Havindustritilsynet

Sement-bond logging, evaluering av skumsement

Report

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THRE360 ENERGY

STUDY REPORT

Havtil – Well integrity Logging foam cement 360NOR-PRJ-338-24

Study Report Information:

Table 1 Study Report Information

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Revision History

Table 2 Revision History

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Innholdsfortegnelse

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1 Executive Summary

The Norwegian Ocean Industry Authority (Havtil) requested Three60 to carry out a study on using cement evaluation logging to verify foam cement barrier elements. The project started on April 11, 2024, and a workshop was held on September 19 to discuss challenges and agree on a way forward.

We collected the limited evidence available in the literature and complemented it with reprocessed cement evaluation logs from Norway. During the workshop, extensive experience spanning more than two decades was shared by two operators and three service companies and supported four main conclusions:

1. Foam cementing activity is expected to increase in Norway, driven by the advantages of foam cement as well as the ability to deploy the technology effectively, efficiently, and safely. In particular, the strengthening of alternative suppliers and the improvement of cement evaluation software and protocols over the last five years were cited as important factors.
2. Since its deployment in Norway in 2000, foam cement has been used in over 500 production strings, reflecting its reliability and suitability in this region. Experience has shown that, despite the occurrence of liquid microannuli, which are comparable to those of unfoamed cement, there is no evidence of slow gas leaks through these defects. Although connected water layers can serve as conduits for gas bubbles, resulting in a very low rate of around 1 ton per year, the lack of evidence suggests that the water layer seen by the logs is encapsulated within the foam cement.
3. The fixed log threshold used by some service companies and operators cbe misleading, based on the lack of leak evidence through foam cement. The issues experienced while qualifying annular cement may thus be a consequence of mismatched expectations rather than actual isolation problems or unusual behaviour of foamed cement. Standardising interpretation protocols adapted to foam cement is key to overcoming this obstacle.
4. Collaborative research between industry and academia is underway to further study the evolution of foam cement over time, including experiments that combine flooding and cement crushing, as well as the development of computational fluid dynamics (CFD) models to simulate the placement of foamed cement slurries.

2 Summary

This report describes a study on foam cement that was carried out by Three60 on behalf of the Norwegian Ocean Industry Authority (Havtil).

The project started on April 11, 2024 and was structured in two phases:

1. An initial review of foam cement as a material, detailing: applications and limitations, placement and barrier qualification, and current industry best practices in Norway and worldwide.
2. A workshop that was held on Sep 19, where NCS operators and service companies shared their insights on both technical aspects and market outlook.

The literature review revealed limited evidence on qualifying foam cement as a barrier: only four SPE papers discuss the issue in any detail, one of them from ConocoPhillips in Norway. A review of the research from Barbara Kutchko's group in the NETL (National Energy Technology Lab-USA) similarly confirmed that very little of their results concerned barrier qualification: the main focus was shallow migration prevention in the Gulf of Mexico, where cement quality doesn't need to be verified.

Foam cement offers several advantages for two main applications:

- Migration Prevention for Shallow Gas and Water: foam cement compressibility compensates cement shrinking early during the cement hydration phase, preventing hydrostatic pressure reduction. This application originated in the Gulf of Mexico in the early 2000s and has also been attempted in Norway. Foam contributes to well mechanical integrity by reducing the risk of cement washout and acts as an annular barrier element for containing shallow gas (and brine), however it is not part of the reservoir barrier system and hence it is not logged.
- Reservoir Isolation and Barrier Reliability: foam is suited to isolating the reservoir and delivering reliable barrier elements, especially when reservoir depletion narrows the drilling window:
    1. Its density can be engineered to be close to the mud's and reduce the equivalent circulating density (which also prevents losses).
    2. Its compressibility prevents fluid migration, as it does when cementing shallow gas sections; it also increases displacement efficiency by compressing and expanding the foamed slurry as it is displaced through the annulus.
    3. Additionally, foam cement has favourable mechanical properties, including higher ductility and therefore better resistance to shattering when perforating. Whereas this it unlikely to play a role at the 30-m scale of a barrier element, it is a big advantage for reservoir isolation.

Due to these advantages, most barrier jobs with a specific operator in Norway are performed with low foam quality (around 10% nitrogen volume). However, foam cement also presents several challenges:

- Complex Design: simulating placement of compressible fluids is a recent innovation, and their viscosity is still poorly understood - and cannot be measured in the lab. Furthermore, the surfactant used to stabilise the foam can be consumed by oil-based mud, so contamination must be avoided (using spacers, among other measures).

- Lab Testing Limitations: routine tests, such as thickening time and compressive strength evolution are hard to mimic in the lab, and rely on a representative sample of foamed slurry, which is difficult to obtain in a laboratory setting.
- Operational Complexity: handling nitrogen equipment requires deck space, and foaming must be controlled carefully, especially where we expect returns as foam compressibility also trigger well control alerts if returns fluctuate during the job. For these reason it is essential for successful operations to thoroughly prepare, maintain clear communication and competency of the foam engineer must be assured.
- Log Interpretation and Placement Qualification: reduced density differences between mud and slurry, coupled with uncertainty in slurry viscosity and high deviation of production strings, are a challenge when matching placement simulations with cement job data. Some operators have used torque when rotating liners to detect foam slurry in the annulus, which, together with return rates and surface pressure has allowed estimating cement coverage at the end of placement.
- Log Response Variability: Early Post-job acoustic properties of foam can be low, making it difficult to distinguish from fluids, especially with liquid-filled microannuli. Foam properties improve over time, which raises questions about optimal timing for logging.

Log interpretation challenges and short barrier intervals after foam cement placement were key motivations for this study.

During the workshop, extensive experience spanning more than two decades was shared by two operators and three service companies and supported four main conclusions:

1. Foam cementing activity is expected to increase in Norway, driven by the advantages of foam cement and the improved efficiency, safety, and effectiveness of deploying this technology. In particular, alternative suppliers growth and enhancements in cement evaluation software and protocols over the last five years were cited as important factors.
2. Since its deployment in Norway in 2000, foam cement has been used in over 500 production strings, reflecting its reliability and suitability in this region. Despite the occurrence of liquid microannuli (similar to those seen in unfoamed cement), there is no evidence of slow gas leaks through these defects. While connected water layers can sometimes channel gas bubbles at a very low rates (around 1 ton per year), the lack of evidence suggests that the water layers observed in logs are encapsulated within the foam cement.
3. Concerns about liquid-filled microannuli possibly affecting slow gas leaks with foam cement imply that the fixed log threshold used by some service companies and operators may be misleading. Qualifying annular cement may therefore reflect mismatched expectations rather than true isolation problems or unusual foamed cement behaviour. Standardising interpretation protocols adapted to foam cement is essential for addressing this issue.
4. Collaborative research between industry and academia continues to study foam cement's long-term evolution, including flooding and cement crushing experiments, and developing computational fluid dynamics (CFD) models to simulate foamed cement slurries placement.

3 Introduction

3.1 Scope and Objectives

The Norwegian Ocean Industry Authority, Havtil, commissioned a study on foam cement bond logging analysis and evaluation. The study was conducted in three main phases:

1. **Phase one:** Gather information on foam cementing:
   - Applications and limitations
   - Placement and barrier qualification
   - Current industry best practices
2. **Phase two:** Facilitate a workshop along with Havtil with NCS operators and Services companies to gain insights on both technical aspects and market outlook
3. **Phase three:** Document and report the conclusions and recommendations

Objectives

The main objective is to collect and share information on foam cementing practices, specifically verifying foam cement's effectiveness as a barrier element. By sharing knowledge and experiences from NCS, Havtil aims to enhance the industry's confidence in using foam cement for robust well barriers.

Background and Rationale

Foam cement, increasingly used in NCS—particularly in depleted reservoirs—presents challenges in logging interpretation due to a reduction in acoustic impedance because of nitrogen mixing. This study investigates methods for interpreting foam cement logs and evaluating its reliability as a barrier. The study includes mapping logging technologies, simulation tools, and alternative approaches used for verification. Additionally, this report includes a review of relevant studies, such as SPE papers, to provide a basis for best practices.

Key Study Topics

The study will address:

- **Challenges in Foam Cement Logging**: Understanding factors that make foam cement log interpretation complex.
- **Logging Technologies and Simulation Tools**: Mapping available logging and simulation technologies for foam cement verification on the NCS.
- **Supplier and Operator Experiences**: Documenting insights from major suppliers and NCS operators on foam cement planning, quality assurance, and post-placement verification practices.
- **Industry Literature Review**: Summarizing key insights from relevant studies and publications on foam cement.

Deliverables and Recommendations

This report outlines conclusions and best practice recommendations based on gathered information, supplier and operator input, and relevant literature. This knowledge sharing is intended to support players who consider foam cement as an alternative to conventional cement, contributing to reliable well barrier verification.

3.2 Timeline

Table 3.1 Study Timeline

WHAT	WHEN	WHO
Kick off	11th April	HAVTIL/THREE60
Data collection	April-June	THREE60
Workshop invite	30th August	HAVTIL/THREE60
Workshop preparations	August-September	THREE60
Workshop	19th September	THREE60
Reporting, QA/QC	September/October	THREE60
Draft report	29th October	THREE60
Final report	December	THREE60

4 Foam Cement

4.1 Foam Cement as a Material

Foamed cement is the coarse dispersion of relatively heavyweight base slurry using gas to achieve the desired much lower downhole density; typically formed by injecting nitrogen.The foam slurry density is adjusted by varying the nitrogen concentrations.

Foam cementing technology has been widely used in oil wells since 1979 and continues to evolve.

Foamed cements are more economical compared to low density cement systems that use microspheres or cenospheres and have a lower carbon footprint than both regular and other lightweight cement systems. This means less cement and potentially fewer chemicals are needed to obtain the equivalent volume of cement slurry for a given job. This reduction in these materials can mean less impact on the environment in manufacturing, transportation and utilization during cementing operations. However, special equipment is required at the wellsite to inject nitrogen. Depending on the nitrogen percentage, it could be argued that the reduction of cement and chemical usage might be equivalent to the carbon footprint of the special foam equipment.

Key advantages of using foam cementing:

- **Tailored density:** With wide range of downhole density extending from 0.71 up to 1.9 SG, because the gas has little effect on placement properties such as thickening time, the system density can be adjusted during the cement job by simply changing the gas concentration.This is crucial especially in low fracture pressure or depleted formations.
- **Enhanced Zonal Isolation:** The gas bubbles in the foam structure increase the cement's ability to expand and maintain contact with the wellbore, even in irregular or washed-out sections. This property enhances zonal isolation, reducing the risk of fluid channelling.
- **Improved Elasticity and Stress Tolerance:** Foam cement exhibits higher elasticity and better stress distribution properties compared to conventional cements. This characteristic helps it to absorb and sustain wellbore stresses, such as those from thermal expansion or pressure cyclical loading, thereby reducing the likelihood of cement sheath failure and experiencing minimal permanent deformation.
- **Lower chance of annular gas flow:** Foam cement has the ability to control water and gas flows, because of its capacity to maintain elevated pore pressures in the cement column while going through the transition stage from liquid to solid phase
- **Efficient Mud Displacement:** The reduced density and increased viscosity of foam cement can improve mud displacement efficiency, leading to more effective removal of drilling fluids and better bonding to the casing and formation.

