well design in the upper part of a well on Valhall DP. Surface casings are typically set in the middle of seal 2, which is the area between DPZ 1 and DPZ 2.

## 7.2 Installation of a Bismuth Plug

Besides daily drilling reports and final installation reports from various vendors, the material presented in this section is based on my own experience from running this operation offshore. All pictures depicted in this section were taken by myself at rig site.

After the bismuth plug tool design had been optimized in the full scale test program, the objective was to verify the bismuth plug in actual well conditions. The plug was to be set inside the surface casing across seal 2, approximately 300 m below mean sea level, which is a potential future application area of this bismuth plug on Valhall. To be able to verify the sealing capacity of the bismuth, a leaking bridge plug was set to act as a base for the bismuth and pressure gauges would be installed both above and below the plug. The intent is to continuously monitor pressure for a two-year period. One of the pressure gauges below the bismuth plug is a memory gauge, requiring the bismuth plug to be drilled out to retrieve the gauge after the monitoring period.

Prior to installing the bismuth plug, DPZ 2 was perforated through the 13 3/8” casing to induce pressure below the bismuth plug. DPZ 2 is known to contain shallow biogenic gas. This way, the ability of the bismuth to withstand a differential pressure over a long time period would be verified, if no pressure increase is seen above the plug.

In short, the plan was to perforate the 13 3/8” casing to induce pressure below the setting depth of the bismuth plug. Secondly, a base for the bismuth would be installed and a window in the 13 3/8” casing would be milled and cleaned to eliminate possible leak paths along the surface casing wall. Thereafter, bismuth is melted in place and pressure gauges installed above the plug. To verify whether the installation of the bismuth plug was a successful operation, a camera run would be performed after the bismuth plug had cooled down. Additionally, the plug would be pressure tested. The operational steps and more details considering the offshore installation are further described in section 7.2.2.

The well found appropriate for a bismuth plug installation had an 18 5/8” outer diameter surface casing. All previous testing was performed using a 20” casing. The difference of the inner diameter is less than an inch (0.975 inches, 24.735 mm), and therefore this was not considered a restriction.

Considering the verification, there is a risk of not achieving the wanted differential pressure across the plug if the gas migration from DPZ 2 is unsatisfactory. Moreover, communicating with the live gauge installed below the bismuth plug is a challenge. If not being able to collect pressure readings from this gauge, the differential pressure across the plug will not be known until the plug is drilled out and the memory pressure gauge is retrieved.

The bismuth plug installation was executed in September 2018 through the use of a jackup-rig. Hence, all depths are in reference to the Rotary Kelly Bushing (RKB) of the rig. In total, 12 days were used for the entire operation. In the future, installation of bismuth plugs will be performed with fewer verification steps, leading to significantly reduced installation times.

### 7.2.1 A-30: Candidate Well Pre-rig Status

Fig. 7.4 shows the ”pre-rig” well status schematic of the upper section of the candidate well, and current well barriers. Previously in the P&A-campaign, seals 7 and 6 were restored. When logging the 13 3/8” casing, only 14 m of circumferential cement was found across seal 2. Therefore, the well was temporarily abandoned.

When re-entering the well, the primary barrier consists of the 13 3/8” casing cement and a bridge plug. The secondary well barrier is the 13 3/8” casing, the 13 3/8” casing cement, the wellhead and a wellhead-cap.

Well parameters:

| | |
|---|---|
| 18 5/8” casing | 87.5 ppf, 17.755” ID |
| 13 3/8” casing | 72 ppf, 12.347” ID |
| Bismuth plug setting depth | 365-367 m (ref. rig RKB) |
| Temperature at setting depth | approximately 30 °C |
| Pressure at setting depth | approximately 31 bar (450 psi) |
| Inclination at setting depth | $\sim 5.9^{\circ}$ |

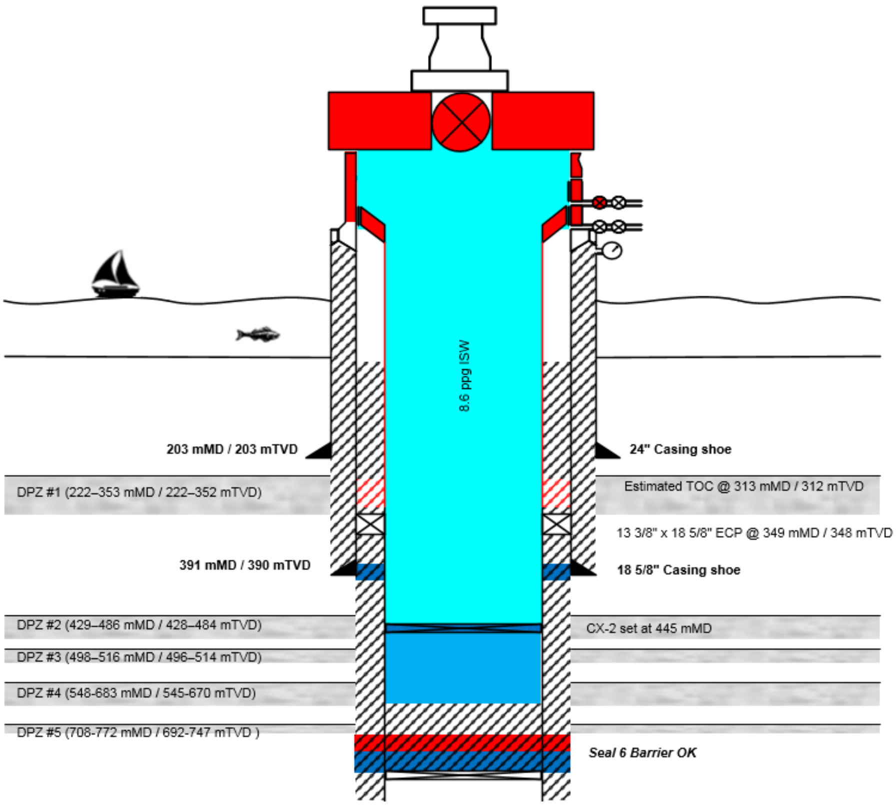



**Figure 7.4:** Temporary abandonment / Pre-rig status of candidate well, A-30 [AkerBP, 2017]

### 7.2.2 Operational Steps

To verify the bismuth plug and enable pressure monitoring, additional operational steps were implemented. Great precision and caution were used during the installation of this bismuth plug, as it would become a world first with respect to its dimension and application. The final operational preparations performed towards installation and verification of the bismuth plug can be divided into 12 steps:

1. Perforate top of DPZ 2 to induce pressure
2. Install leaking bridge plug with gauge hanger below
3. Cut opening hole in 13 3/8" casing prior to milling
4. Section mill a 4 m window in 13 3/8" casing
5. Underream section milled window
6. Clean out section milled window
7. Fill sand on top of bridge plug
8. Run camera to verify top of sand
9. Run and set bismuth plug
10. Monitor temperature above bismuth plug
11. Run camera to inspect section milled window and bismuth plug
12. Install 5 1/2" tubing with pressure gauges for pressure monitoring

Well schematics in Fig. 7.5 shows the step-wise well status throughout the operation. Well fluid is the primary barrier, and the secondary barrier is formed by the 18 5/8" casing, 18 5/8" casing cement, wellhead, riser and drilling BOP.

