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ON TECHNOLOGIES FOR SHALE BARRIER EVALUATION IN THE NORTH SEA

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ABSTRACT

Cement evaluation tools have been used in the oil industry for decades to examine the integrity of cement bonding to the well casing and openhole. It has been suggested that such tools also can be used to verify the presence of a crept shale formation that has formed a barrier outside the casing. However, the ability of these tools to help determine an acceptable leakage risk level, which results from sufficient hydraulic isolation outside and between casing remain a subject of dispute from experiences in the industry. In this paper we present results from ongoing research that may help contribute to resolving this dispute. The research objective is to design and build a 'shale as barrier' reference calibration cell. The reference cell is to be designed and made accessible to existing and emerging annulus barrier evaluation methods. The purpose is to help increase the quality of decisions made from such barrier evaluation technologies in an explicit well plug and abandonment context. The technical complexity of dispute coupled to the voice of business and stakeholder interests have been identified as a factor that could make project execution challenging. As result, a method to assist the execution of the project has been developed to systematically assure necessary stakeholder and end-user involvement. In this paper we present the method and demonstrate its application as an useful basis for project decision making and documentation. The method focuses on the capture and treatment of stakeholder preference elicitation, which is framed by traditional stages defined in the reference cell development process by adopting the concept of quality function deployment.

INTRODUCTION

The number of brown fields in the North Sea are steadily increasing as more and more wells are reaching their tail-end of productive life. Two main challenges today are therefore: (i) To maximise recovery from remaining, and (ii) to safely abandon unproductive wells and structures. Plug and Abandonment (P&A) operations are known to be costly, for instance, a cost estimate made for the UK offshore sector in 2016 suggest a median offshore structure abandonment cost of £59.7 Billion, whereof 48% of this cost due to well P&A activities [1]. The objective of P&A is to isolate the well 'forever', which pragmatically can be interpreted as 'to restore the overburden back to its original virgin state'. To restore the overburden back to its original state it seems attractive to use natural well plugging materials, and it is recognised in some fields that creeping shale and salt formations may create a competent permanent barrier outside the well casing [2, 3]. For example, eleven 'formations types' found in dozens of fields on the Norwegian continental shelf (NCS) has been reported successfully tested as barrier in wells, which implications on overall well life-cycle planning so far has produced cost savings in excess of 6.5 Billion NOK [4].

Requirements that follows from the industry two-barrier rule suggests that plug isolation needs to be verified by testing or equivalent method independent of the plugging materials used in P&A. As such, the acceptance criteria and the means established for verification of plug isolation will be critical to identify the most cost effective well P&A solution. Cement bond evaluation tools (CETs) have been used in the oil industry for decades to examine the integrity of cement bonding to the well casing and openhole. It has been suggested that such CETs also can be used to verify the presence of a shale formation that has formed a barrier outside the casing. However, the ability of CETs to help determine an acceptable risk level, which results from sufficient hydraulic isolation outside and between casing remain a subject of dispute in the industry [5]. For example, mismatches between observed annulus isolation versus interpretations made are

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readily found in literature from laboratory tests, field studies, and from comparing individual interpretations and conclusions made among log experts.

In this paper we present results from ongoing research from the NCS that may help contribute to resolving this dispute. The research objective is to design and build a full-scale 'shale as barrier' reference calibration cell. The reference cell is to be designed and made accessible to existing and emerging annulus barrier evaluation methods. The purpose is to help increase the quality of decisions made from such barrier evaluation methods in an explicit P&A well safety context. The technical complexity of dispute coupled to the voice of business and stakeholder interests have been identified as a factor that could make project execution challenging. As result, a method to assist the project has been developed to systematically assure necessary stakeholder and end-user involvement, for example from; (i) the authorities, (ii) service providers, (iii) researchers and (iv) operators. In this paper we present the method developed and demonstrate its application as a useful tool for purpose of, among other, project preparations, decision making and documentation.