On the other hand foam cementing imposes some challenges

- **Foam Stability:** Maintaining foam stability during pumping and setting is crucial. Loss of foam integrity can lead to density variations between the bottom and the top of the cement column, if not designed properly may potentially introduce well control issues.
- **Complex Design and Execution:** Foam cementing requires precise control over slurry design, gas injection, and downhole conditions. It demands specialised equipment and expertise to ensure successful implementation., the industry is currently unable to accurately predict foam viscosity, also because it is very difficult to measure it in the lab. Up until 10 years ago placement models had been unable to simulate pumping of a compressible fluid, which has added to difficulties in foam cement job design and evaluation.
- **Logging and Evaluation:** Evaluating the integrity and quality of foam cement after placement poses significant challenges. Traditional cement bond logging techniques may not provide accurate readings due to the heterogeneous nature of foam cement, leading to potential misinterpretation of bond quality and zonal isolation effectiveness. Also, the acoustic behaviour (including foam stability) and evolution with time is still poorly understood and documented. Advanced logging tools and interpretation methods are necessary to accurately assess foam cement integrity, which adds complexity and cost to the well evaluation process.
- **Higher dependence on good mud removal:** With oil/synthetic based mud, any contamination will lead to the surfactant that stabilises gas bubbles being taken up by the oil phase and to the bubbles losing stability and migrating, defeating the purpose of foam cement. For this reason, contact between slurry and OBM/SBM must be avoided.
- **Handling foam cement returns at the surface:** In cases where foam cement returns are expected at the surface, managing these returns presents unique operational challenges and additional well control requirements. Unlike conventional cement, foam cement contains nitrogen or other gas, which makes it highly compressible. This compressibility can result in unpredictable fluctuations in return volumes and pressures at the surface, particularly if wellbore conditions change during pumping.When returns fluctuate unexpectedly, operators may encounter issues such as pressure spikes or sudden decreases in return flow, which can disrupt the well’s stability. Such fluctuations necessitate extra monitoring and control measures to ensure well integrity, as even minor pressure changes can lead to risks of well influxes or losses of returns. Specialised well control procedures are often required, including real-time monitoring of surface pressures, flow rates, and returns, to detect and respond promptly to any variations. Surface handling of foam cement also requires proper equipment setup, such as separators and gas-handling systems, to safely deal with the potential release of nitrogen and prevent any uncontrolled venting of gases. Additionally, a high level of preparedness, communication, and coordination among the crew and foam engineers is essential to manage the job effectively and maintain well control throughout the cementing process.

4.2 Foam Cement Applications

Foam cementing has been used for over 40 years in oil wells. Initially, it was employed primarily to solve severe lost circulation problems, mostly in land wells, due to its ability to provide ultra-lightweight cement systems with densities of less than 1.32 SG and rapid compressive strength development.

The technique was later extended to include the squeeze cementing of weak zones that could not support conventional cement columns.

Subsequently, foam cementing was deployed in shallow water/gas flow scenarios, particularly during the cementing of surface casing in deepwater environments, such as the Gulf of Mexico. It was then expanded to all offshore applications, not necessarily limited to deep water, and to other regions around the world.

Furthermore, in HPHT wells, foam cementing is valued for its high ductility and robustness against temperature and pressure changes throughout the well's life, preventing the formation of cracks in the cement sheath.

Recently, foam cementing has been widely deployed in many challenging conditions, including:

1. **Depleted Reservoirs:**
    - Advantageous in scenarios where formation pressures are low and there is a high risk of lost circulation.
    - The reduced density of foam cement helps prevent formation breakdown while ensuring effective zonal isolation.
2. **Deepwater Wells:**
    - Useful in deepwater drilling where narrow pressure windows make it challenging to balance formation pressures during cementing.
    - Foam cement's tailored density allows for better control over wellbore pressures, reducing the risk of fractures and ensuring successful cement placement.
    - Prevents water flows when cementing surface casing in deep-water applications, such as in the Gulf of Mexico.
3. **High-Angle and Horizontal Wells:**
    - Addresses the elevated risk of cement slumping or poor displacement.
    - Foam cement's improved viscosity and compressibility enhance mud displacement and ensure a uniform cement sheath, which is critical for well integrity.
4. **Weak or Fractured Formations:**
    - Reduces hydrostatic pressure exerted on the formation, minimising the risk of lost circulation and formation damage.
    - Ensures successful cementing operations in weak or naturally fractured formations, because of its viscosity and compressibility.
5. **HPHT Wells:**
    - Utilised for its high ductility, reducing cement failure (cracking) caused by temperature and/or pressure changes during the well's life.
6. **Hydrostatic Pressure Maintenance:**
    - Maintains hydrostatic pressure across high-pressure gas and water zones during the transition from liquid to solid, preventing gas or water influx into the cement column (flow after cementing).

4.3 Acoustic Logging of Foam Cement

4.3.1 Experience with Different Tools

Cement job evaluation through acoustic log interpretation is the most widely used and effective method to evaluate cement jobs in general. Interpreting the acoustic signal response aims to find a relation between this acoustic signal response and the cement behind the casing and hence be able to qualify and possibly quantify the results in terms of cement quality and defect geometry. The result is typically a visual map of whether it's hard cement, a liquid mixture or simply free pipe.

There are two main categories of acoustic logging tools available today:

- **Cement Bond Log (CBL)**: Measures the attenuation of lower-frequency acoustic (sonic) waves travelling through the casing and cement to assess the quality of the cement bond. Even if it indirectly measures acoustic impedance, it works primarily by measuring the presence of shear bonding between casing and annular solids, i.e., it detects the presence of microannuli or the absence of annular cement (also called "free pipe").
- **Pulse-Echo Ultrasonic Imaging Tools (e.g., USIT)**: Use high-frequency ultrasonic pulses to create high-resolution images of the cement sheath. These tools rely on acoustic impedance variations between the casing, cement, and formation to generate images.

Fig. 4.1

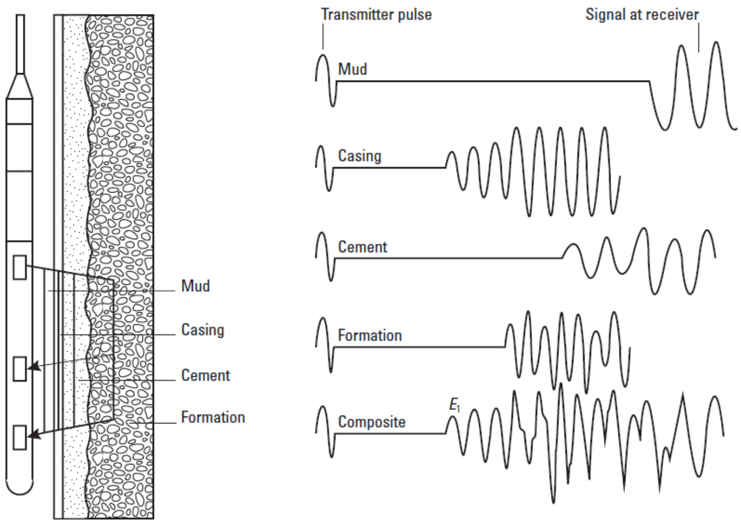


Fig. 4.1 Sonic tool response
Nelson, E. G. (2006). Well Cementing, Second Edition

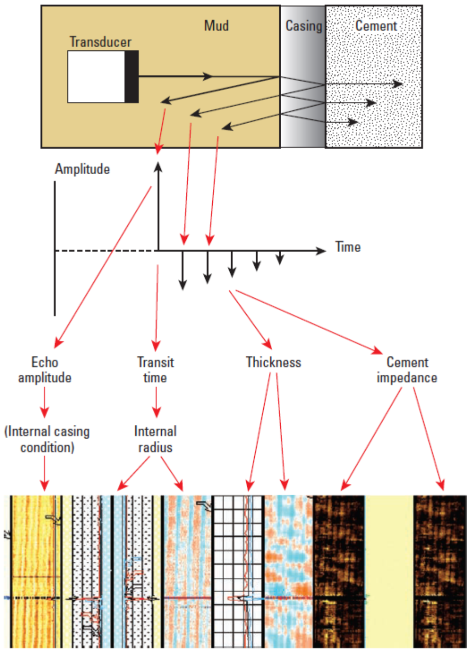


Fig. 4.2 Ultrasonic principles and measurements
Nelson, E. G. (2006). Well Cementing, Second Edition

When it comes to foam cement characterised by its low density and nitrogen spheres, it results in unique acoustic properties:

- **Low Acoustic Impedance**: The impedance can be lower than water, drilling mud, or spacer fluid, sometimes approaching that of a liquid mixture.
- **High Intrinsic Attenuation**: Acoustic waves weaken more rapidly when passing through foam cement compared to conventional cement.
- **Scattering Effect**: Gas bubbles in the cement cause scattering of acoustic waves, leading to signal distortion and thus high attenuation.

This presents a distinct challenge in well logging and evaluation, as it is difficult to distinguish the cement from drilling mud since the impedance of the foamed cement can even be lower than that of water, drilling mud or spacer fluid.

However, there are two main advancements in ultrasonic physics available today that have improved the evaluation:

- **Flexural Wave Attenuation:** By adding a separate emitter and two receivers, the attenuation of a casing plate mode - the flexural mode - can be determined. This new high-resolution ultrasonic measurement, which is acquired by SLB Isolation Scanner and by Baker Hughes INTeX is independent of the acoustic impedance and can be calibrated before the job, providing more information about annular materials. SLB Isolation Scanner records the whole flexural wave train, enabling detection of any acoustic reflector within the annulus and measuring annular wave speed directly.
- **Horizontal Shear Attenuation**: This new ultrasonic measurement, introduced by Baker Hughes in the INTeX

tool, excites a pure shear mode of the casing by using electromagnetic transducers. Pure shear means that any signal attenuation depends on bonding to a material that can transmit shear waves, such as cement or thick mud.

In conclusion, logging tool selection combined with advanced interpretation methods offers reliable evaluation of foam cement quality and continued research and development will further improve the ability to accurately assess foam cement in wellbores.

4.3.2 Uncertainties and Limitations

As explained in the previous section, foam cements have particularly low impedance and pose special interpretation problems and a simple threshold interpretation may be ambiguous, because a number of conditions may cause solid materials to have a low impedance as measured ultrasonically. These conditions include genuinely low-impedance cement (e.g., foam), poor bonding (especially dry microannulus), and mud contamination. While neat cement has an impedance of about 6 MRayl, lightweight cements can have impedance as low as 2.5 MRayl, overlapping with the liquid range.

Fig. 4.3 The table illustrates the acoustic properties across different cement types, showing that low-density slurries with a low solid-volume fraction often have very low acoustic impedance, which can vary significantly over the first few days after placement. In contrast, higher-density slurries show more stability, with impedance changing by less than 20% between the first and seventh day. Fig. 4.4 shows that the properties of annular fluids can be high enough to overlap with foam cement response, further complicating evaluation.

Cements modified with hollow microspheres or nitrogen tend to have exceptionally low acoustic impedance, sometimes making it challenging to differentiate them from water in acoustic logs. Improvements in impedance readings are often observed over days or even weeks in time-lapse logging, likely due to the natural evolution of acoustic properties as the cement cures.

These variations are commonly linked to an overestimated bottomhole circulating temperature, which can lead to excessive slurry retardation. Additionally, ignoring temperature variations along an extended cement column may also result in such fluctuations in impedance readings.

Slurry Type	Density (lbm/gal [kg/m³])	Time (days)	Sound Velocity in Cement (m/s)	Acoustic Impedence (MRayl)	Change in Acoustic Impedence Over 1 Day (%)
Neat Class G	15.8 [1.89]	1 2 7	3,000 3,250 3,400	5.68 6.16 6.44	0 8 13
Class G + latex + hollow silica microspheres	11.2 [1.34]	1 2 7	1,650 2,200 2,500	2.21 2.95 3.36	0 33 52
Class G + soluble silicate extender	12.0 [1.44]	1 2 7	1,600 1,750 2,000	2.30 2.52 2.88	0 9 25
Class G + hollow silica microspheres + 4% $CaCl_2$ (BWOC†)	12.0 [1.44]	1 2 7	2,600 2,800 3,000	3.74 4.03 4.32	0 8 16
Class G + soluble silicate extender	13.3 [1.59]	1 2 7	1,750 2,200 2,500	2.79 3.51 3.99	0 26 43
Class G + latex	15.8 [1.89]	1 2 7	2,900 3,150 3,350	5.49 5.97 6.35	0 9 16
Class G + 18% NaCl (BWOW‡)	16.1 [1.93]	1 2 7	2,850 3,200 3,375	5.50 6.18 6.51	0 12 18
Class G + hematite weighting agent	19.0 [2.28]	1 2 7	3,300 3,400 3,530	7.59 7.74 8.04	0 2 6
36% quality foam	10.0 [1.20]	7	2,300	2.76	–§
Conventional low-density system	12.51 [1.50]	7	2,000	3	–
Engineered-particle-size low-density system	10.0 [1.20]	7	2,900	3.48	–
Engineered-particle-size ultralow-density system	8.61 [1.03]	7	2,790	2.87	–

† By weight of cement
‡ By weight of water
§ Not available.