**Perforate Top of DPZ 2**
As previously mentioned, the 13 3/8" casing was perforated in the intersection between DPZ 2 and seal 2, approximately 70 m below the planned setting depth of the bismuth plug. This way, shallow gas from DPZ 2 can easily flow into the well, and hopefully develop a differential pressure across the bismuth plug. The perforation interval was 5 m (427-432 m), where the bottom 2.5 m covers the top of DPZ 2. Inhibited Seawater (ISW) with a density of 8.6 ppg was used during the operation.

**Install Leaking Bridge Plug With Gauge Hanger**
A bridge plug was set to act as a base for the sand, and consequently as a base for the bismuth plug. Fig. 7.6 (a) shows the final tool assembly with the bridge plug and the gauge hanger, while Fig. 7.6 (b) shows only the bridge plug. To make sure it is the bismuth holding pressure, and not the bridge plug, the bridge plug was modified to leak pressure. A slotted liner was therefore included below the bridge plug,

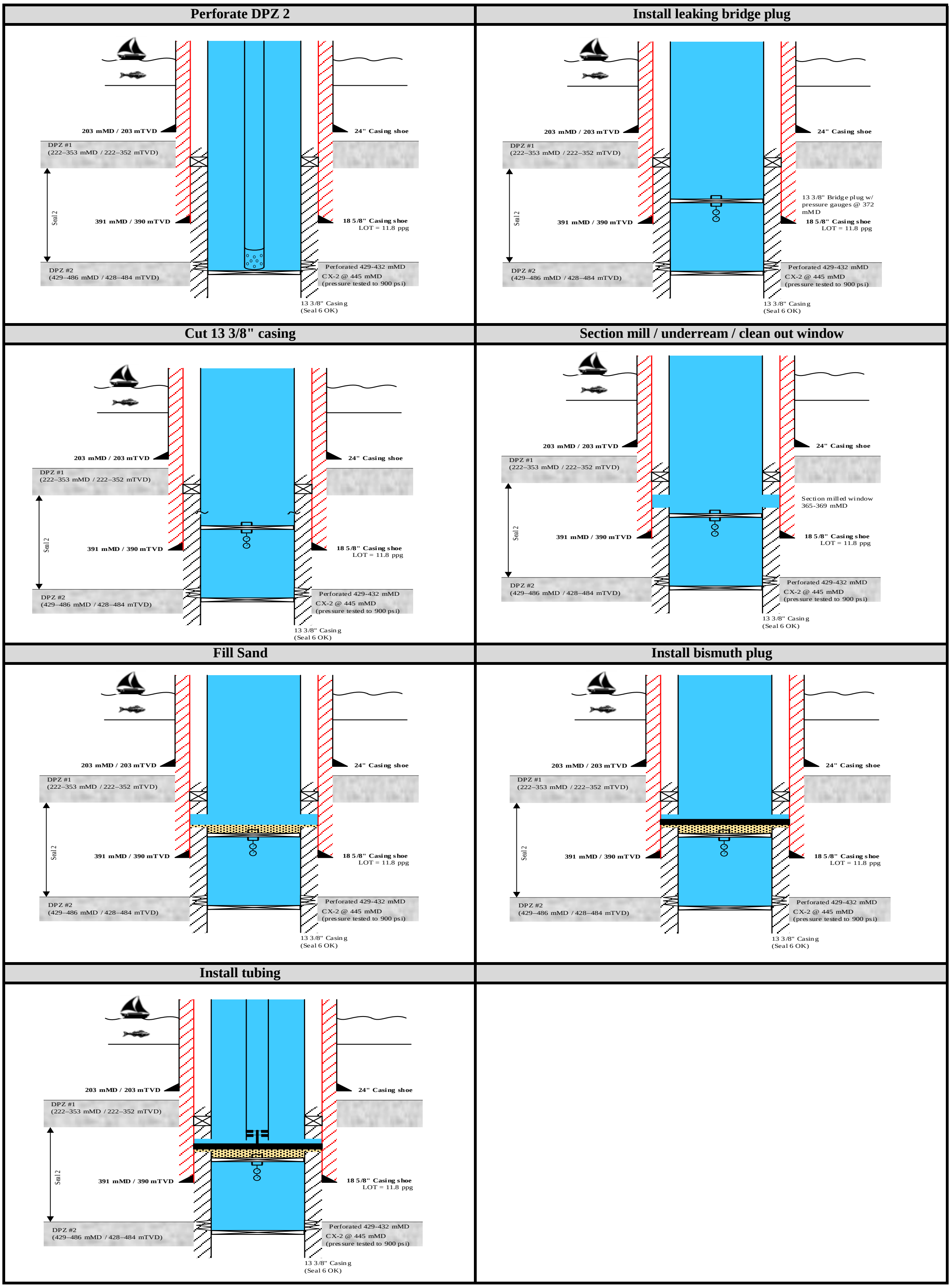



**Figure 7.5:** Well status schematics demonstrating the operational sequence when installing the bismuth plug.

allowing gas migration through the inside of bridge plug. The slotted liner was placed inside a ported sub, as shown in Fig. 7.6 (c). Simultaneously, the bridge plug houses two pressure gauges. One of the pressure gauges is a memory gauge, while the other one is an acoustic gauge for live monitoring.