TECHNOLOGIES FOR EVALUATION OF AN ANNULUS BARRIER

The popular CETs found in the market today may all be considered sonic tools where principle method includes an attempt to measure and interpret the attenuation of scattered pressure waves. A reduced wave amplitude may be interpreted as a firm cement to casing bond and therefore implied can also be hydraulic isolation. The amplitude decay is typically expressed as a ratio made from first received peak amplitude normalised against a baseline free- or cemented pipe amplitude, which is assessed by measurements of (i) transit time (micro-seconds), (ii) amplitude (millivolts) and (iii) attenuation rate (decibel per feet).

The first generation cement bond log (CBL) and variable density log (VDL) services based on acoustic technology have been offered for many decades [6]. The use of ultrasonic pulse-echo type tools as a CBL/VDL supplement in the 1980ies could be considered a second generation of CETs. Today, multi-frequency and multi-directional sonic CETs introduced within the last decade may be viewed as the latest, third, generation of CETs. This last generation also including electromagnetic sonic devices [7]. As with current CETs, also near future CETs may seem based around interpretations of scattering patterns produced by sonic or electromagnetic waves. For example, special focus for many sonic CETs today is that the contact interfaces between different medium in and around the wellbore represents an acoustic impedance mismatch, $\Delta Z_{1,2}$, from which waves are reflected and refracted. I.e. that sonic waves are scattered as result of different velocities, v_1 and v_2, or densities, ρ_1 and ρ_2, found between contacting medium around the well. The reflection and refraction of sonic waves can be described as for electromagnetic waves by wave theory, which according to Snell's law give direct relationship between the direction of incident-, reflected- and refracted waves. For example, a sonic wave striking casing at angle of ca. 17 degrees will refract parallel to casing wall. A result from literature search on experiences with CET technologies developed and demonstrated for cement bond evaluation is summarised in Table 1, Annex A. Modern services include use of all generation CETs as complementary to take advantage of the many decades of experiences. As result, the table show a summary that includes claims made about all generation CETs, from the conception around the early 60ies, and including CETs developed and refined as of today.

The CET related discussions in Table 1, Annex A are about confirmation of Portland cement that has bonded to casing. In comparison, shale is described as a fissile rock that is created by the consolidation of clay, mud, or silt, that has a finely stratified or laminated structure. The pores are primarily described as intergranular with secondary being fissures as one cause of high permeability noticed in some shale formations. As such, shale is found to be an inhomogeneous and anisotropic rock that is difficult to study from core samples due to, for example, sensitivity to contacting fluids and explosive decompression. In spite of challenges, the sonic properties of NCS shale formations have been studied with use of core samples. For example, Holt, Furre and Horsrud [8] reports that the P-wave velocity may be up to 25% higher in orientation parallel to versus normal to the bedding plane, and that the P-wave velocity measured from 2100 to 2400 m/s in higher porosity shale also seems insensitive to formation stress. Further, Horsrud [9] indicate a P-wave velocity of some relevant NCS shale formations in order of 1700 m/s to 3000 m/s normal to bedding.

As such, the higher porosity and clay rich NCS shales may be found to have significant different sonic properties when compared to the higher density cement slurries used on the NCS. For example, a simple $\Pr(X > Y)$ [10] consideration made based on Normal approximation of P-wave velocities reproduced from Jutten, Guillot and Parcevaux [11] and Horsrud [9] indicate less than 1% probability of shale representing a fast formation over cement in the vertical plane. Field trials by Williams, Carlsen, Constable and Guldahl [2] also indicate that the attenuation and impedance of NCS shale is "significantly lower than that expected of good cement". Shale may be considered a non-elastic rock and this suggests that most of an isolated annulus will be occupied by plastically deformed shale. No explicit sonic data was found in a literature search for plastically deformed NCS shale, which could potentially in-situ represent a separate impedance layer outside the casing.