Fig. 4.3 Acoustic properties of various cement materials
Nelson, E. G. (2006). Well Cementing, Second Edition

Material	Density (lbm/gal [kg/m^3])	Slowness (µs/ft)	Velocity ft/sec [m/sec])	Acoustic Impedance (MRayl)
Water	8.33 [998]	206	4,860 [1,482]	1.48
Water + 10% NaCl	8.98 [1,075]	193	5,180 [1,580]	1.70
Water + 25% NaCl	9.90 [1,186]	175	5,710 [1,740]	2.06
Water + 36% $CaCl_2$	11.3 [1,350]	170	5,870 [1,790]	2.42
Water + KCl	9.18 [1,100]	189	5,280 [1,610]	1.77
Water + 58% $CaBr_2$	15.2 [1,824]	179	5,580 [1,700]	3.10
Sea water	8.56 [1,025]	199	5,020 [1,531]	1.57
Kerosene	6.74 [808]	230	4,340 [1,324]	1.07
Diesel	7.09 [850]	221	4,530 [1,380]	1.17
Air at 15 psi, 32°F [0°C]	0.01 [1.3]	920	1,090 [331]	0.0004
Air at 3,000 psi, 212°F [100°C]	1.59 [190]	780	1,280 [390]	0.1

Fig. 4.4 Acoustic properties of various homogeneous fluids
Nelson, E. G. (2006). Well Cementing, Second Edition

Solid-free liquids show consistent activity levels in logs, whereas mixtures of solids with fluids or gases tend to produce irregular activity. In the case of foamed cement, there is a mix of gas and solids that displays significant variability in impedance measurements. A single phase, such as water, gas, or drilling mud-will exhibit less variation in the computed impedance. Analysing the vertical rate of impedance change, once the tool's position is taken into account, allows for easy determination of whether foamed cement or liquid is present. Goodwin (1989) pioneered the use of acoustic-impedance variations to help distinguish solids from fluids in the annulus. The guiding principle is that a liquid or gas in the annulus has a constant, uniformly low impedance, while a “low-impedance” solid material usually has a more variable measured impedance.

4.4 Alternative Techniques to Qualify Foam Cement

While there are no explicit requirements for foam cementing evaluation and qualification, there are general guidelines for acceptance criteria and the evaluation of the cement in the annulus. In this section, three main guidelines were compared :

1. **NORSOK D-010 (Standards Norway):**
    - Cement evaluation logs are mandatory for dual annular cement barrier verification and creeping shale barrier verification.
    - For cased hole sections with available logs, 1 or 2 X 98 ft (30 m) of good cement is required.
    - If no logs are available, 164 ft (50 m) of cement based on displacement calculations is required.
    - Logs must provide azimuthal/segmented data and be verified by qualified personnel.

2. **BSEE (Bureau of Safety and Environmental Enforcement) - Gulf of Mexico:**
   - Cement evaluation logs are typically required to verify the presence and quality of cement.
   - A minimum of 100 ft of cement above the uppermost hydrocarbon-bearing zone is required.
   - Logs should be run after the cement has reached a compressive strength of at least 500 psi.
   - If logging results are inconclusive, additional testing or remedial cementing may be required.
3. **OEUK (Oil & Gas UK) Wellbore Decommissioning Guidelines:**
   - If a log is available, 100 ft of good cement is considered sufficient.
   - Without logs, 1000 ft of cement based on theoretical calculations is required.
   - in addition, it is crucial to have "sufficient confidence in the quantity and quality of the cement in the annulus."

Comparing the three guidelines:

1. Mandatory logging: NORSOK D-010 explicitly requires cement evaluation logs for certain situations. BSEE typically requires logs, while OEUK allows for alternatives if logs are not available.
2. Cement length requirements: All three guidelines have similar requirements for the length of good cement (100 ft with logs, up to 1000 ft without logs), but BSEE focuses on coverage above the hydrocarbon zone.
3. Job performance and charts: While all guidelines consider job performance, hydrostatic lift pressures, and cement volumes calculations, they are generally not considered sufficient on their own. Logs are preferred or required to verify cement placement and quality.
4. Evaluation criteria: NORSOK D-010 specifies the need for azimuthal data, while OEUK emphasizes "sufficient confidence" in cement quantity and quality. BSEE focuses on verifying cement presence and quality.

In conclusion, while most guidelines strongly recommend or require cement logging for verification, some allow for alternative methods, such as studying job performance and cement pressure charts with lift pressure comparison between the designed simulated and the actual obtained pumping pressures, or theoretical calculations when logs are not available. Additionally, even when logging is not explicitly mandatory, it is generally considered best practice to use cement evaluation logs when possible to verify the integrity of annular cement as a well barrier element, especially in dual well barrier situations

While the volumetric analysis and job performance can be used to have an indication of the overall job performance, it is not possible to gain qualitative certainty of the cement in the annulus. On top of that the challenge with foam cement is that its density closely matches that of mud (a requirement when there is a risk of lost circulation), and that it is used in highly deviated wells. For these reasons, no difference in surface pressure can be used to compute the top of cement in the annulus. Some operators have been using torque readings while rotating the liner to detect viscous slurry turning around the shoe. This, together with other operational parameters (especially return volumes), can be used to estimate annular coverage.

5 Foam Cement Worldwide Litertaure Review

1. SPE 79912, K.Green, et al., 2003
   - Eldfisk field (CoP), 10 wells, 5" liner
   - 1.83 SG base slurry, foamed to 1.34-1.39 SG (27% FQ)
   - "*Although the average absolute value of acoustic impedance of foam cement is typically similar to wellbore fluids or gases, it is still possible to distinguish cement using statistical variation techniques. […] The statistical variance method was applied, and the results were very good*"
2. SPE 199097, Jose Vela, et al., 2020
   - Chichimene field (Ecopetrol, Colombia), 20 wells, 7" liner
   - 1.98 SG base slurry, foamed to 1.62 SG
   - "*Physical properties of Foam cement have demonstrated its great advantages for achieving good zonal isolation; high apparent viscosity, low density-high compressive strength ratio, expansion gave great value-added benefits for cementing the wells presented in this paper, where associated problems such as washed out zones, loss circulation, highly fractured depleted reservoirs were presented*."
   - Following is shown the log evaluation response for each of the jobs above presented to corroborate the operational results (Fig 4-A–B). Log tracks from different logging companies and tools are presented. It can be seen that complete zonal isolation for all wells with excellent bond to pipe and formation, was confirmed for each subsequent log track.
3. SPE 55649, Gary J. Frisch, et al., 1999
   - Halliburton
   - "*The new [statistical variation process] has been successfully applied to data from several service companies throughout the world*"
4. SPE11980, Rod Bruckdorfer, et al., 1984
   - SLB
   - "*This laboratory study […] confirms that the CBL log can be used to evaluate the quality of foam-cemented casings by adjusting the cementing interpretation chart.*"

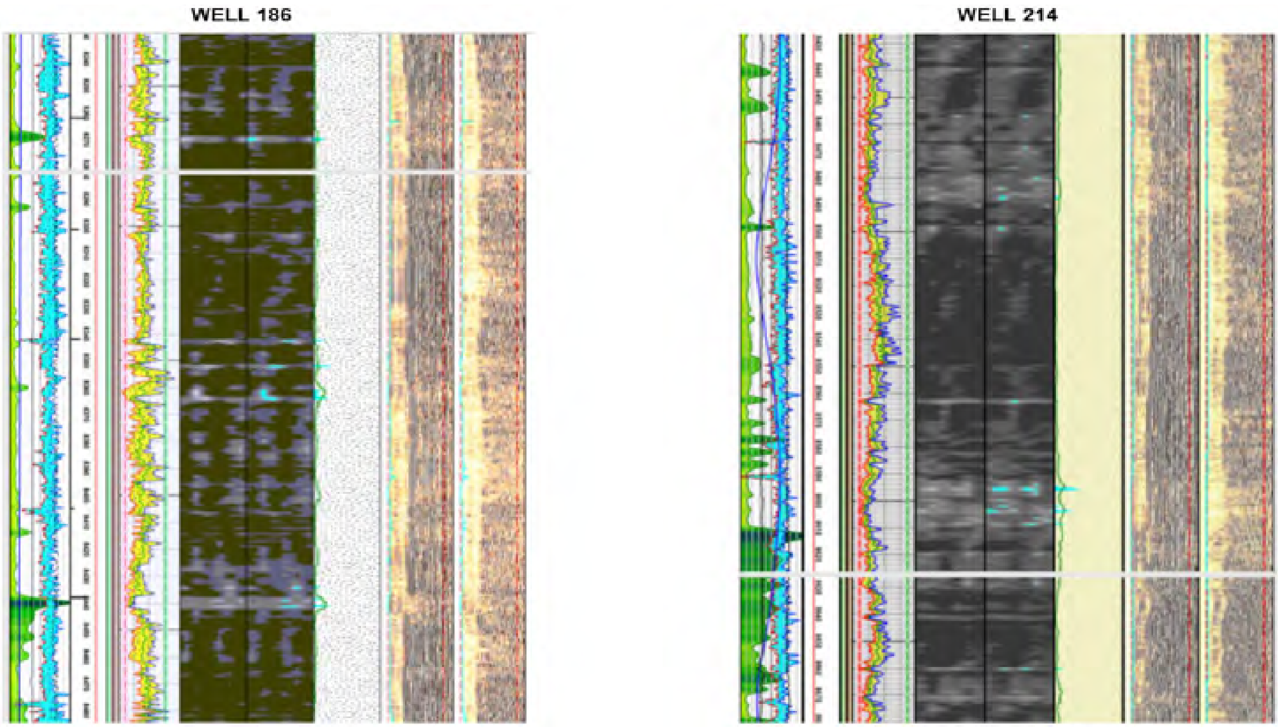


Fig. 5.1 Cement Log Response for wells 186 and 214
SPE 199097, Jose Vela, et al., 2020

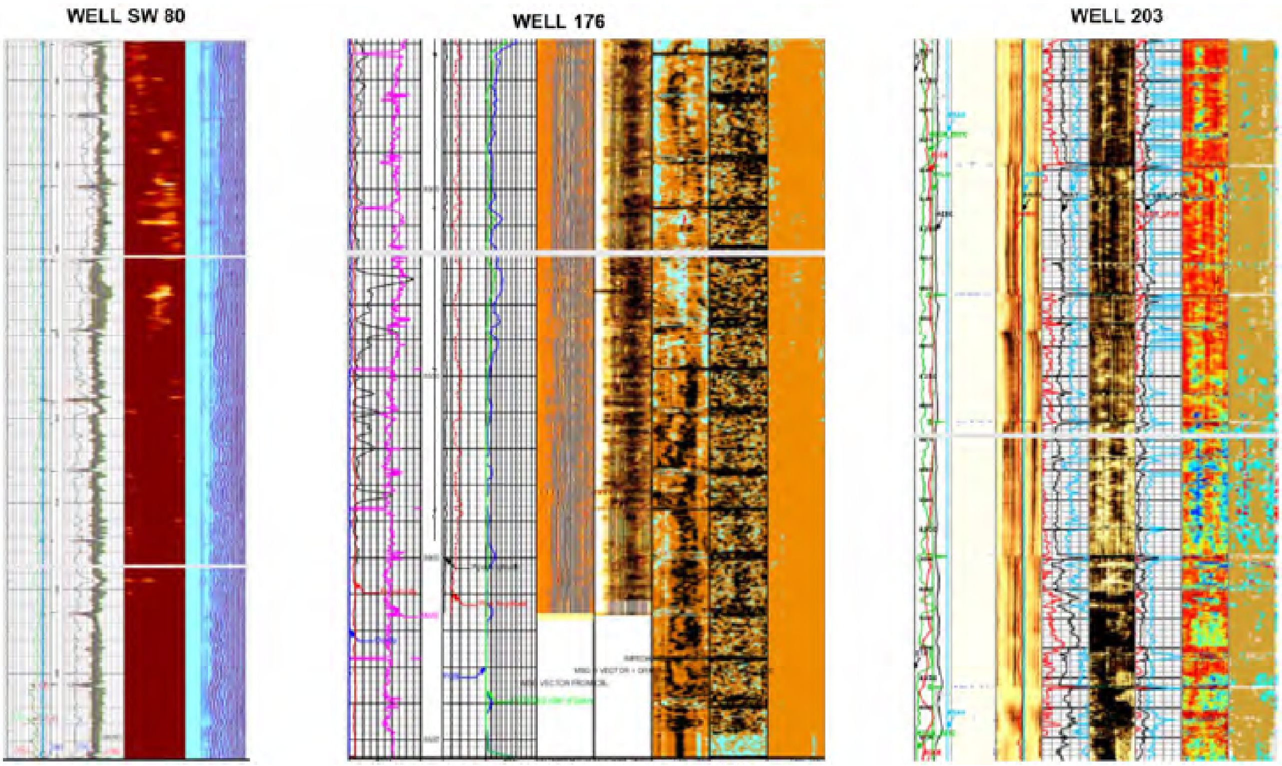


Fig. 5.2 Cement Log Response for wells SW 80, 176 and 203
SPE 199097, Jose Vela, et al., 2020

6 Foam Cement in the NCS

6.1 Applications in the NCS

In the NCS, the foam cementing has been used for two main applications thus far:

1. Shallow gas/water top sections

2. To cement production strings in which there is a small difference between pore/collapse pressure and frac pressure (i.e., narrow formation pressure window)

6.2 Logging and Barrier Qualification in the NCS

A goal of the foam cement logging project was to investigate whether the difficulties in qualifying barrier elements using logs was due to specific characteristics of the material that affect ultrasonic and sonic measurements, or if they are rather caused by a mismatch between our expectations and foam cement's properties.