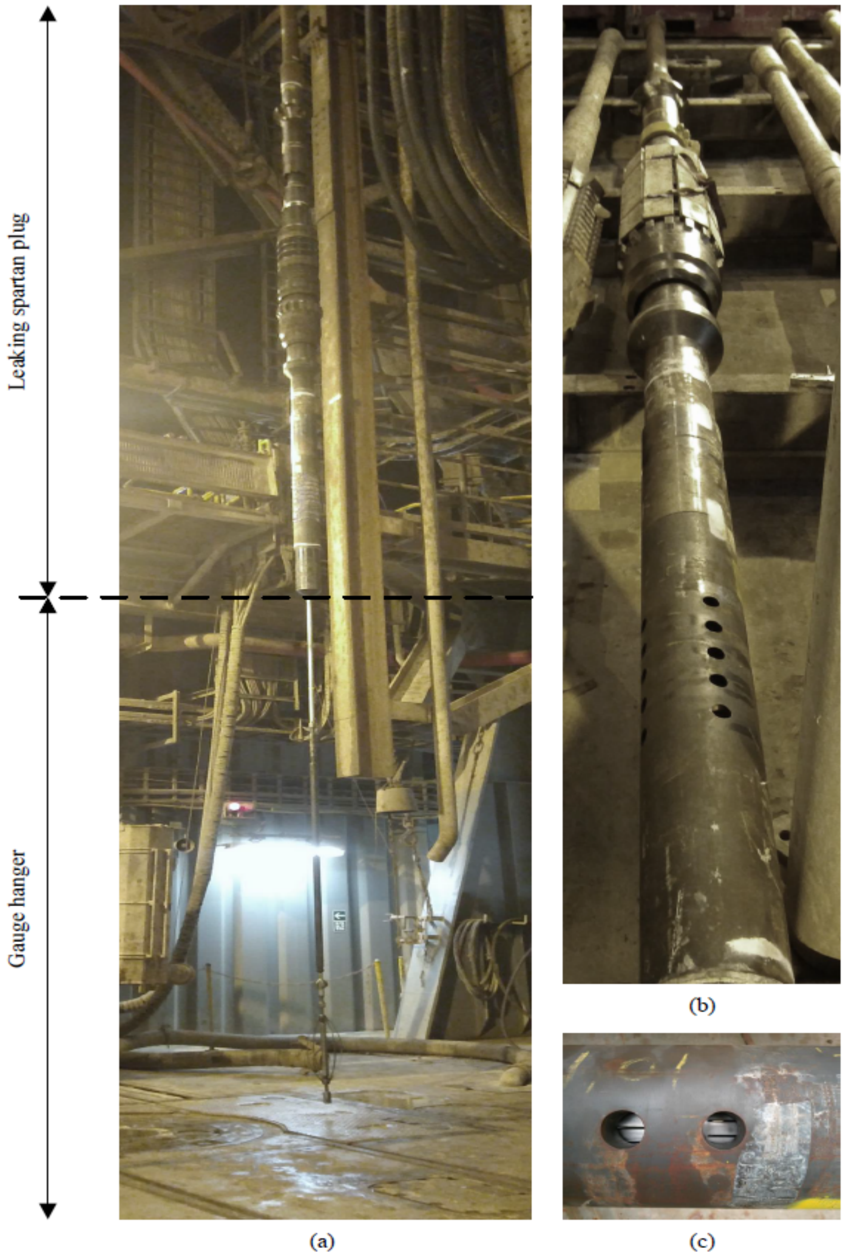



**Figure 7.6:** Leaking bridge plug with gauge hanger. (a) Final assembly ready to be run in hole with gauge hanger below the bridge plug. (b) Leaking bridge plug. Anchor of plug shown in upper part of picture and the ported sub below. (c) Slotted liner placed inside the ported sub.

### Cut opening hole in 13 3/8" casing prior to milling

To enable section milling of the 13 3/8" casing, the casing needed to be cut to have a starting point for the milling. At 365 m, the casing was cut and the opening hole for the section mill was enlarged to 0.5 m. The well fluid was ISW at 8.6 ppg. To remove swarf downhole, generated when cutting the casing and enlarging the cut section, sweeps were pumped. ISW has no viscosity and lifting capacity, hence sweeps were pumped and proven sufficient to help remove swarf downhole. Sweeps are small volumes of high viscous fluid pumped in addition to the seawater after performing the cut to help lift swarf. The number of sweeps pumped were decided from observing swarf recovered over the shakers.

**Section Mill Window**

Access to the 18 5/8” surface casing was obtained through section milling. A 4 m window was milled from 364-368 m. Well fluid was ISW at 8.6 ppg, and sweeps were pumped to help remove swarf downhole.

**Underream Section Milled Window**

An underreamer with special designed arms were made for this application. The underreamer, shown in Fig. 7.7 (a), was applied to clean the inside of the surface casing and remove debris and cement, representing potential leak paths along the casing wall. Steel wire brushes were mounted at the end of the extending arms of the underreamer to improve the cleanliness. Well fluid was still 8.6 ppg ISW with sweeps pumped to help clean out and remove solids from the well. Fig. 7.7 (b) shows the condition of the underreamer after use.

(a) (b)

**Figure 7.7:** Special designed underreamer tool before and after. (a) Before run in hole. (b) After use.

**Clean Out Section Milled Window**

Swarf generated when section milling a window inside the 13 3/8" casing was removed using a modified Tornar tool. This tool included a magnet and a junk basket to help recover swarf from the well, as ISW still was used in the well. The Tornar tool is normally used for cleaning the BOP after a milling job, but was modified for this special application by including the junk basket and reducing the OD. Also, sweeps were pumped to help lift the swarf.

Tests in Houston showed particles like swarf would most likely float on top of the bismuth plug due to the high density of the bismuth. However, the Tornar tool was included to ensure the area above the bridge plug was clean, as the bridge plug will be retrieved after the monitoring period. Swarf settled on top of the bridge plug would complicate the plug retrieval.

Fig. 7.8 (a) and (b) shows the magnet covered with swarf after a clean out run, while Fig. 7.8 (c) shows the junk basket filled with swarf. Section milling a window of 4 m in the 13 3/8" casing (72 lbf) theoretically generates a total of 428.6 kg of swarf. After four runs with the modified Tornar tool, the clean out was concluded to be sufficient. Then, 189 kg swarf had been recovered by the magnet and junk basket on the Tornar tool. In addition, swarf was continously returning over the shakers. However, the amount of swarf returning over shakers was not measured.

(a) (b) (c)

**Figure 7.8:** Tornar tool. (a) Magnet on Tornar tool covered by swarf after run in hole. (b) Swarf on magnet. (c) Junk basket filled with swarf, positioned above the magnet.

**Fill Sand**

Sand was pumped on top of the bridge plug for various purposes. Since the bismuth plug eventually will be drilled out to recover the memory pressure gauge, melting the bismuth directly on top of the bridge plug would complicate the future recovery of the bridge plug. Therefore, sand was pumped to protect the bridge plug housing the pressure gauges. Secondly, pumping enough sand to cover the bottom of the section milled window ensures that gas can easily migrate through the sand out to the surface casing. As a result of this, the bismuth plug will prove its capacity to seal across the entire cross section inside the surface casing.

Two barrels of 20-40 gravel pack sand was pumped and placed downhole through open ended drill pipe. This volume was calculated to be sufficient to fill the inside of the slotted liner in the leaking bridge plug and cover the area above the plug. Estimated top of sand was approximately 0.7 m above the bottom of the section milled window.

Prior to pumping the sand downhole, the carrying liquid was gelled up to some extent using duotec to keep the sand in suspension while pumping to avoid fall-out. Duotec is a polymer that adds viscosity to the mixture of sand and seawater. However, the amount of duotec was minor. This way, it was faster to break the gelled liquid after pumping the mixture into the well, and thereby allowing the sand to quickly fall out after being pumped into the well.

**Run Camera: Verify Top of Sand**

A downhole camera, shown in Fig. 7.9 (a) and (b), was run on drill pipe to verify and confirm top of sand. Visibility was limited to some extent due to sand downhole, but camera tagged top of sand at the calculated depth. Fig. 7.10 shows the top of sand observed by the downhole camera. The top of the sand was confirmed at 367 m.

(a) (b)

**Figure 7.9:** Downhole camera run on drillpipe. (a) Downhole camera before assembled. (b) Camera assembled and ready to be run in hole.