CREEPING SHALE FORMATIONS AS AN ANNULUS BARRIER

The elements that may be considered required of a permanent creeping formation barrier includes a good physical understanding of the long-term displacements mechanisms taking place, which needs to be combined with existing well caprock requirements such as: (i) Must be a low permeability

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formation, which may be verified by formation evaluation logs combined with analysis of drill cuttings. (ii) Must have sufficient formation integrity (strength), which may be verified by earth stress model calculations combined with formation integrity tests. (iii) Must be cross-sectional and cover a sufficient length interval, which may be verified with pressure testing or logging tools.

The main mechanism that drive NCS shale displacement are suggested to be creep, described similar to hydraulic movement of blowout preventer rams, which possibly may be in combination with shear stress failure, compaction and consolidation as more consequential factors [2]. It is also suggested that an annulus bond log response can be made highly reproducible in a particular shale formation as means to verify the presence of a qualified annular barrier [2]. This could be a result of crept shale acting as a solid impermeable material that firmly grasps the casing. A literature search suggests that the description of the physical creep behaviour of NCS shale is scarce. On displacement mechanisms, Fjær, Folstad and Li [12] provides some geo-mechanical considerations on the shale barrier creeping process. They suggest that the best shale formation candidates are those with a low threshold for plastic flow and a high ability to sustain large plastic deformations. This is considered formations with a low content of Quartz and high content of clay such as Smectite. For example, Statoil [4] from field studies suggest that clay content should be greater than 45% and Quartz content less than 20-25%. Further, their studies also suggest that: (i) The shale formation barrier may only take a few days to form. (i) The creep process appear insensitive to drilling fluids. (ii) There are well cases where no creep has occurred over decades. (iii) A 'vent port' such as a permeable formation layer for annulus fluid displacements is considered beneficial for the creep process to occur.

The experiences with use of formation as explicit P&A barrier are scarce from a literature search, and found with regards to shallower wells used for disposal [13], and CO_2 or natural gas storage [14]. The following formation barrier issues can be noted: (i) Hydraulic fracturing, (ii) bedding plane slip, (iii) fault re-activation. Further, the failures can typically be linked to geological uncertainties, 'the geology of field was not properly characterized', which again often is coupled with too high pore pressure as result of the injection operations [14, 15]. As such, the lessons learned and risk assessment methods suggested, for example, in CO_2 storage may not be representative for deeper NCS shale formations. For example, deeper shale formations represent a natural and chemically stable material, which also have 'self healing' capabilities as a hydraulic barrier despite of deformation or fracturing from mentioned geo-hazards.

IMPACT OF BARRIER EVALUATION TECHNOLOGIES ON SHALE CELL DESIGN

This section describes how the research project has adopted the quality function deployment (QFD) process in project planning and execution to facilitate active end-user involvement in developing the final shale cell design. QFD can be defined as [16]: "Managing of all organizational functions and activities to assure product quality". QFD is a well-known concept applied in product and process development advocated by quality management theory. QFD is described as a systematic method focused towards identification and evaluation of the voice of customers or stakeholders targeted or affected by a new or existing product or service. Customer and stakeholder satisfaction is achieved in QFD by multi-disciplinary evaluation of elicited stakeholder preferences at various knowledge places, so-called 'gembas', which are identified at different phase in the product development process. The preference evaluations are made around positive and negative relationships associated, among others, with product characteristics identified. For example, conflicts may need to be resolved that stem from preferences for both minimal lifecycle cost and maximum research parameter accuracy and variability. The main objective of QFD is to assure that such major decision trade-offs become factually based, which also include key decisions required that concerns further work at the end of each product development stage. The QFD based product development stages defined for the reference cell project are illustrated in Figure 1, Annex A. Each project stage is seen represented with a generic quality house for preference evaluations. More details of each quality house is given in next section, but a short introduction follows.