To better understand the causes of this problem, we started by developing a material model that can predict the acoustic properties of foam cement and their evolution with time under a number of plausible scenarios. We then applied a Bayesian model-based inversion algorithm, called VM, to the acquired ultrasonic and sonic (i.e., CBL) data in 7 logs provided by a Norwegian operator. The logs, comprising Slb Isolation Scanner and three different sonic tools[1], were measured at different time delays after pumping cement, allowing us to better understand the material evolution with time. A subset of three wells, numbered 1 to 3, will be used in the rest of this chapter.

The delay between cement placement and logging was 10 days in well 1, 7 days in well 2, and 9 years (3299 days) in well 3.

The VM algorithm applies classic inverse problem techniques to the problem of reconstructing material properties behind the pipe by using a series of direct models i.e., functions that predict tool readings from the unknown material properties and bonding conditions (well-bonded cement, liquid microannulus and dry microannulus).

A liquid microannulus is a gap, usually 50-300 μm thick and filled with a liquid - usually water. The defect is found between casing and cement (or cement and formation, though this latter can be identified on logs only after extensive processing) and is either created as a result of a leak, when formation fluids push apart an interface's walls and climb up, or by mix water separating during the early stages of cement hydration.

A dry microannulus, on the other hand, is a much thinner gap (<10 μm) which is empty and is created by a local separation of casing and cement; cement expansion can cause it under special circumstances, but the most common scenario is casing shrinkage as a result of hydrostatic pressure reduction.

Log inversion is achieved by comparing the evidence of each scenario at its best-fitting point (i.e., the parameters that best match the measurement) while accounting for the "handicap" of the number of parameters of each material-bonding model: a model with two parameters will always provide a better match than one with no free parameter, even when the simpler scenario is correct. The SLG (solid-liquid-gas) map computed by Slb Isolation Scanner tool is an example of a very simple inverse problem.

The VM algorithm thus computes a map of material properties and bond conditions for each of the 36 points (6 for Baker tools) at each depth. This first pass estimation is then corrected by fusing the high-resolution map with the CBL results, which provide one sonic attenuation measurement that averages conditions around the pipe. Since the CBL is very sensitive to bonding, we can use it to update the evidence for bond condition models so that we match the sonic attenuation. This estimation-correction approach allows us to match all measurements and improves output accuracy.

Material model:

Acoustic properties of solid materials include density (ρ, measured in kg m^{-3}), compressional and shear wave speeds (indicated, respectively, with c_p and c_s and measured in m s^{-1}). The wave speeds describe the velocity with which a pulse travels: compressional refers to tiny volumetric changes in the direction of propagation e.g., when knocking on a wall; whereas shear waves transmit slight changes in shape in the plane orthogonal to their propagation direction e.g., when planing wood. Acoustic properties are related to elastic moduli: for instance, the ratio of c_s over c_p is equal to sqrt((1-2ν)/2(1-ν)), which shows that shear waves are always slower than compressional ones, and can vary between c_s=0 for a liquid (ν=0.5) and c_s=0.7c_p (ν=0). Formation wave speed or its reciprocal, called the slowness, is a key petrophysical property routinely measured in logs.

Oilfield cement is a well-behaved material: specific cement systems have one degree of freedom, meaning that density ρ and shear wave speed c_s can be calculated from the material's compressional wave speed c_p. If we want to compute foam cement acoustic properties, we also need to be able to account for two possible scenarios that describe how foam evolves with time:

- Part of the original nitrogen fraction, which we shall call φ_{sat}, may be filled with brine from the formation, leading to a heavier solid[2]; this hypothesis was first formulated by Roy Middleton, from ConocoPhillips.
- Empty pores could potentially be crushed by creeping shales, resulting in a foam cement with less nitrogen-filled bubbles i.e., with less foam quality (FQ, the volume fraction of nitrogen at a given depth). If all bubbles were to collapse, we could be observing the original base slurry.

In order to speed up calculations, we replaced the micromechanical material model with a neural network approximation that provides ρ and c_s as a function of c_p, the fraction of the original nitrogen bubbles filled with water (φ_{sat}), the density of the base slurry (ρ_{base}), and the degree of hydration of cement (χ). This latest parameter is used to model the behaviour of foamed cement at lower degrees of hydration (χ≅50%-60%) which are observed in earlier logs.

Slb Isolation Scanner acquires two independent ultrasonic measurements with a resolution of at least 36 pixels per depth: the acoustic impedance Z (which is the product of density ρ and compressional wave speed c_p) and the flexural attenuation α_g. The latter is a plate acoustic mode (i.e., a stable superposition of compressional and shear waves), which belongs to the class of Lamb waves and is also called A0 (antisymmetric Lamb wave of order zero) by Baker Hughes when they measure it using the INTeX tool. Flexural attenuation does not have a simple definition as acoustic impedance, and must be computed by searching a self-sustained mode with a given propagation velocity and attenuation.

Our ability to distinguish between different evolution scenarios rests of the materials having different signatures on the measurement Z-α_g plane. Fig. 6.1 shows the ultrasonic tool readings predicted under three scenarios: base slurry with varying water content foam cement with a fixed base slurry density but varying foam quality; and for the same material after all the bubbles have been filled with brine. The measurements describe the response of Slb Isolation Scanner, as well as Baker Hughes combination of INTeX (a six-pad tool) and ULTeX (a tool with a rotating pulse-echo transducer similar to Slb USIT or Halliburton CAST). The curves demonstrate that foam diagenesis changes tool response - something that has been repeatedly observed in Norway - and that water flooding and pore crushing diverge slightly at higher impedances.

[1] One of the logging strings contained an older sonic tool, the DSLT, whereas the other 6 were acquired using the newer MAST and ASLT. These array sonic tools have 5 receiver stations as well as two transmitters. The presence of a series of receivers allows us to measure attenuation directly, whereas averaging the response to the two transmitters cancels out the effect of different transducers' sensitivity on the measurement (what is a called borehole compensated configuration, or BHC).

[2] Nitrogen inclusions in the cement matrix behave as any other fluid, including water in the base slurry porosity: wave speeds do not distinguish between gas-filled and liquid-filled pores.

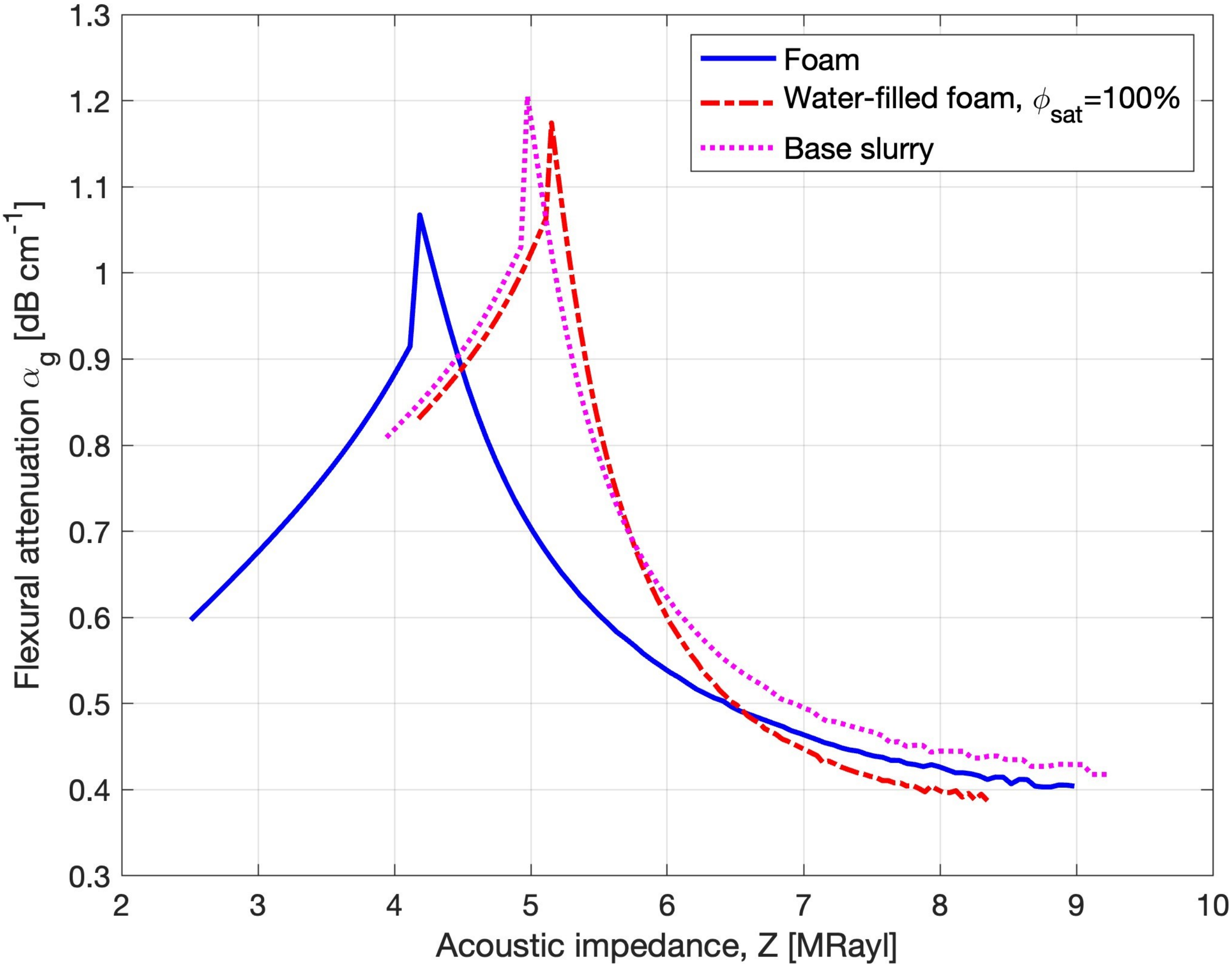


Fig. 6.1 Prediction of log response to foam cement

Prediction of log response to foam cement under three assumptions: original cement, with Nitrogen filling the original bubbles; water-filled foam, with water flooding 100% of the bubbles; and the base slurry, representing the effect of mechanical crushing of the bubbles. Flexural attenuation (measured by SLB Isolation Scanner and Baker Hughes INTeX) has been computed for a 9⅝" casing 53.5 ppf and fresh water as the logging fluid within the casing.

Evolution of log response with time:

We now have two tools at our disposal: a direct model of foam response, which allows us to calculate log response based on base slurry density, foam quality and evolution parameters (flooding and crushing of bubbles); as well as an inversion framework, the VM algorithm, which calculates the unknown parameters from the known ultrasonic and sonic measurements. The first step is to validate the chain by checking whether it can correctly reconstruct the foam properties in logs acquired soon after placement. By fixing the base slurry density to its design value (16.3 ppg, equivalent to 1.95 SG), and the degree of hydration to χ=68%, its long-term limit, we can compute foam quality from the ultrasonic logs: Fig. 6.2 and Fig. 6.3 reveal consistent FQ around 10%, the value computed for pressure and temperature conditions at the bottom of the 10¾" liner for two different wells. This initial validation shows that "fresh" foam cement behaves as expected i.e., that at the resolution of an ultrasonic beam (around 1 in, or 25.4 mm) the material appears smooth and consistent, without gas or water separation.