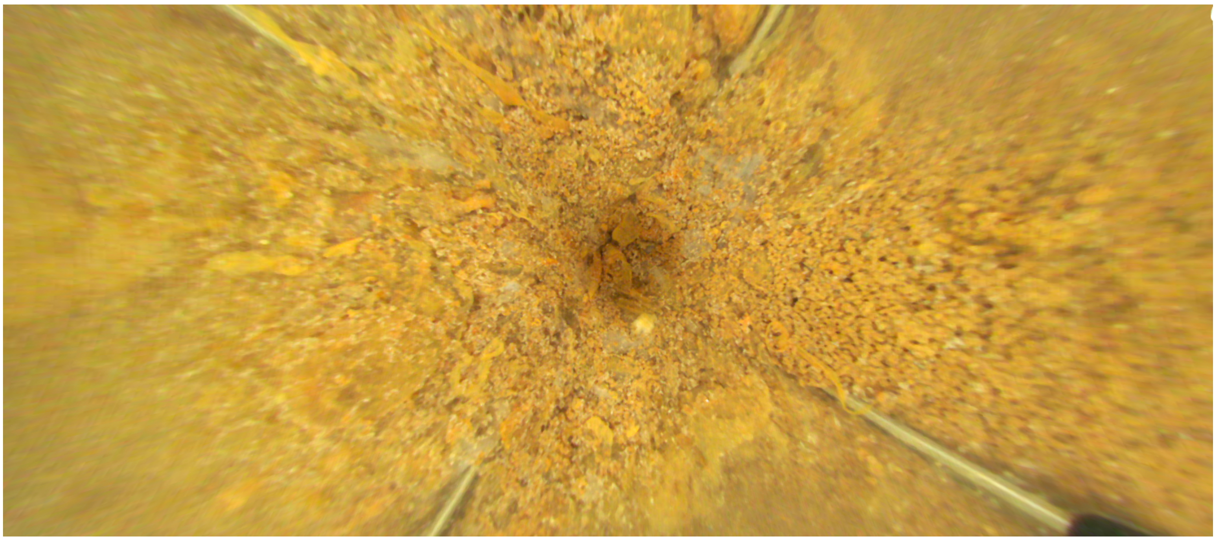


**Figure 7.10:** Top of sand observed from downhole camera

**Run and Install the Bismuth Plug**

Before initiating the installation of the bismuth plug, the well was displaced to $CaCl_2$-brine, which was the well fluid used in the final successful tests in the full scale test program. The brine had a density of 10.8 ppg. Thereafter, the bismuth plug was run into the hole on wireline, using a special designed 7/16" monocable. In total, the bismuth plug and the heater weighted 9400 lbs. That weight by far exceeds the strength of normal wireline. Fig. 7.11 (a) shows both primary and back-up bismuth/heater ready for installation, where the grey is the bismuth alloy and the black section is the heater sleeve. Fig. 7.11 (b) shows the assembly being elevated into position on drill floor before being run in hole.

The top of the sand was successfully tagged with 1930 lbs set down weight at 368.6 m. Then, an electric signal was sent from surface, initiating the starter that provided heat to ignite the thermite burning process. After having burnt for 37 minutes, the heater was successfully pulled out from the melted alloy, leaving a 2 m long bismuth plug downhole. First, the heater was only pulled 10 m above the melted alloy and positioned here for two hours. This allowed the heater to cool down before pulling it out of the hole. Visual inspection of the pulled heater, seen on Fig. 7.11 (c), confirmed that all bismuth alloy was melted downhole.

To avoid disturbing the solidification process of the bismuth plug, re-entering the well was purposefully delayed by several hours. Meanwhile, the BOP was inspected as this is a requirement after performing milling operations.


(a) (b) (c)

**Figure 7.11:** Bismuth plug assembly consisting of bismuth alloy and heater (a) Primary and back-up bismuth assembly. Heater sleeve is the upper black section. (b) Bismuth lifted in place and ready to be run in hole. (c) Thermite heater after melting bismuth. No bismuth alloy was observed on the heater.

**Monitor Temperature**

Due to uncertainties whether the plug had successfully cooled down and solidified, it was decided to cool down the brine and monitor the temperature above the plug. Cooling down the bismuth was attempted through circulating brine while continuously monitoring the downhole temperature. The formation temperature at this depth at Valhall DP is normally around 30 °C. Temperature readings vs. time are plotted in Fig. 7.12, and a declining temperature is observed before it flattens out. Temperatures measured when circulating fluid is lower than the formation temperature, hence the subsequent temperature increase observed when stopping the fluid pumps has a natural explanation. Cooling of the bismuth plug was ended when it was observed that temperature peaks normalised over several build-up periods.

The drill pipe and the temperature gauge was located 2 m above the plug. The temperature monitoring schedule was:

1. 30 minutes cool down (pump brine)
2. 15 minutes build up (stop pumpes)
3. 60 minutes cool down
4. 30 minutes build up

This system was cycled three times before lowering the drill pipe and the temperature gauge to 1 m above the plug.

Subsequently, the monitoring schedule was modified to:

1. 60 minutes cool down
2. 30 minutes build up

After cycling this schedule four times, the well was displaced back to seawater, and thereafter, the open ended drill pipe was pulled out of the hole.

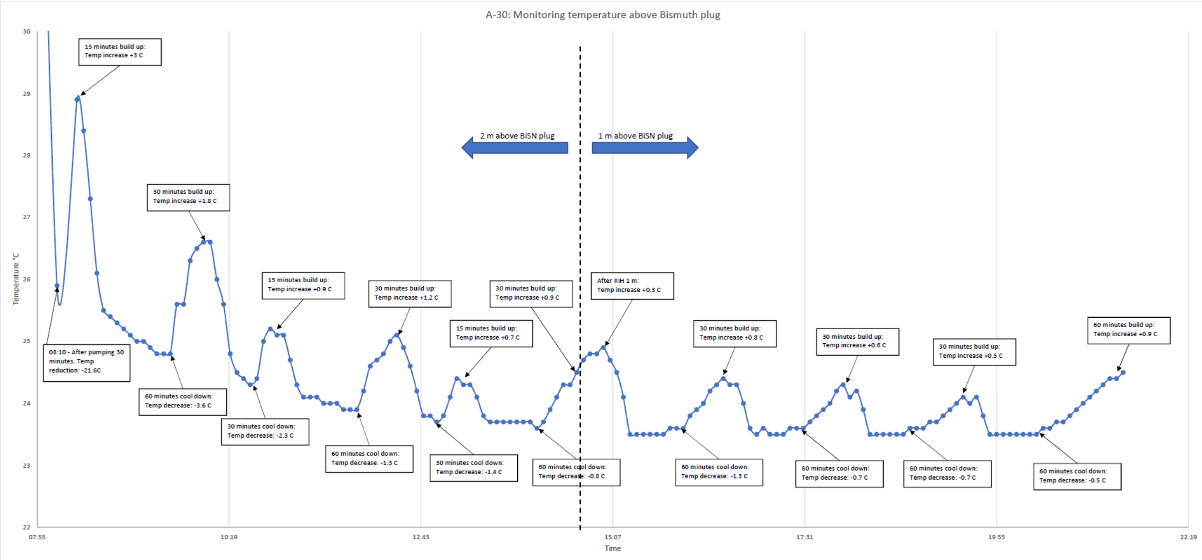



**Figure 7.12:** Monitoring temperature above bismuth plug and cycling circulation to cool down the plug. First monitoring temperature 2 m above the plug, and thereafter 1 m above the plug.

### Run Camera: Inspect Section Milled Window and Bismuth Plug

The same downhole camera used to inspect the top of the sand was again run down on drill pipe to inspect the section milled area and the bismuth plug. This time, the well was displaced to drill water before running the camera to improve downhole visibility. The section milled area was investigated, seen in Fig. 7.13, and the effect of the underreamer was proven sufficient.

Subsequently, the placement and the top of the bismuth plug was verified. The downhole camera revealed a seemingly smooth surface at the top of the plug, observed in Fig. 7.14. Unfortunately, during maintenance, an o-ring had fallen into the wellbore, hence the black "ring" on the picture.