From Figure 1, Annex A, Stage 1 is seen denoted product description and includes an evaluation of stakeholder preferences from a reference cell marketing perspective. The evaluations are seen focused from quality house on relationships between a reference cell system characteristics against existing and emerging CETs that are discussed in Section 2. The main objective of Stage 1 is the evaluation of industry needs, priorities and knowledge gaps in order to identify key research objectives for the cell development project. Stage 2 through Stage 4 include a breakdown of product development in traditional stages: (i) Concept design and selection, which includes evaluations made of product characteristics derived from concepts proposed against the characteristics and priorities established as product description in Stage 1. (ii) Product design and selection, which includes evaluations made of component characteristics against the items and priorities assigned to product characteristics established from design concept(s) selected in Stage 2. (iii) Product specification that includes an evaluation of component characteristic established against documentation requirements for manufacturing, instrumentation and usage associated with the end product. Table 2, Annex A shows the column headings considered in the quality house(s) defined for each development stage of the project.

RESULTS FROM THE SHALE CELL PROJECT

This section presents project results from Stage 1 and Stage 2 ongoing work as indicated in Figure 1, Table 2 and Table 3, Annex A. The results are being produced based on literature reviews, meetings, seminars and workshops held at different knowledge places identified. Figure 2, Annex A shows a mock-up cell concept developed in Stage 1 on basis of the literature

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review presented in previous sections. This mock-up design has been used as part of communications during project execution as a tangible basis for the stakeholder evaluations performed. The following subsystems and components can be seen treated in the preference evaluations from Figure 2, Annex A:

(i) Inner casing system that emulate the well production casing logged inside with the CET. The system components defined includes inner casing section, instrumentation (pressure and vibration indicated) and 'well fluids'.

(ii) Shale element system that emulate the potential creep of shale formations outside the production casing in a well. The system components defined includes free pipe section, shale elements, instrumentation (pressure indicate) and 'formation fluids'.

(iii) Shale element stress system that emulate radial stress in crept shale creating a contact pressure on inner casing. The system components of the actuator system defined includes outer casing (shroud), bellow, instrumentation (pressure indicated) and 'hydraulic fluids'.

The quality house enclosed as Table 4 in Annex A provides a summary of the evaluations performed at Stage 1 of the project on conceptual level. This QFD table is seen to include a product description priority, which is derived from normalized weights combining the basic priority with the relationship evaluation categories. The description ranks are then reapplied in next Stage 2 evaluations as a representative priority by rounding the value up. The initial priority assigned to each CET technology was determined in the project based on official stakeholder preferences and literature review presented in previous sections. The most important reference cell properties may be considered those given rank 4 or rank 3 in the preference evaluations, which from the quality houses developed in the project Stage 1 and Stage 2 so far are:

- The system characteristics from evaluations of existing and emerging technologies (Stage 1):
    - Minimum cell diameter and shale element system fluids, minimum cell length, shale element section length, vibration/resonance (instrumentation) and hydraulic pressure
- The subsystem characteristics from evaluations of product descriptions (ongoing Stage 2):
    - For inner casing system: Length, base material, inside diameter
    - For shale element system: Length, base material / base fluid, inside diameter, thickness
    - For shale element stress system: Length, base material / base fluid, thickness

As such, main cell development challenges have been identified at an early stage in the project by adopting a systematic method. The challenges identified are related to the development of two subsystems denoted as the shale element system and the shale element stress system. More specifically, extra efforts may be sought related to solving more detailed aspects that concerns reference cell instrumentation, dimensions and shale element material selection. These aspects are now being addressed according to the plan for the further work shown in Table 3, Annex A with aim to next produce a product requirement document as outcome of Stage 2.

CONCLUSIONS AND FURTHER WORK

The objective of P&A is to isolate the well 'forever', which pragmatically can be interpreted as to restore the overburden back to its original virgin state. To restore the overburden back to its original state it seems attractive to use natural well plugging materials, and it is recognised that creeping shale and salt formations may create a competent barrier outside the well casing. The two-barrier rule suggests that plug isolation needs to be verified by testing or equivalent means. CETs have been used in the oil industry for decades to examine the integrity of cement bonding to well casing. It has been suggested that such CETs also can be used to verify a shale formation that has crept and created a barrier outside the casing. However, the ability of CETs to help verify an annulus barrier in terms of providing an acceptable well leakge risk level remain a subject of dispute.