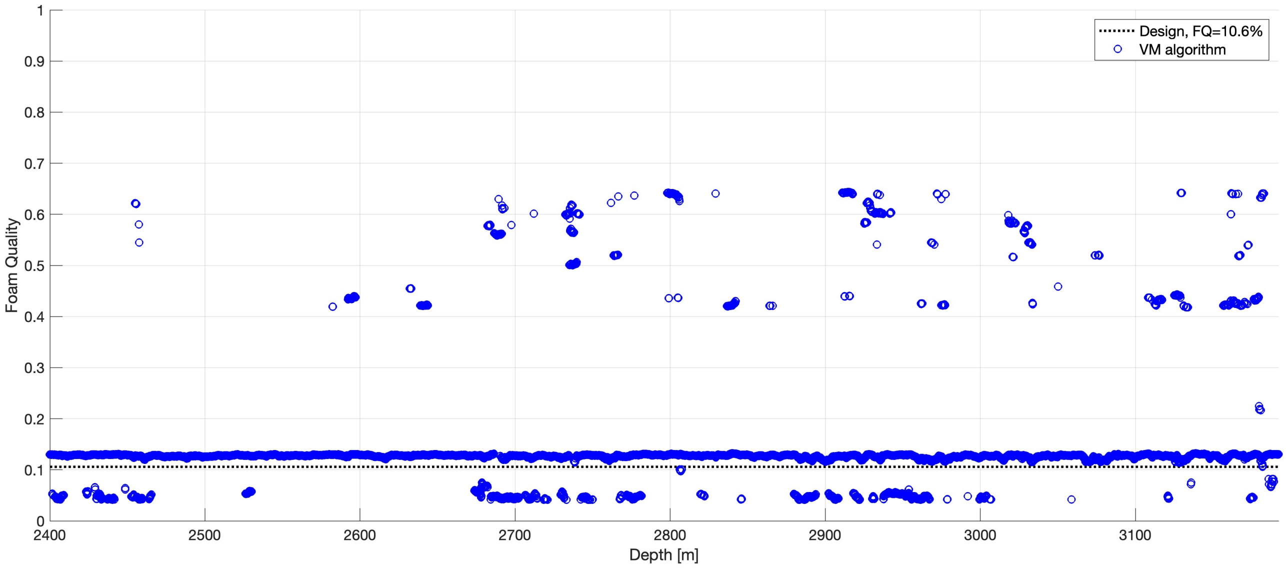


Fig. 6.2 Well 2 Designed and simulated pumped slurry foam quality

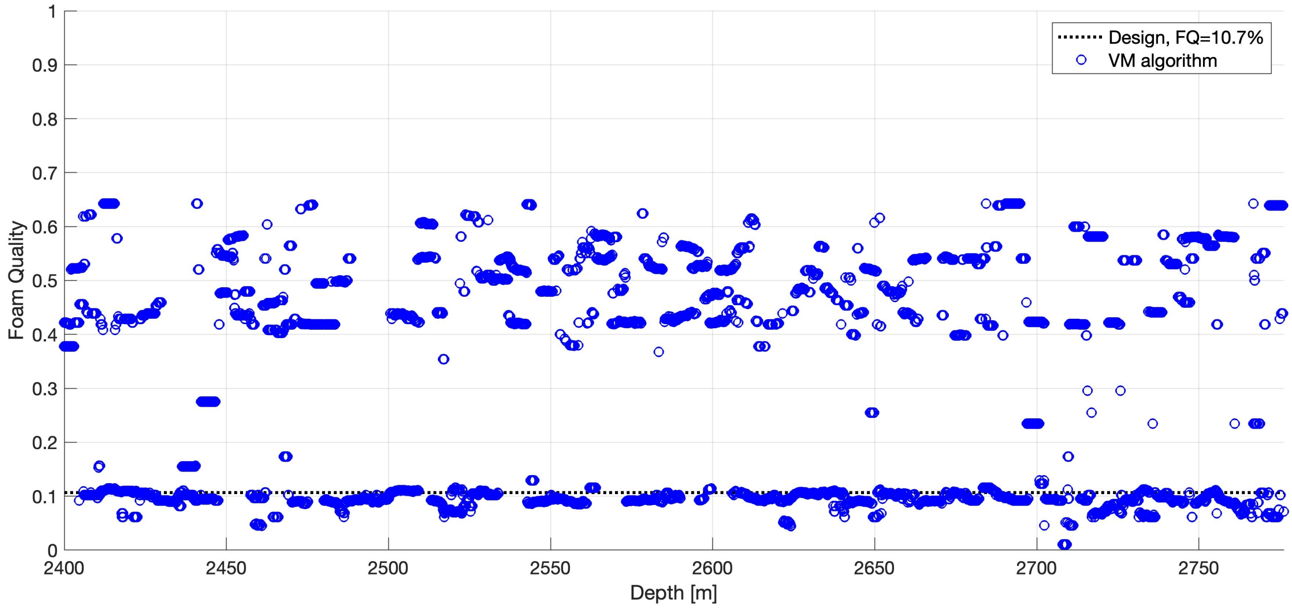


Fig. 6.3 Well 3 Designed and simulated pumped slurry foam quality
Peak of the distribution of cement density values in a 5-m sliding window, computed by the VM algorithm using the foam cement material model.

The ability to reconstruct the annular materials' properties, in particular density and thus foam quality, is confirmed by Well 1: Fig. 6.4 compares the result of inversions using foam cement and Class G material models. In this case, the foam cement model would be able to correctly compute annular density, since the base slurry is a special case with FQ=0%. In fact, both models compute correctly the design density ρ=1.95 SG across the base slurry interval closer to the shoe, highlighting the difference between with the foamed middle section. Even the unfoamed cap close to the top of cement shows a slightly different behaviour from foam underneath, with slightly more accurate values provided under the Class G assumption.

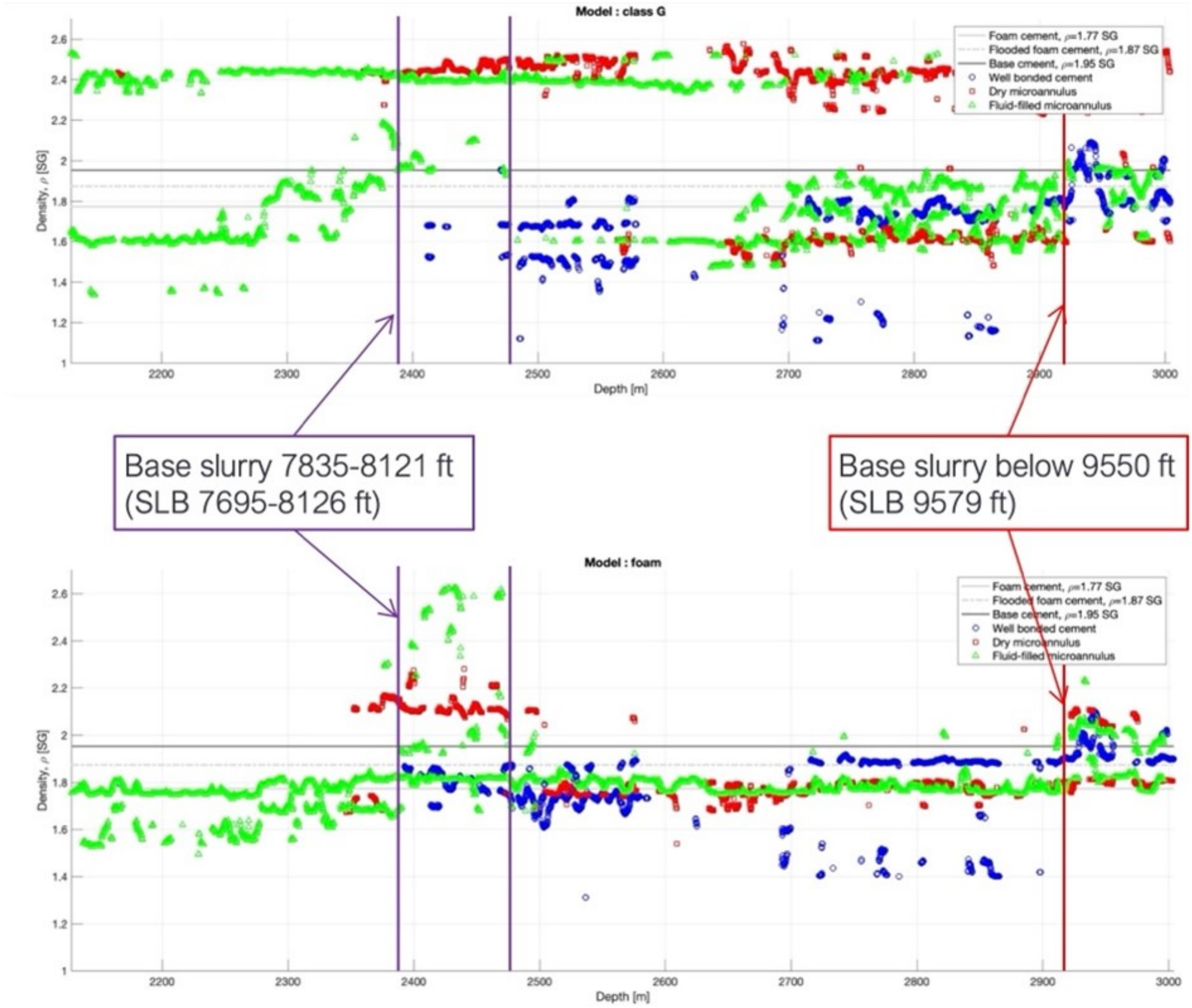


Fig. 6.4 Well 1 Designed and simulated pumped slurry denisty
Peaks of the distribution of cement density values in a 5-m sliding window, computed by the VM algorithm using two different material models (base slurry at the top and design foam at the bottom). The vertical lines delimit intervals of different behaviour that correspond to two batches of base slurry that were pumped ahead and behind the foamed slurry.

The conclusion is that at an early age foam cement behaves as expected, with the design foam quality clearly preserved downhole and no sign of bubble coalescence and phase separation.

Norwegian operators who are most active in using foam have repeatedly underlined how diagenesis i.e., the changes in structure and properties of the cement system, is a puzzling and consistent characteristic of the material.

Testing different scenarios of material evolution with time, we can determine which one is better able to reproduce the ultrasonic measurements, acoustic impedance Z and flexural attenuation α_g. This material selection step is not full-proof: the behaviour of different materials can be similar, and the measurement noise can cause shifts in attribution. On average, however, the correct model should be preferentially selected. Fig. 6.5 shows the fraction of each material model that is better able to account for the log measurements at each depth in Well 1. The plot at the top excludes points where the VM algorithm indicates we have a dry microannulus, which are included in the bottom plot: whereas it is plausible that larger nitrogen bubbles at the casing could appear as a dry microannulus

- and logs suggest they do - the algorithm tends to associate these thin, sparse gaps to the shale material model, which is unrealistic. The actual presence of small scale empty (or nitrogen-filled) thin gaps is therefore still uncertain. Even though noise causes the answer to alternate between competing scenarios, it seems that both pore flooding by formation water and pore crushing are present in the same well – together with the original foam cement.

Nitrogen separation can be ruled out as the reason behind the presence of points classified as unfoamed Class G since logs at an early age consistently reveal homogeneous foam quality. Bubble coalescence and nitrogen migration, if it happens at all, would be over soon after pumping when cement starts setting: any subsequent disappearance of bubbles is most probably due to pore crushing.