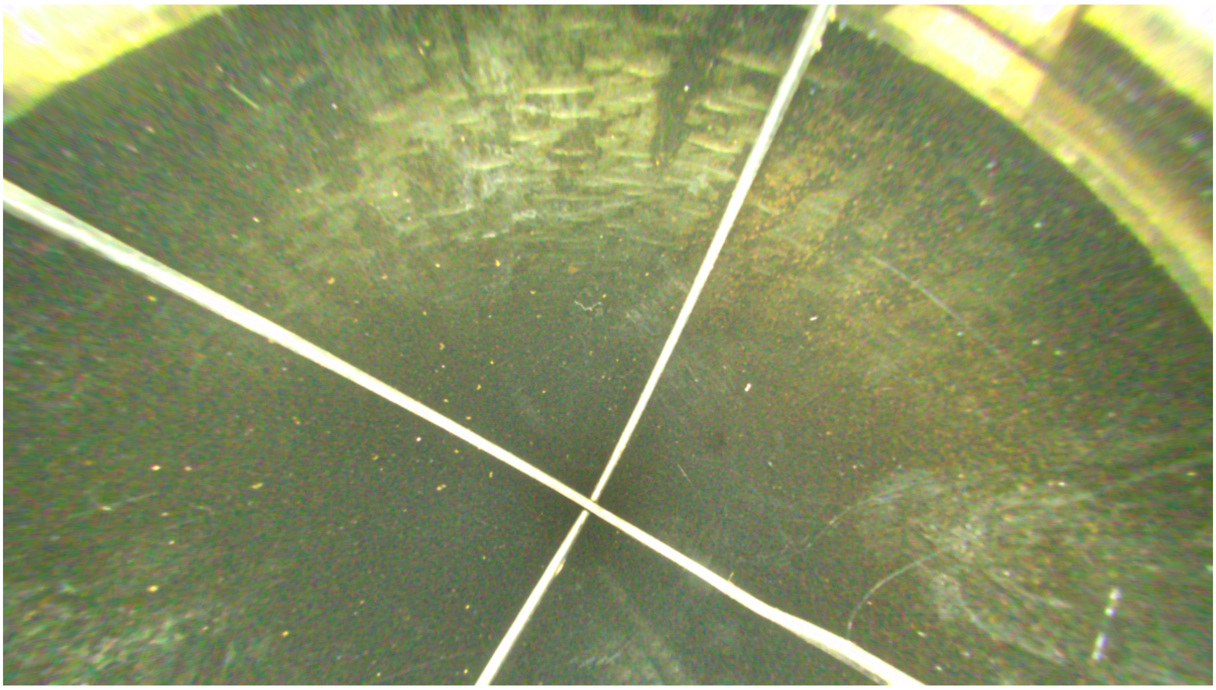


**Figure 7.13:** Inspection of section milled window with downhole camera. Observing scraping lines on the ID of the surface casing in section milled window shows the effect of the underreamer.

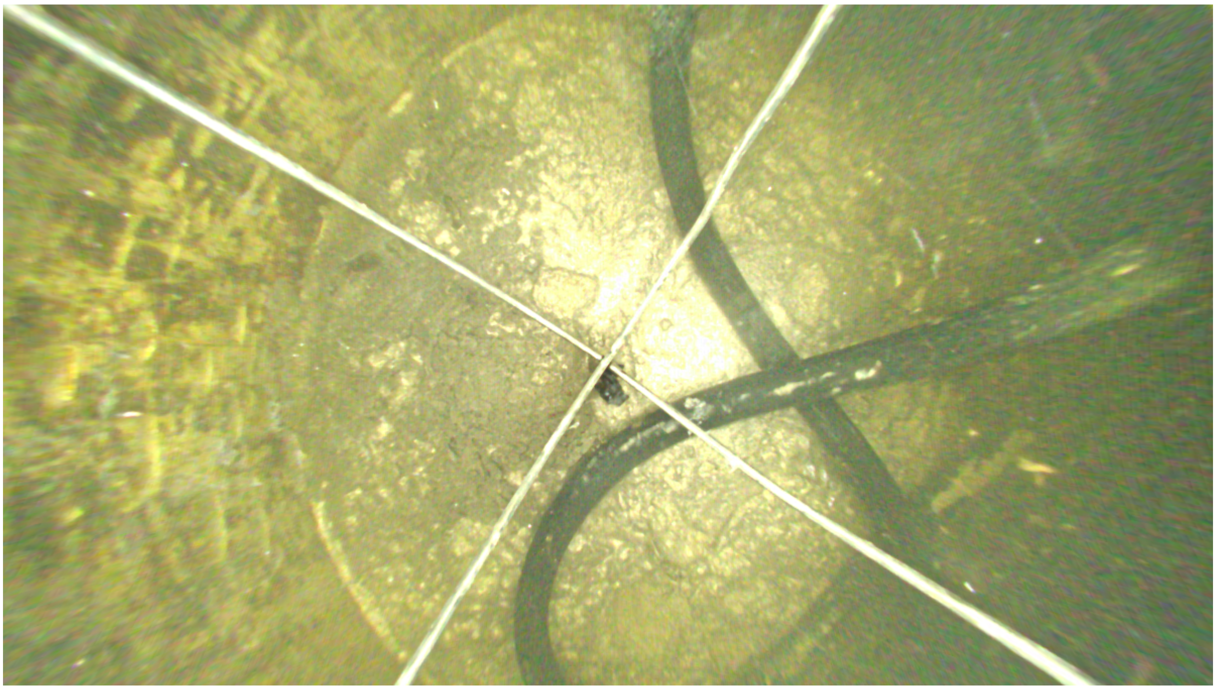


**Figure 7.14:** Downhole camera showing top of bismuth plug (in addition to an o-ring lost in the well during maintenance).

### Install 5 1/2" Tubing For Monitoring

To enable live monitoring from the acoustic pressure gauge below the bismuth plug, a downhole receiver and transmitter was required. Therefore, a 5 1/2" tubing was installed in the well containing an acoustic data receiver and transmitter. Tubing was spaced out and landed with an acoustic data receiver in contact with the bismuth plug. In addition, a combined acoustic data receiver and transmitter was installed in the wellhead to transmit signals from the downhole gauges to the Aker BP internal network for live monitoring.

### 7.2.3 Verification of Installed Bismuth Plug

After installation, the bismuth plug was verified through tagging, running of a downhole camera and pressure testing. Tagging and visual inspection by a camera verified its position, while its sealing capacity was verified through pressure testing. Also, the camera verified no gas bubbles above the plug. The plug was tagged with 10 klbs at 366.23 m, which was the calculated and projected depth for the top of bismuth.

Pressure testing the plug was performed using 8.6 ppg ISW, applying a differential pressure of 330 psi for 1.5 hour from the jack-up rig. The pressure test was successful, having full returns of the same volume pumped to pressurize the wellbore. In the test program, the bismuth plugs were tested to 500 psi as this was the test pressure limitation for the surface casings on Valhall DP. For cement plugs inside a surface casing, NORSOK D-010 requires pressure testing to 1000 psi above estimated leak-off pressure at shoe, but not exceed the pressure test of the casing or its burst rating [NORSOK, 2013]. Due to casing wear, as a result of performing sidetracks, the surface casing on Valhall DP has been de-rated to 330 psi. Hence, pressure tests should not exceed 330 psi.

In addition, pressure monitoring above and below the plug was included to verify the integrity of the plug over a longer period of time. Hopefully, shallow gas will migrate through the perforations and the bridge plug, creating a differential pressure across the bismuth plug. However, the pressure below the bismuth is still unknown. Communication with the acoustic gauge included for live monitoring has not yet been established. The readings from the memory gauge will not be available until after the two year monitoring period, when the bismuth will be drilled out and the bridge plug retrieved.