In this paper we present results from ongoing research that may help contribute to resolving this dispute. The objective of research is to design and build a full-scale 'shale as barrier' CET reference calibration cell. The technical complexity of dispute coupled to the voice of business and stakeholder interests have been identified as a factor that could make project execution challenging. As result, a systematic method has been developed to assist in the execution of the project. The method is presented and results demonstrated in this paper. The method is framed by literature study, stakeholder elicitations and traditional stages defined in a product development process by adopting the concept of QFD. As significant results, the following research questions have been identified early in project, which should help assure successful completion of the reference cell development project:

- What exactly do we want to measure and calibrate with the reference cell?
    - What is the relationship between radial stress in shale element system and; (i) CET interpretations or (ii) degree of hydraulic isolation?
- What material may be used to emulate crept shale?
- What are the key cell variables that we want to control in cell use?
- Are there elements related to cement job slurry design and mud removal that should be reflected in the cell design?

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ANNEX A

TABLES AND FIGURES

TABLE 1. SUMMARY OF LITERATURE SEARCH ON EXPERIENCES WITH TECHNOLOGIES DEVELOPED AND DEMONSTRATED FOR CEMENT EVALUATION

Type CET	Claims and experiences reported of interest to shale as barrier project	Sources
Acoustic <20 kHz)	Straightforward relationship between attenuation and variables like detector spacing and percentage of casing circumference bonded. Sheath needs to be (firmly) 'bonded' because cement not set, or not bonded, has relatively little attenuation effect. Thickness of sheath should be > 0.25 times wavelength of sonic pulse. 'Forerunners' difficult to detect if cemented casing. 'Late arrivals' are unpredictable in regards to amplitude. Bond between formation and cement is difficult to resolve, and assumed is that good casing bond also imply good formation bond.	[6]
	Floating gates with setting of bias level not recommended - may impair log reproducibility. Higher sonic frequency may produce pessimistic log since wave tends to follow pipe paths along unbonded cement. Small CET eccentering could produce significant attenuation and an optimistic log. Run logs with speed less and 1 ft/sec, and under 1000 psi pressure to avoid micro-annuli effects. Erroneously (weak) formation signal can be caused by: (i) Formation with high acoustic attenuation like soft shales and unconsolidated sands, (ii) presence of free gas and (iii) tool eccentering. An amplitude curve by itself is not sufficient for proper interpretation because gating and centering problems can cause low amplitudes. A VDL with a transit time curve can help identify centering and gating problems.	[17], [18]
	CET unable to determine cement bond index and quantify compressive strength of cement. Poor interpretation habits are misleading: (i) Dependence on- and oversimplified use of pipe amplitude curve, (ii) lack of understanding the full acoustic waveform, (iii) failure to compare and link actual physical and technical conditions in the well to the log measurements made. Of primary interest are S-waves through solids and amplitude of original P-wave. P-wave amplitude interpretation affected by: (i) TR and gate setup, (ii) logging speed, (iii) fast formations like low porosity limestone and dolomites, (iv) tool eccentering, (v) cement not set, (vi) thin cement sheath (<2 cm), (vii) micro-annuli, (viii) free gas, (ix) channels/voids in cement sheath, (x) pipe wall thickness. Mud wave amplitude increases with larger pipe. Formation arrivals are sensitive to lithology/porosity changes.	[19]
	A main challenge of CBL/VDL is difficulty in identifying smaller channels. Main requirements to obtain valid CBL/VDL log: (i) Run under pressure (1000 Psi) to mitigate micro annulus effects. (ii) Tool must be centered (omnidirectional setup). (iii) Gating (bias level). (iv) Thin cement sheaths (<2 cm) must be recognized by interpreter as attenuation rate may be significantly affected. (v) Well fluids affect free pipe transit time like freshwater vs. CaCl-brine ('faster') or OBM ('slower'). (vi) Casing string interference like from outer string if sheath is thin.	[20]
Ultrasound (>20 kHz)	If sheath is less than about 1 inch, and the acoustic impedance of material behind the cement is much different from the cement, a reflection from this boundary can interfere with the resonance window causing inaccurate interpretations. Use of a shorter TR window reduce this effect. Interpretations made can be significantly affected by surface roughness of casing	[21]
	The attenuation rate is directly related to acoustic impedance of the cement behind casing regardless of slurry type. Knowledge of cement acoustic impedance vs. time is mandatory for an improved CET interpretation.	[11]
	Attenuation rate is function of acoustic impedance, and is not related accurately to compressive strength. Ultrasonic CETs are less sensitive to tool eccentering and micro-annuli effects, but low density or gas cut cement may have acoustic impedance approaching that of mud.	[20]
	Cement bond evaluation in large or thick-wall casing is challenging due to the reduced cement response.	[22]
	Ultrasonic CETs should be used together with conventional CBL and VDL logs.	[7]
	With newer ultrasonic tools the formation signal is not as visible as with CBL/VDL logs. Should use multi-frequency setup with focus on peaks and troughs for purpose of complete interpretation.	[23]
	Do not depend on a single set of data, for example compressive strength or acoustic impedance, for interpretation (or calibration) of CET results.	[5]
All	"Whether fluids will communicate behind pipe cannot be determined from a cement evaluation log alone" (p. 86). Evaluation of CET logs requires thorough assessment of cement job success factors such as slurry design and mud removal. CETs require a minimum 0.75 inch (~2cm) cement sheath thickness for sufficient sonic attenuation. All sonic CETs are affected by microannulus. Acoustic tools are most sensitive. For sonic type CETs: Consider in order to obtain a valid log: (i) tool eccentering, (ii) gas and air in fluids, and (iii) cement residue and scale on casing wall.	[24]