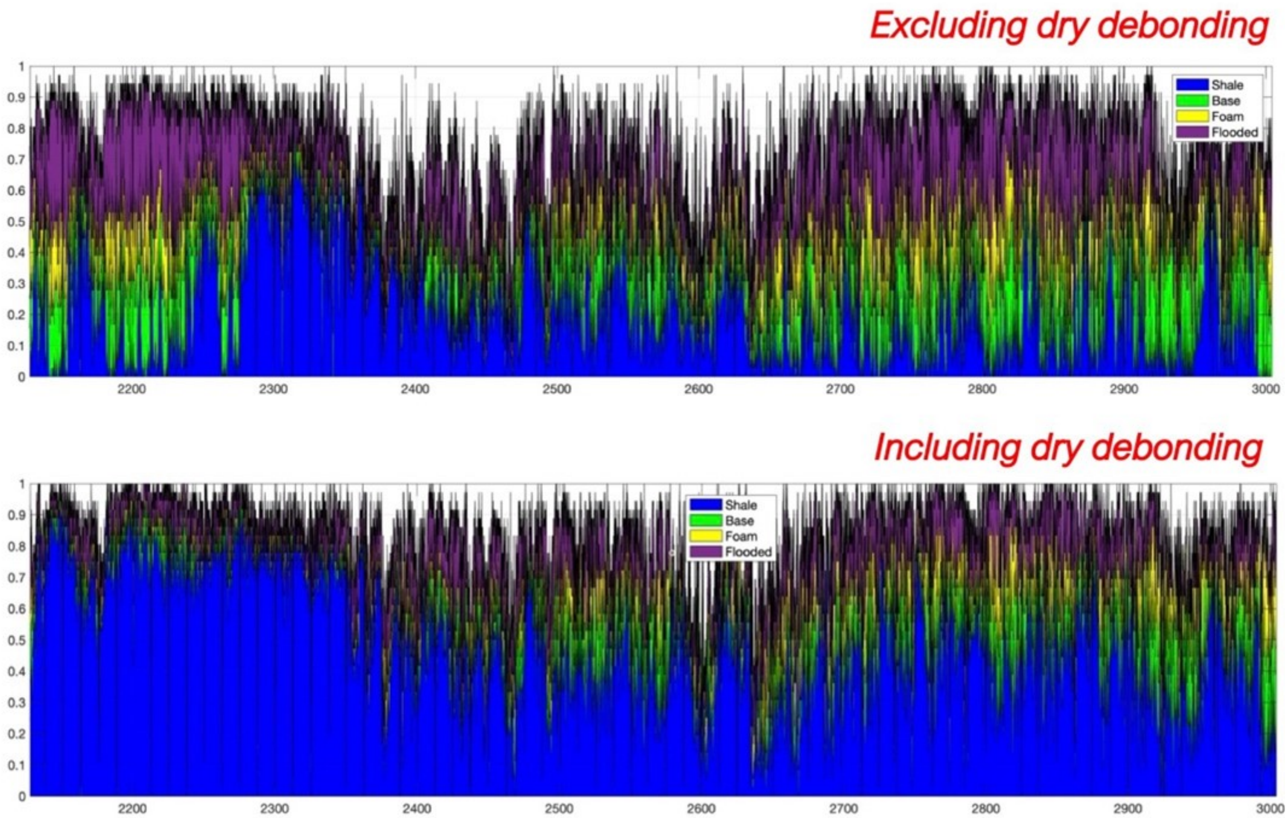


Fig. 6.5 Well 1 fraction of different material models vs. depth (in meters).
For each pixel the model that provide the best match to the ultrasonic measurements (acoustic impedance and flexural attenuation) is selected. The plot at the top excludes dry debonding from the conditions tested by the VM algorithm.

A study of Well 3 has revealed two interesting aspects of foam's evolution with time. Fig. 6.6 shows that:

- Flooding seems to be concentrated in vertical bands e.g., in the interval 2040-1860 m. Such sections, particularly if transitions are sharp, are an indication of formation bedding effects, since cement placement results in sharp transitions around the pipe (because of mud channeling) and much smoother ones along depth (because of contamination). Banding is consistent with the hypothesis that formation water availability controls pore flooding.
- Base cement is more likely to be observed along the high side of the casing. This is not obvious, since stress may be expected to be higher along the low side of the pipe where the cement sheath is thinner.

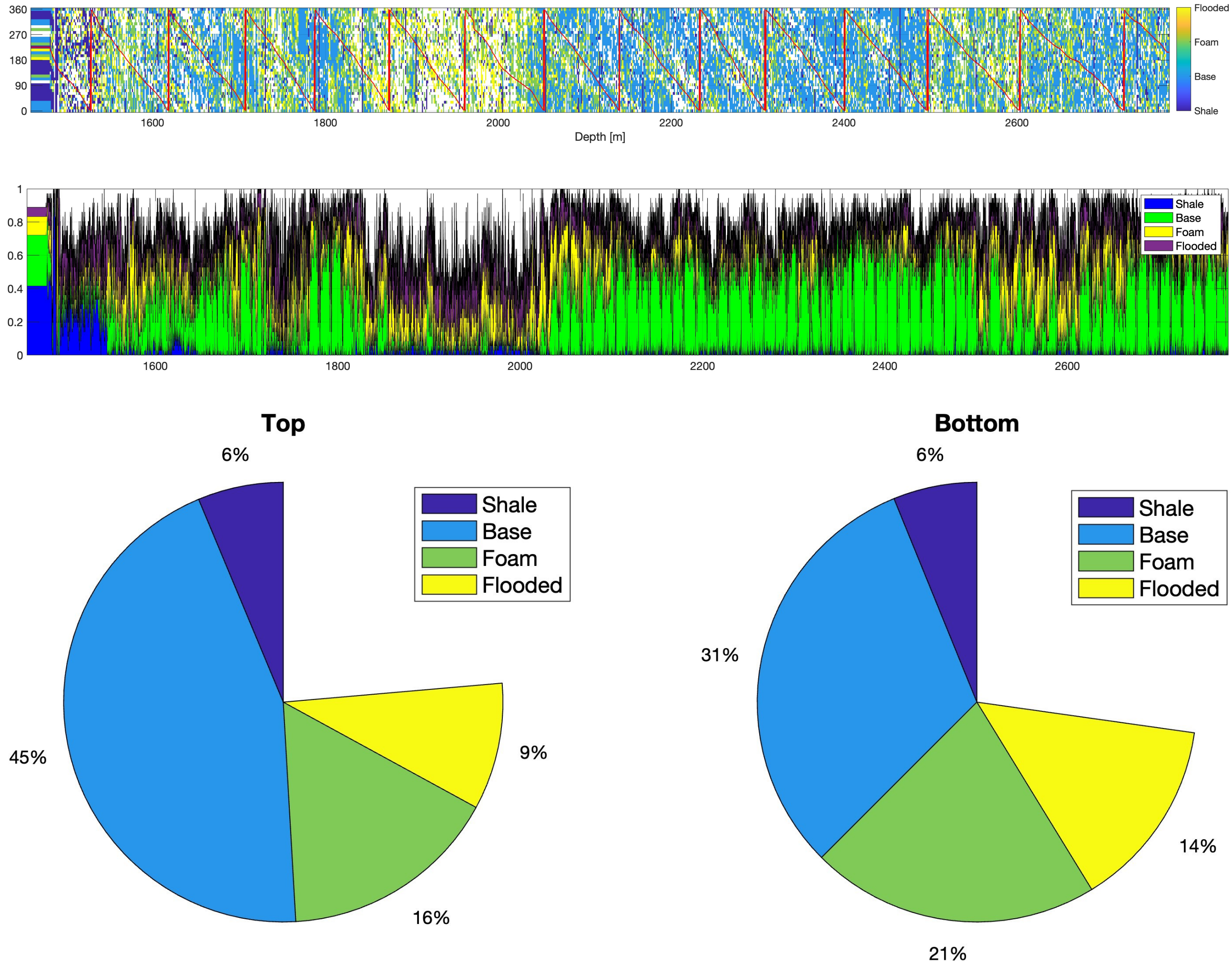


Fig. 6.6 Well 3 Ultrasonic measurements modeling
Map of the pixels for which each model provides the best match to the ultrasonic measurements (acoustic impedance and flexural attenuation, top). Fraction of the different material models vs. depth (in meters, middle). Fraction of each material model for the whole logged section computed using 90° windows centered along the top and bottom of the casing (bottom).

Even though the exact processes driving foam cement diagenesis, in particular pore crushing, haven't been clarified yet, this log review confirms that foam acoustic properties increase markedly with time, making the material more visible on logs.

Since elastic properties, Young's modulus E and Poisson's ratio v, can be computed from compressional and shear wave speeds, we can conclude that cement becomes stiffer (i.e., less elastic) with time. In the case of pore crushing, permeability would also decrease - even though a high-density cement with 10% foam quality would have a permeability of around 10 nD (10^{-8} Darcy), undistinguishable from the base cement value.

As the Young's modulus increases, so does the unconfined compressive strength and all other parameters that determine cement ultimate mechanical resistance. The conclusion is that the initial foam cement quality is the same as what is expected based on lab tests, and will improve with time. Logs are therefore suitable for assessing barrier element quality.

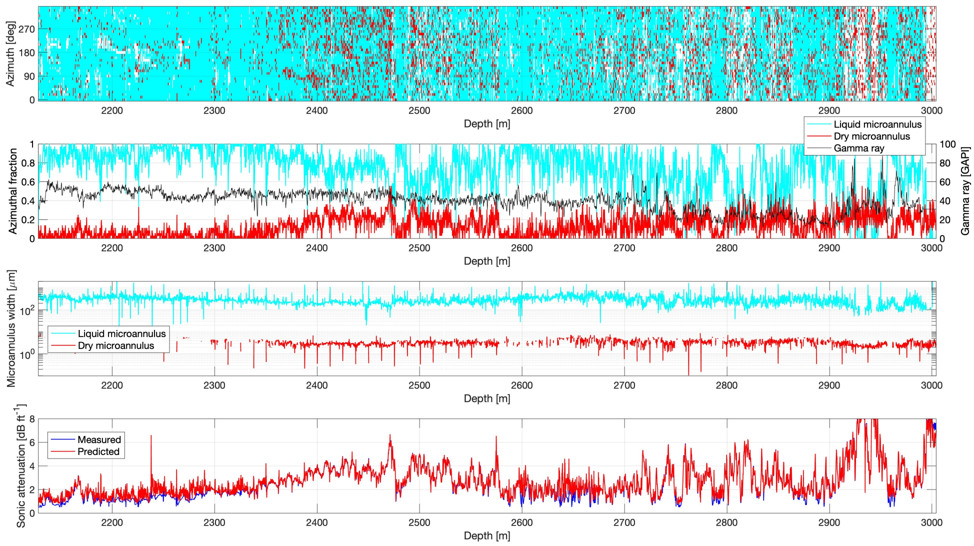
Foam cement bond:

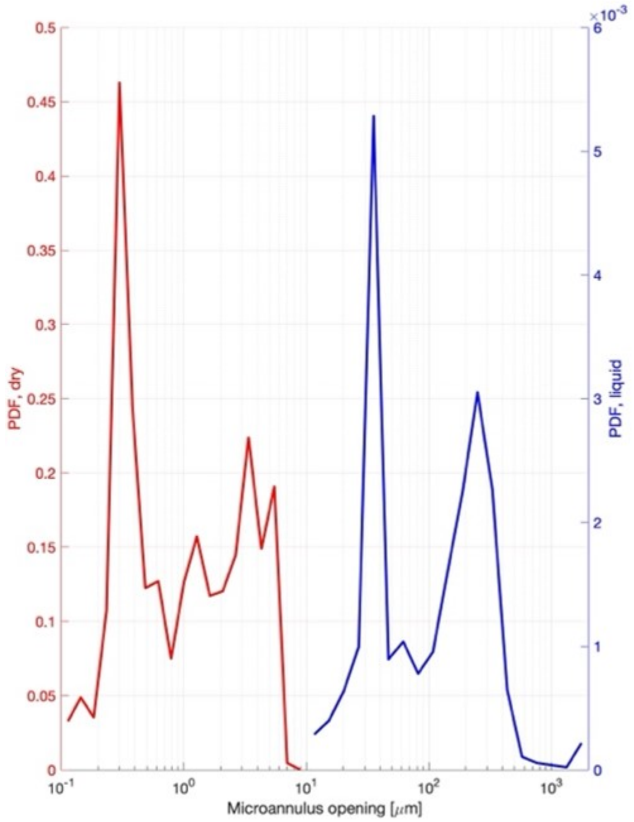
The last question that the log analysis addressed is whether bonding between casing and cement is statistically difference between unfoamed and foamed Class G cement. Bonding refers to the possible existence of a liquid layer ~100 µm thick, called a liquid-filled microannulus, or of a much thinner (<10 µm) empty gap created by casing shrinkage or cement expansion, which is called a dry microannulus. Logs show that foam – like standard cement – is affected by the two types of debonding. This is not unexpected for two reasons:

- In Norway a foam quality FQ≅10% is routinely used for the production string, since this value is a good compromise between low density and bubble stability. The thin water film, typically <100 µm across, that separates from the setting slurry and is routinely seen on logs (even though a satisfactory explanation has not yet been proposed) can still separate from the remaining 90% of volume which is taken by the base slurry.
- Even though the very small nitrogen-filled bubbles may not provide enough volume to materially affect free water separation during hydration, they may nonetheless act as reservoirs, especially when the bubbles are at the interface between casing and cement. These thin water layers will affect the CBL response and lead the VM algorithm to label the pixel as a liquid-filled microannulus. This would lead to widespread yet unconnected debonding: since connectivity is necessary for the water layer to be a conduit for gas bubble migration, isolated bubbles wouldn't affect the ability of cement to be an effective barrier element, even against gas. Empty half-bubbles at the casing interface may alsoexplain the frequent and unexpected presence of dry microannuli (i.e., empty gaps <10 µm thick).