Per date, pressure readings above the plug indicate the bismuth plug is successfully sealing inside the surface casing as there has been no pressure build-up after the plug was set.

# Chapter 8

# Defining critical risk related issues

Before utilizing bismuth as a barrier material, it is important to be aware of all risk related issues of a bismuth plug. Understanding how the material can fail and what may cause a potential failure is important in optimizing the design and the installation procedure. The issues addressed in this chapter are based on my own thoughts in addition to discussions with colleagues and supervisors in Aker BP.

## 8.1 Failure Modes of a Bismuth Plug

Considering the potential failure modes identified by UK Oil & Gas, described in section 3.4.2, two out of the three failure modes are relevant for a bismuth plug; leakage around the bulk material and shift in barrier position.

Leakage around the bulk material is the primary failure mode in terms of risk. Since the bismuth is non-wetting and not bonded to the casing, there is a risk of leakage on the outside of the bismuth. Leak paths and micro-annuli along the interface between the bismuth and the casing wall may prevent the plug to seal and withstand differential pressure.

Secondly, a shift in barrier position is also a failure mode, and since the bismuth is not bonded to the casing, that is also a risk. If expansion is insufficient or the material creeps, there is a risk of shifting the position of the bismuth plug if it experiences high loads.

## 8.2 Failure Mechanisms and Root Causes

After identifying how the bismuth plug can fail to maintain its sealing capacity, it is important to understand why the bismuth plug could fail and what could cause failure. Uncertainties, potential failure mechanisms and other risk related issues are identified and categorized for three phases; Design/Pre-installation phase, operational phase (installation), and post-placement phase.

### 8.2.1 Pre-Installation/Design Phase

The risk of a failed bismuth plug is considerably reduced by performing thorough preparatory work and planning. Collecting information about the well conditions at setting depth is crucial for constructing a successful and sealing bismuth plug. Primarily, downhole temperature and pressure are needed to achieve an appropriate design of the bismuth alloy and the thermite for the desired application. As mentioned previously, the bismuth alloy has to be selected by comparing downhole temperature and melting temperature of the alloy. Subsequently, the thermite selection is based on the bismuth alloy selection to ensure complete melting of the alloy without burning through the heater.

Casing size and well inclination are also essential parameters when estimating the volume of bismuth alloy needed to ensure the bismuth plug is sealing properly. As mentioned in section 5.3.1, BiSN has performed tests to analyse the relationship between the length/diameter of the plug and the maximum differential pressure capability. The relationship was found to be approximately linear, shown in Fig. 5.1. However, most data points in this graph are for higher length/diameter ratios. Using the length and diameter ratio from the plug set on Valhall DP, it should be able to withstand approximately 2400 psi, with water as test medium. Since the bismuth plugs was not pressurized to failure with water during the test program, the linear relation shown in by this graph was not confirmed. For plugs with lower length/diameter ratios, there is a risk of overestimating the sealing capacity of the plug. Performing sufficient testing will address, and most likely confirm, this relation.

Furthermore, since the boiling point of a well fluid reduces as pressure is reduced, there is a risk of generating gas bubbles if the fluid starts to boil from the high temperatures generated by the heater. Gas bubbles generated could potentially disturb the solidification process and affect the uniformity of the plug. This risk is most relevant for a shallow set plug where the hydrostatic pressure is relatively low. A mitigating action towards reducing this risk could be to pressure up the wellbore.

Another important part of the pre-installation phase is to perform Computational Fluid Dynamics (CFD) modeling. CFD modeling is used to analyse and predict the behavior of the bismuth alloy. This includes estimating the time it takes to melt the entire volume of bismuth alloy and when the alloy will solidify. Results from these analyses will give an indication as to when the heater should be pulled from the melted alloy, in addition to when the plug could be safely pressure tested. However, the CFD modeling is dependent on exact input parameters, such as formation temperature and conductivity, to produce a valid result. Otherwise, there is a risk of failing the bismuth seal if the calculations are wrong. Estimation of when the heater can be pulled and the solidification of the bismuth plug can not be correlated against yard-tests. This makes the assessment more complicated. In contrast to the low conductivity of air, the heat conductivity of the formation has a thermos-like effect on the bismuth. Hence, determining when to pull the heater and when the bismuth is completely solidified will be dependent on the CFD-analysis.

Moreover, leak paths and micro-annuli at the interface between the bismuth plug and the casing can occur from insufficient cleaning of the casing wall prior to setting the plug. The 13 3/8”x20” test program revealed the importance of having a clean casing wall before setting the bismuth plug to prevent micro-annuli along the plug-casing interface. Therefore, when determining how to access the outer annulus (drilling holes or section milling) it is important to evaluate how to ensure the ID of the outer casing will be cleaned efficiently. A mitigating action to help preventing micro-annuli along the interface is to use particle-free fluid when installing the bismuth plug. Placing the bismuth downhole in brine proved efficient in the test program, whereas drilling mud left silt-lines along the casing wall.

Finally, there are risks related to manufacturing of the bismuth plug. The entire assembly, consisting of bismuth based alloy, thermite heater and thermite mixture, is manufactured and assembled before being transported for installation. As previously mentioned, all bismuth plugs are exclusively designed for their setting environments. Thus, a future mass production could be a challenge in regards to keeping consistency of the alloy, the thermite and the coating of heater. For example, coating of the heater is manual work, which may increase the risk of inconsistency and faulty coating.

### 8.2.2 Operational Phase

During the operational phase when installing the bismuth plug, depth control is crucial. In contrast to setting cement plugs over a 100-200 m interval, a bismuth plug could be as short as 2 m. Hence, accuracy regarding depth control is very important, for instance when cutting and milling casing.

To avoid leak paths along the interface between the bismuth plug and the casing wall, the setting area for the plug needs to be cleaned. During this operation, it might be difficult to evaluate when the casing is clean enough and ready for installation of the bismuth plug.

Reliability of logs is a concern as an annular base for the bismuth plug can be confirmed by logging the 13 3/8” casing. If the log is implying an annular base of cement, which later is found to be incorrect, there is a risk of not achieving a sealing bismuth plug. Due to the high density of the bismuth, it could displace annular fluids and slump downwards into the 13 3/8”x20” annulus. However, due to the eutectic characteristics of the bismuth, the melted alloy is assumed to experience a candle-light effect when flowing into the annulus. As a candle light burns, tallow will solidify before it runs off. Similarly, melted bismuth alloy is presumed to solidify instantly when the temperature drops below its melting temperature, and therefore building an annular base as it solidifies. However, no tests have been performed to justify this argument.

Another concern is the unknown temperature effect on the surrounding environment downhole from the high temperature of the melted alloy. There is a potential risk of damaging both casing and casing cement in the setting area when setting the plug. BiSN has performed studies to investigate to which extent this is an issue, but test results are not published yet.

Operational accuracy regarding time is also required as solidification of the bismuth is crucial. For instance, if the heater is pulled too late, there is a risk of not being able to pull the heater at all, since bismuth would have started to solidify. Also, retrieving the heater too early could cause incomplete melting of bismuth. The time interval between initiating the burning process and the heater retrieval is specified in minutes, calculated from CFD-modeling. In addition, the vulnerability of the bismuth with respect to heater removal speed/rate is an uncertainty, hence, a future testing subject. The plug should not be tagged or pressure tested prematurely either, as there is a possibility of damaging the bismuth seal if it is not completely solidified. As previously mentioned, the solidification time of the bismuth is also an output from the CFD-modeling.