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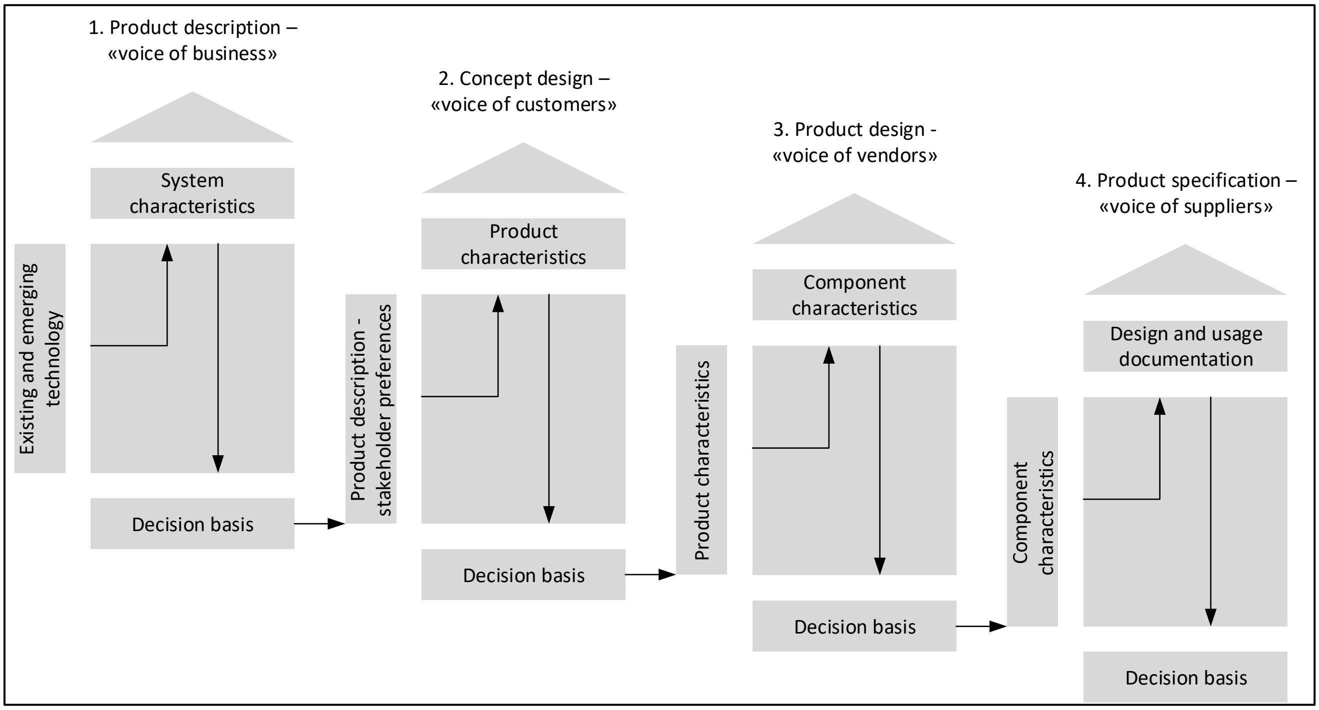