Fig. 6.7 (Well 1) and Fig. 6.8 (Well 2) demonstrate the frequent presence of microannuli, even though there are reasonable doubts about the defect's connectivity. The vertical banding in Fig. 6.8, in particular, reveal that debonding is modulated by formation creep, with intervals characterised by much better bond, possibly affected by pore crushing.

We can conclude that foam cement bonding is broadly similar to what is observed with Class G cement, even though the presence of "empty" pores in the material may cause the defect at the casing-cement interface to be disconnected and thus unlikely to become a leakage pathway.





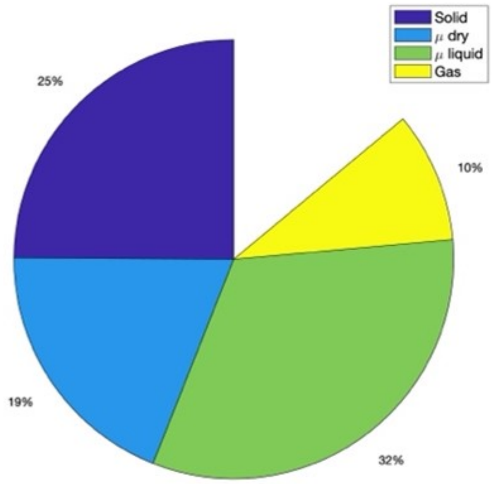
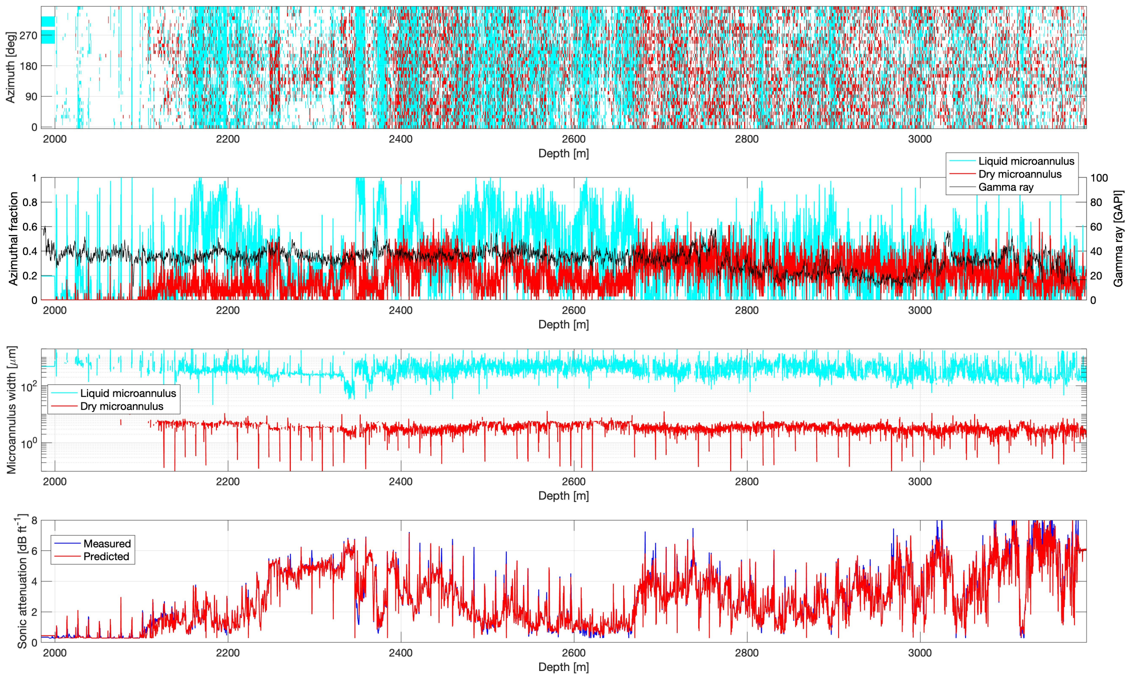


Fig. 6.7 Well 1 VM algorithm results Micro annulus opening and solid/Gas percentage

VM algorithm results after sonic correction supposing brine is filling the microannulus: map of liquid microannulus (blue) and dry microannulus (red) distribution (top); azimuthal coverage of dry and liquid microannulus compared with gamma ray (second from top); average microannulus opening (third from top); comparison between measured sonic attenuation and the values predicted based on VM algorithm results (fourth from top). Along the bottom the distribution histogram of microannulus opening (left) and the fraction of points for each material and bond condition (right). The calculations were done using the lead cement material model.



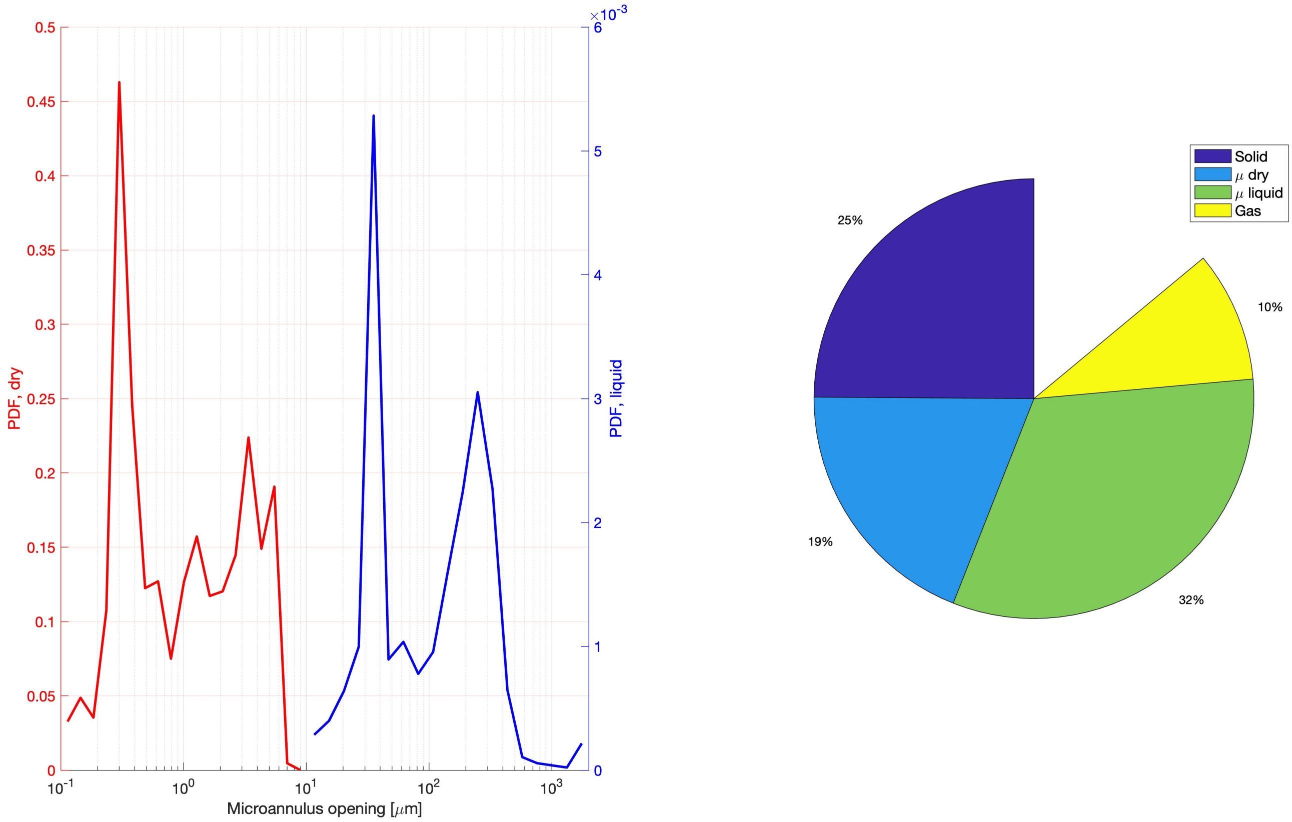


Fig. 6.8 Well 2 Micro annulus opening and solid/gas percentage

VM algorithm results after sonic correction supposing brine is filling the microannulus: map of liquid microannulus (blue) and dry microannulus (red) distribution (top); azimuthal coverage of dry and liquid microannulus compared with gamma ray (second from top); average microannulus opening (third from top); comparison between measured sonic attenuation and the values predicted based on VM algorithm results (fourth from top). Along the bottom the distribution histogram of microannulus opening (left) and the fraction of points for each material and bond condition (right). The calculations were done using the lead cement material model.

7 Workshop Presentations and Minutes

7.1 Introduction

On September 19, 2024, a workshop was held at Havtil to discuss foam cementing and gather participants insights on key aspects related to its application. Representatives from four operator companies (O1, O2, O3, O4) and three service providers (S1, S2 ans S3) on the Norwegian Continental Shelf (NCS) were invited.

O1, O2, S1, S2 and S3 presented their local and global experiences, with focus on the local challenges for foam cementing operations and evaluation as well. Followed by presentation from Three60 energy on literature review of foam cementing logging.

After that the participants were split into two discussion groups to help understand and get feedback on both the current status and foam cementing future. Notes from the presentations and the group discussion are summarizedin the following sections.

7.2 Presentations

O1, having the most extensive experience in foam cementing as a barrier application, presented an overview of their history with foam cementing along with current projects, including Computational Fluid Dynamics (CFD) development and laboratory experiments.

O2, with a smaller portfolio of foam cementing jobs, shared their insights and valuable contributions.

Following these operator presentations, each of the three service providers showcased their technologies for foam cement logging, along with their logging interpretation approaches and methodologies.

Finally, **Three60** delivered a global overview and literature review on foam cementing practices and innovations worldwide.

Presentation Summary from O1 (Extensive Experience on the Norwegian Continental Shelf):

Historical Use and Applications:

- Foam cement was first applied at Ekofisk in 2000, becoming the primary method for reservoir liner cementing due to its enhanced zonal isolation and displacement efficiency.
- As Ekofisk matured and field conditions became more challenging, foam cement became essential for production string installations, providing stability under narrower formation pressure margins.
- Over 560 foam cement jobs have been completed by O1, emphasizing foam cement's reliability in challenging conditions.

Foam Cement Evaluation and Logging:

- **Timing for Logging:** Foam cement logging often shows improved results when performed after several days or weeks, as the material's acoustic properties continue to develop. O1 demonstrated this with time-lapse logs showing enhanced responses post-curing.

- **Tool Selection:** O1 primarily uses Schlumberger's IBC tools, supplemented by Baker's INTeX and ULTeX combinations, indicating the need for high-quality tools to achieve accurate readings on foam cement logs.
- **Influencing Factors:** Variability in bubble size, distribution, and formation conditions can affect the acoustic impedance (AI) and, therefore, the accuracy of logging results. Access to formation water over time can improve AI readings by enhancing cement coupling.

Challenges and Factors Affecting Logging Accuracy:

- Foam cement's acoustic response may vary due to factors like density variation, micro-bubble accumulation, and uneven bond quality, which can result in "micro annuli" and challenges in bond interpretation.
- Lab and field studies indicate that bubble size is notably smaller in field applications compared to laboratory settings, suggesting that field-specific parameters impact bubble size and distribution, but the integrity remains equal or better than the bubbles produced in the lab.
- Additional water and production temperature exposure have been found to increase foam cement's compressive strength and improve acoustic impedance over time.

Future Directions:

- Ongoing efforts focus on enhancing the understanding of foam cement behavior, including computational fluid dynamics (CFD) analysis, advanced lab testing, and well-life studies.
- The development of standardized logging methodologies, accounting for foam cement's unique properties, remains a priority for improving accuracy in barrier verification.

Presentation Summary from O2 (Limited Experience on the Norwegian Continental Shelf):

Historical Use and Applications:

- Foam cementing has seen limited use in O2 fields, with only a few jobs completed between 2014 and 2024.