In contrast to cement, where contamination is a risk as the slurry is mixed at surface and pumped downhole, the risk of contaminating the bismuth is very low. Since the bismuth plug is melted downhole, pumping is avoided and the risk of contamination is reduced significantly. In addition, the risk of contamination from well fluids can be more or less neglected due to the considerable density differences between the melted bismuth alloy and conventional well fluids.

As the bismuth solidifies and expands, the quality of the seal is dependent on radial expansion. If the bismuth mainly expands vertically the surface friction along the interface between the bismuth and the casing will not be sufficient to withstand the differential pressure required to act as a seal. However, temperature measurements have confirmed that the bismuth will first solidify in the top and bottom. Then, the melted alloy will be trapped and forced to expand radially, creating a sealing plug.

### 8.2.3 Post-Placement Phase

If the bismuth is not confined properly, there is a risk of de-bonding due to casing expansion. BiSN's small scale testing has shown bismuth keeps expanding even after the melted alloy has solidified. Therefore, if the setting area is not confined and not able to withstand the expanding forces from the bismuth, the plug will not be able to provide a proper metal-to-metal seal. However, whenever set inside a cemented casing, the bismuth is likely to be sufficiently confined.

Pure bismuth is known as a non-corrosive element, but the corrosion resistance of the alloy needs to be verified to eliminate corrosion as a risk and failure mechanism. As mentioned earlier, comprehensive testing is currently being performed to investigate and confirm the bismuth based alloy's resistance to a corrosive environment and long term integrity. The results currently provided from BiSN are in accordance with the standards used in Aker BP to evaluate corrosion resistance (ISO 15156 and NORSOK M-506). Thus, the bismuth alloy is considered as a corrosion resistant material.

Additionally, as for all barrier materials, tectonic movement and stresses developed at the setting depth can potentially cause cracks and deformation of the casing and the plug. As a result, flow paths can be established along the bismuth-casing interface and cause the plug to fail.

# Chapter 9

# Conclusion

## 9.1 Summary of Qualification Process

Today, the industry is looking for alternatives to cement for P&A applications, and bismuth is one of the new barrier materials being considered as an alternative. Before being able to utilize bismuth for permanent P&A of a wellbore, the material needs to be qualified. Qualifying new barrier materials is an industry responsibility, hence, Aker BP initiated a testing and verification process together with BiSN. The objective was to qualify bismuth as a barrier material for permanent P&A while ensuring the process was in line with the most recent and conservative requirements for qualifying new technology.

The flowchart shown in Fig. 3.2 in chapter 3 outlines the qualification process defined by UK Oil & Gas for qualifying new technology. In this case, a new barrier material was to be qualified. The work presented in this thesis is in accordance with this flowchart. Data and information about bismuth has been collected, failure modes and risks have been identified, and the material has been verified both through full-scale yard testing and field installation.

After optimizing the bismuth plug and the heater design in the full-scale yard testing, the bismuth plug was successfully installed and verified in a field installation. Final verification is still ongoing as the plug is currently being monitored, and current pressure readings (after 8 months) indicate no leakage. Consequently, the bismuth plug may be recognized as a qualified barrier material for the specific well conditions and geometry presented in this thesis. However, this statement is made assuming all currents tests, including accelerated long term integrity tests, prove bismuth as a suitable barrier material.

Several learnings were made, and the main learnings from this qualification process includes:

- It is recommended to set bismuth plugs in a particle-free well fluid
- It is important to sufficiently clean the plug setting area to eliminate potential leak paths
- Bismuth alloy requires a sufficient concentration of bismuth to achieve adequate expansion rates
- Thermite mixture and heater need to be selected on a case by case basis

## 9.2 Proposed EAC-Table for a Bismuth Plug

Table 9.1 is a proposed EAC-table for a bismuth plug, made as a result from the verification process presented in this thesis. Acceptance criteria are based on descriptions and formulations from existing EAC-tables in NORSOK D-010, in addition to specific requirements for the bismuth plug. In particular, the acceptance criteria in feature C (”Design, construction and selection”) are set by combining the critical design factors and essential learnings from the full scale test program.

| Features | Acceptance criteria | See |
|---|---|---|
| **A. Description** | This element consists of a bismuth based alloy in solid state that forms a plug inside a cased wellbore (and in the annulus between two casings) | |
| **B. Function** | The purpose of the plug is to prevent flow of formation fluids inside a wellbore between zones and/or to surface/seabed | |
| **C. Design, construction and selection** | 1. A Program shall be issued for each bismuth plug placement operation, covering as a minimum:<br>a. Diameter/length ratio of the bismuth plug<br>b. Melting and solidifying processes<br>c. Foundation requirements in casing and annulus<br>d. Approach to cleaning setting area<br>e. Properties of well fluid<br><br>2. The bismuth based alloy shall<br>a. Be designed and qualified for the highest downhole temperature and highest differential pressure expected (including installation and test loads)<br>b. Be designed to have sufficient expansion rate<br>c. Meet the requirements for material used for permanent abandonment<br>d. Be lab tested in full-scale under representative well conditions<br>i. If full-scale testing of the bismuth alloy has previously been performed for the same geometry and well conditions no further testing is required<br><br>3. The melting and solidifying processes shall<br>a. Be designed based on bismuth alloy selection<br>b. Be designed to prevent damaging the downhole environment<br>c. Be lab tested in full-scale under representative well conditions (together with bismuth alloy)<br><br>4. Minimum length of bismuth plug shall be designed to provide sufficient permanent seal, based on full scale testing (see C. 2d.) | |
| **D. Initial verification** | 1. Bismuth plug shall be tested either in direction of flow or from above<br>2. The bismuth plug installation shall be verified through evaluation of job execution considering temperature profile downhole<br>3. The bismuth plug shall be verified by<br>a. Tagging<br>b. Pressure test which shall:<br>i. Be 70 bar (1000 psi) above estimated leak off pressure (LOT) below casing/potential leak path, or 35 bar (500 psi) for surface casing plugs; and<br>ii. Not exceed the casing pressure test and the casing burst rating corrected for casing wear | |
| **E. Use** | None | |
| **F. Monitoring** | For temporary abandoned wells: The fluid level/pressure above the bismuth plug shall be monitored regularly, or inspected for leaks, when access to the bore exists. | |
| **G. Common well barrier** | None | |

**Table 9.1:** Proposed EAC-table for a bismuth plug.

## 9.3 Recommendations for Future Work

Below is a list of suggestions and recommendations for future work that could be conducted, identified respectively for ”short”, ”medium long” and ”long” term periods:

**1. ”Short” Term:** The recommended future work in the short term primarily includes completing the tests and studies currently ongoing to further investigate the characteristics and corrosion resistance of the bismuth alloy. More information about the plug length required could also be obtained if bismuth is applied to one of the leakage calculators mentioned in chapter 4. The vulnerability of the heater removal speed/rate is also a potential testing area, in addition to performing tests on milling of the bismuth. If further verification of bismuth plugs are required, it could be performed by inflow-testing the plug.

**2. ”Medium Long” term:** When characteristics of the bismuth plug is confirmed, the geometry and type of application of the bismuth plug can be varied. An option is to increase the geometry of the bismuth plug to seal across the conductor, and install a 20”x30” bismuth plug. It is Aker BP’s ambition to install a 20”x30” bismuth plug just below the seabed to act as an open hole to surface plug prior to retrieving surface casing and conductor.

An alternative application is to apply the 13 3/8”x20” bismuth plug as a temporary abandonment plug during wellhead removal before performing a slot recovery. For this application, access to the annulus would be obtained through drilling holes in the 13 3/8” casing to allow installation of a bismuth plug. After wellhead change out, the bismuth inside the 13 3/8” wellbore would be drilled out. Hence, for this purpose, it needs to be verified that the bismuth located in the 13 3/8”x20” annulus is able to isolate the annulus from pressure during future well construction after drilling out the part of the bismuth plug located inside the 13 3/8” casing.

A potential improvement to the installation of bismuth plugs is to include temperature readings downhole. Live temperature readings during the installation enables a better understanding of the downhole temperature during melting and solidification.

**3. ”Long” term:** To further develop the range of application for bismuth technology, tests should be performed towards applying a bismuth plug to an open hole solution. This enables a cross sectional barrier consisting exclusively of bismuth, and it would not be dependent on the integrity of annular casing cement as the 13 3/8”x20” bismuth plug is.

Considering that bismuth is typically run on wireline, bismuth plugs can be set as part of a rig-less solution. Being able to set well barriers rig-less is another focus area presented in the ”Roadmap for New P&A Technology” (Fig. 1.1). However, the requirements recommended in the proposed EAC-table (Table 9.1) would still apply and need to be resolved for a rig-less solution. Finally, combining bismuth with a rig-less solution can have a huge potential for great cost-savings in P&A.

# Bibliography


[AkerBP, 2017] AkerBP (2017). AkerBP Internal Document: Final Well Status Schematic A-30B.

[AkerBP, 2019] AkerBP (2019). Aker BP ASA Divests 10% in Valhall/Hod - About Valhall and Hod. https://www.akerbp.com/aker-bp-asa-divests-10-in-valhallhod/. Accessed: 27.03.2019.

[BiSN, 2019] BiSN (2019). BiSN Oil Tools, Services. https://www.bisn.com/. Accessed: 07.03.2019.

[BP, 2013] BP (2013). Aker BP Internal Document: Field Basis of Design Valhall Wells Abandonment - Permanent Plug & Abandonment. BP North Sea - Norway.

[BP, 2016] BP (2016). Valhall DP P&A Projekt: ”The Project that has it all”. https://www.norskoljeoggass.no/globalassets/dokumenter/drift/presentasjonerarrangementer/plug--abandonment-seminar-2016/07-bp-norge-valhall-panda-experience.pdf. Valhall P&A Team Presentation, P&A Forum Stavanger.

[Carragher, 2017] Carragher, P. (2017). BiSN Sealing Solutions Wel-lok M2M. https://www.norskoljeoggass.no/globalassets/dokumenter/drift/presentasjonerarrangementer/plug--abandonment-seminar-2017/09-field-experience-of-alternative-sealing-materials-and-barriers---paul-carragher-bisn-20171022192332.pdf. Presentation, P&A Forum Stavanger.

[Carragher and Fulks, 2018a] Carragher, P. and Fulks, J. (2018a). A New Look at Sealing with Bismuth and Thermite. In *SPE Annual Technical Conference and Exhibition*. Society of Petroleum Engineers. SPE-191469-MS.

[Carragher and Fulks, 2018b] Carragher, P. J. and Fulks, J. (2018b). Well Abandonment Solutions Utilizing Bismuth and Thermite. In *Offshore Technology Conference*. Offshore Technology Conference. OTC-28897-MS.

[Godoy et al., 2015] Godoy, R., Fontan, M., Capra, B., Kvalsund, R., and Poupard, O. (2015). Well Integrity Support by Extended Cement Evaluation-Numerical Modeling of Primary Cement Jobs. Society of Petroleum Engineers. SPE-177612-MS.

[Khalifeh et al., 2013] Khalifeh, M., Hodne, H., Saasen, A., and Vrålstad, T. (2013). Techniques and Materials for North Sea Plug and Abandonment Operations. Offshore Technology Conference. OTC-23915.

[Moeinikia et al., 2017] Moeinikia, F., Ford, E. P., Lohne, H. P., Arild, Ø., Majoumerd, M. M., and Fjelde, K. K. (2017). Leakage Calculator for Plugged and Abandoned Wells. Society of Petroleum Engineers. SPE-185890-MS.

[Nelson and Guillot, 2006] Nelson, E. B. and Guillot, D. (2006). *Well Cementing*. Schlumberger, 2nd edition.

[NORSOK, 2013] NORSOK (2013). NORSOK D-010 - Well integrity in drilling and well operations. *Standards Norway*, rev. 4.

[Oil & Gas UK, 2015a] Oil & Gas UK (2015a). Guidelines for the Abandonment of Wells. Issue 5.

[Oil & Gas UK, 2015b] Oil & Gas UK (2015b). Guidelines on Qualification of Materials for the Abandonment of Wells. Issue 2.

[PetroWiki, 2019] PetroWiki (2019). Cement Composition and Classification. https://petrowiki.org/Cement_composition_and_classification. Accessed: 06.02.2019.

[Price and Elizondo, 2018] Price, M. and Elizondo, B. (2018). BiSN Oil Tools Ltd Internal document: Engineering Test Program Report, Aker BP 13-3/8"x20" STC.

[PSA Norway, 2019a] PSA Norway (2019a). Petroleum Safety Authority: Regulations. http://www.psa.no/standards/category884.html. Accessed: 22.01.2019.

[PSA Norway, 2019b] PSA Norway (2019b). Petroleum Safety Authority: Standards. http://www.ptil.no/regulations/category216.html. Accessed: 22.01.2019.

[Samad, 2017] Samad, N. N. (2017). A historical Development of P&A Requirements on the NCS and its Effects on Permanently Plugged and Abandoned Wells. Master's thesis, University of Stavanger, Norway.

[Stoll, 2017] Stoll, C. (2017). Facts About Bismuth. https://www.livescience.com/39451-bismuth.html. Accessed: 04.03.2019.

[Straume, 2015] Straume, M. (2015). P&A in the Past, Present & in the Future. https://www.norskoljeoggass.no/globalassets/dokumenter/drift/presentasjonerarrangementer/plug--abandonment-seminar-2015/04---pa-in-the-past-present-and-in-the-future---martin-straume.pdf. Presentation at P&A Forum Stavanger(PAF).

[Sæth, 2018] Sæth, C. A. (2018). A Risk Based Approach for Calculating Barrier Lengths. Master's thesis, University of Stavanger, Norway.

[Underwood, 2019] Underwood, L. (2019). BiSN Oil Tools Ltd Internal document: Qualification of Bismuth Alloy Plugs for Plug & Abandonment.

[Vrålstad et al., 2016] Vrålstad, T., Todorovic, J., Saasen, A., and Godøy, R. (2016). Long-Term Integrity of Well Cements at Downhole Conditions. Society of Petroleum Engineers. SPE-180058-MS.

[Vrålstad et al., 2015] Vrålstad, T., Skorpa, R., Opedal, N., and De Andrade, J. (2015). Effect of Thermal Cycling on Cement Sheath Integrity: Realistic Experimental Tests and Simulation of Resulting Leakages. Society of Petroleum Engineers. SPE-178467-MS.