Foam Cement Evaluation and Logging:

- **Timing for Logging:** Logging foam cement often yields better results after several days or weeks, as its acoustic properties mature over time.
- **Tool Selection:** O2 has primarily used SLB IBC tools and is now planning to use Baker's INTeX and ULTeX combinations for trial logging to qualify the tool for future logging.
- **Influencing Factors:** Slurry density significantly impacts logging accuracy, with heavier slurries proving easier to verify than lighter ones.

Challenges and Factors Affecting Logging Accuracy:

- The time delay between cementing and logging can impact accuracy.
- The type of fluid in the well during logging also affects readings.

Future Directions:

- O2 is planning more foam cementing applications to leverage its advantages, and the development of standardized logging methodologies for foam cement remains a key focus to enhance accuracy in barrier verification.

Presentation Summary from S1:

S1 has the widest experience of logging foam cement jobs, and efforts are being made, along with O1, for developing a consistent approach for log interpretation when it comes to foam cementing. Some papers are to be published soon under the paper "SPE-223648-MS." Below are the key points presented by S1:

Lightweight Cement Properties and Challenges:

- Lightweight cements, including foam cement, have low densities and low acoustic impedance, making them challenging to evaluate using traditional cement logging tools.
- Foam cement's unique properties, such as heterogeneity and time-dependent acoustic evolution, necessitate advanced evaluation techniques.

Technological Innovations in Cement Logging:

- **Ultrasonic Tools:** S1 showcased advanced ultrasonic logging tools designed to address the challenges of low-density cements. These tools can analyze acoustic impedance variations and improve detection of lightweight cement quality.
- **Time-Lapse Logging:** Highlighted as a critical approach for capturing the curing evolution of foam cement over days or weeks, leading to improved evaluation accuracy.
- **Advanced Processing Techniques:** S1 proprietary interpretation models are tailored to handle the unique challenges of lightweight and foam cement, enhancing the reliability of barrier verification.

Field Experiences and Case Studies:

- S1 presented real-world data from lightweight cementing projects, demonstrating the effectiveness of their logging technologies in distinguishing lightweight cement from fluids.
- Key insights included examples of successful identification of zonal isolation and improved bond assessment in challenging well environments.

Presentation Summary from S2:

S2 has the largest number of pumped cementing jobs in the NCS, according to internal statistics: 235 jobs performed where cement was a part of the barrier system (148 intermediate string) out of 1058 total.

S2 has developed local guidelines for lab testing, attempting to mimic foam creation and keep samples under pressure for acoustic impedance measurement in the ultrasonic analyzer.

Challenges in Logging Foam Cement:

- **Low Acoustic Impedance:** Foam cement's impedance can be close to that of water, complicating differentiation.
- **Time-Dependent Properties:** Acoustic properties improve over time, making timing critical for accurate

logging.

- **Tool Sensitivity:** Conventional tools may misinterpret results due to high attenuation and signal scattering caused by nitrogen bubbles.

Evaluation Techniques:

- **Time-Lapse Logging:** Repeated logging improves assessment by accounting for changes in foam cement properties.
- **Advanced Tools:** Multi-transducer ultrasonic tools and flexural wave analysis are emerging technologies that improve foam cement evaluation by distinguishing solids from fluids.
- **Simulation and Modeling:** Computational models are increasingly used to predict placement quality and optimize tool parameters.

Industry Experience:

- Operators and service companies shared case studies showcasing successful foam cement applications and their approaches to logging and interpretation.
- Example Tools: slb IBC tools and Baker Hughes' INTeX and ULTeX were highlighted for their capabilities.

Presentation Summary from S3:

- **INTeX Tool:** The INTeX tool is fit for purpose in foam cement logging. It delivers horizontal shear in addition to flexural waves, which may help determine the width of any micro annuli.
- The tool was qualified for O1 and is soon to be qualified for O2 as well.
- **Shear Moduli Measurement:** If the shear moduli of the cement are measured in the lab, it can advance the accuracy of log interpretation.

7.3 Breakout Sessions

After the presentation, the participants were divided into two groups to gather the experiences and feedback, below is the summary for the main takeaways from the session:

1. Foam Cementing applications in the NCS is inevitable, specially with the proven track record with the application, specially in specific fields with O1, and in fact more future applications in some other fields are coming.
2. it is agreed that the foam cementing is something that can't be replaced looking at the challenges it addresses compared to the conventional cement, and hence it definitely has a future application in the NCS
3. There is room of improvement in the interpretation of the logging when it comes to the foam cementing, that can be achieved by more publications and also cooperation between the different parties, and since in cases where the foam cementing qualify as a barrier it is the responsibility of the operator to make sure the interpretation is verified using the experience from the service providers.
4. A qualification matrix can be developed tailored specifically for the foam cementing jobs to perhaps avoid logging all the wells, specially where there is a wide database of executing and qualifying the same job, for cases where is it a single double barrier.

5. Evidence of leaks
    1. Logs don't show any fluid migration above TOC in liners.
    2. May have been flow on a field from O3, but it's very uncertain, and the job was not ideal.
    3. Some platform wells have been cemented with forma, without reported issues.
    4. S2 noted that some Nitrogen flow through permeability - at the beginning - could be expected.
6. Logs/interpretation
    1. Operators tend to rely on vendors. There was an unwanted sidetrack in 2005.
    2. Now we can log in heavy muds: O2 pointed out that technology improved (PowerEcho transducers in SLB IsoScanner) AND in-house interpretation with software (Techlog) superseded old pdf reading. There was a step change in logging & interpretation in 2014-2018, which contributes to better outcomes with foam now. Hence, more willingness to go for foam.
    3. Service company competency in interpretation big hurdle: no standardisation.
7. Issues - positive or negative
    1. Rheology downhole is largely unknown (hard to measure and to model) but this is not important since most foam is pumped at 10% quality (i.e., volume fraction of Nitrogen).
    2. It is very expensive to test, but does it matter?
    3. Pressure vs. flow rate comparison for job evaluation is hard to do (matching density) but torque response while rotating liner could give an indication of the placement.
    4. Low excess volume to be pumped since it's slightly complex and have special safety considerations to handle the nitrogen safely on surface the excess volume has to go through a poor boy degasser.
    5. Choice of surfactant to add to the spacer and the surfactant added to the base cement to stabilise the foam is very important: poor mud removal can lead to mud-foam mixing, where the surfactant that keeps the bubbles stable is taken by oil- or synthetic-based mud and destabilize the foam.
    6. There is still a limitation on deck space on the NCS, especially when using Nitrogen bottle racks, as opposed to liquid N2. Simpler process but bigger footprint for larger jobs. Permanent installation of N2 lines can lighten the load and reduce risk, while being usable by all service companies, howeverthe nitrogen compressed gas that is used in Norway is much more practical than the liquefied nitrogen used elsewhere in the world.
    7. Free fall (u-tube) is hard to manage and may look like a well control issue: the foam engineer must work hard with the driller to explain what will be experienced and agree on adapted protocols.
    8. The market is still lopsided, with 50-70 jobs per year with S2 and 12 jobs over ~5 years with S1.
    9. Foam is firmly in the future in the NCS, after a recent renaissance. This applies both to riserless applications (shallow gas/water and weak formations) and as a well barrier.
    10. With foam as a barrier, operator company should maintain in-house logging interpretation to ensure proper interpretation and hence qualification.
    11. Lab is a weak spot: we know foam work, but it's very hard to generate realistic foam and testing it in the lab. There may be room for standardisation (e.g., what rheology values to use in modelling).specially that testing requirements in the API testing requirements can be improved.
    12. Standardisation of the logging interpretation among the different service companies/operators could solve the issue with a consistent approach and barrier qualification.

7.4 Conclusion

The workshop underscored foam cement's value in zonal isolation and highlighted the complexity of evaluating its integrity.

O1 approach of combining high-quality logging tools, delayed logging for improved results, and advanced modelling and testing techniques provides a robust framework for foam cement application in challenging well environments.

Key Takeaways:

- Ongoing collaborative research between industry and academia into material behaviour and advanced logging techniques to address unique challenges posed by lightweight cement.
- Recommendations for Lightweight Cement Evaluation:
- Adoption of advanced tools and interpretation models to address the limitations of traditional methods. Increased use of time-lapse logging for better assessment of lightweight cement properties.
- Collaboration among industry stakeholders to develop standardised evaluation protocols for lightweight and foam cement.
- Collaboration between operators and service providers to improve interpretation consistency.
- Development of consistent, standardised methodologies for foam cement logging. Contrast on logs between cement and mud will improve with time, so interpretation protocols should include this material evolution and the small likelihood that liquid microannuli seen by logs are leakage pathways.
- Better integration of advanced modelling and simulation tools in planning and evaluation.

8 Recommendations and Best Practices

There are ongoing research projects using advanced Computational Fluid Dynamic (CFD) models to accurately simulate foam cement placement. These applications, however, take a long time to run and model set up requires specific competence and experience. Work on developing and deploying lab testing equipment and methods may provide more reliable information on foam cement viscosity, but at the moment values measured with the base slurry are used instead. Even if our ability to model foam cement flow improves, the majority of foam cement jobs are done in deviated wells and with small density differences between mud, preflushes and slurry: this means that studying placement pressure alone cannot reveal the top of cement. Integrating all available records, such as return volumes and torque when rotating a liner, can better reveal cement coverage at the end of placement.

In order to qualify single barrier elements, NORSOK D-010, paragraph C.22.D.2.b requires that "*actual parameters [to] be compared with simulations using industry recognized software to take into account well geometry, fluid properties and friction contribution*." Return volumes are the best way to detect losses, whereas torque has the potential to reveal directly the annular length of cement slurry (which could be affected by an over-gauge hole). Job parameters can thus complement surface pressure to determine the top of cement, even though the demand for simulation software to predict observed variables means that qualification with "*displacement calculations*" is currently challenging.

Logging thus remains a viable method for qualifying foam cement as a barrier, and a required one when dealing with multiple barrier elements in the same string.

Recommendations for Lightweight Cement Evaluation:

- Adopt advanced logging tools and interpretation methods to overcome limitations of traditional approaches.
- Increase the use of time-lapse logging to capture changes in foam cement acoustic properties over time. This improvement and the resulting higher contrast and cement visibility on logs should be documented on a field-by-field basis and incorporated into interpretation protocols for fresh foam cement, ensuring that an early evaluation reaches the same conclusions as a late one.
- Establish an industry-wide team, including operators and service companies, to develop a standardised qualification process. A closer and open collaboration will allow benchmarking of methods and results and ensure consistent interpretation, especially confirming whether liquid-filled microannuli are a leak pathway with foam or can be added to barrier intervals.
- Ensure training is available so all stakeholders (land and offshore personnel, as well as regulators) understand the advantages and peculiarities of foam cement, in particular the unusual behaviour during placement that can create confusion with well control practices.
- Integrate advanced modelling and simulation tools in planning and evaluation processes.

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10 Glossary

α_g, flexural attenuation [dB cm^{-1}]

α_s, sonic attenuation [dB ft^{-1}]

ν, Poisson's ratio

ρ, density [kg m^{-3} or SG]

φ_{sat}, fraction of the bubble volume saturated with water

χ, degree of hydration

c_p, compressional wave speed [m s^{-1}]

c_s, shear wave speed [m s^{-1}]

ASLT, Array Sonic Logging Tool, Slb sonic tool to measure CBL

BHC, borehole compensated, a technique that uses two separate transmitters to measure sonic attenuation independently of transducers' sensitivity

CAST, Halliburton ultrasonic pulse-echo tool to measure acoustic impedance

CBL, Cement Bond Log, a standard sonic (i.e., lower frequency) cement evaluation measurement

DSLT, Digital Sonic Logging Tool, previous generation Slb sonic tool to measure CBL

E, Young's modulus [Pa]

FQ, Foam Quality (volume of nitrogen per unit volume of foamed slurry)

INTeX, Baker Hughes ultrasonic pad tool to measure flexural and horizontal shear attenuation

MAST, Multimode Array Sonic Tool, Slb sonic tool to measure CBL

NCS, Norwegian Continental Shelf

ULTeX, Baker Hughes ultrasonic pulse-echo tool to measure acoustic impedance

USIT, Slb ultrasonic pulse-echo tool to measure acoustic impedance

VDL, Variable Density Log, a visual representation of stacked waveforms recorded by the 5 ft receiver of CBL tools

VM algorithm, Bayesian model-based inversion algorithm to compute annular material properties and bond conditions from ultrasonic and sonic measurements

Z, acoustic impedance (AI) [Rayl]

11 Client Comment Sheet

Better Energy Together