FIGURE 1. QUALITY HOUSES OUTLINED AT DIFFERENT SHALE REFERENCE CELL DEVELOPMENT STAGES BASED ON ISO 16355-1 [16]

TABLE 2. OVERVIEW OF PRODUCT CATEGORIES ESTABLISHED FOR QUALITY HOUSES AT DIFFERENT CELL DEVELOPMENT STAGES (IN PROGRESS)

System characteristics	Product characteristics	Product design / specification
Maximum cell length	Basematerial / Basefluid	Straightness
Minimum cell length	Outside diameter	Hardness
Maximum cell OD	Inside diamater	Permeability
Minimum cell ID	Thickness	Porosity
Maximum cell weight	Inner surface treatments / Inner surface roughness	Yield / Copmpressive strength
Pressure rating	Outer surface treatments / Outer surface roughness	Youngs modulus, E
Temperature rating	Length	Shear modulus, G
Free pipe section length	Density / Nominal weight	Poisson ratio
Shale element section length		Compressibility, c
Vibration/resonance		Magnetic susceptibility
Internal pressure		Relative permittivity (dielectric constant)
External pressure		Estimated weight
Hydraulic pressure		Estimated P-wave speed
Inner casing system fluids		Estimated S-wave speed
Shale element system fluids		Estimated acoustic impedance
Shale stress system (hydraulic) fluids		Estimated effective stress

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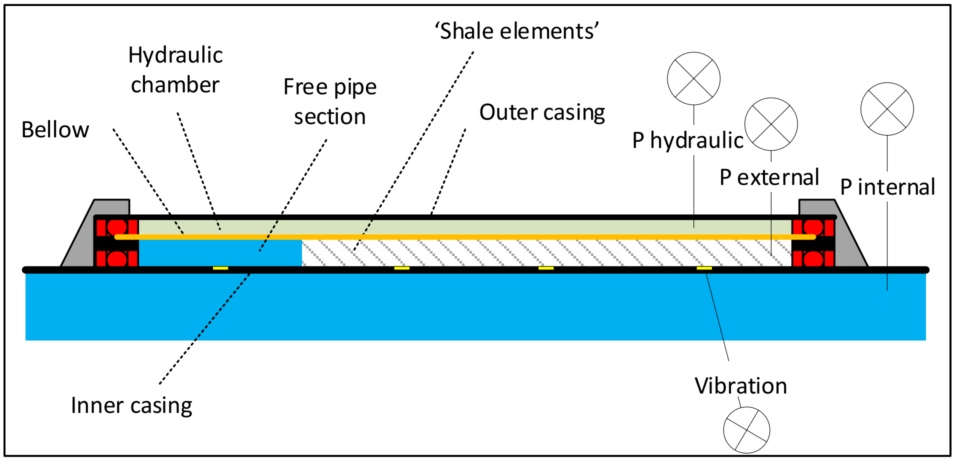

FIGURE 2. CONCEPT CELL DESIGN USED AS BASIS IN EARLY ELICITATIONS TO HELP IDENTIFY AND EVAULATE STAKEHOLDER PREFERENCES

TABLE 3. PLAN FOR DEVELOPMENT WORK BASED ON THE PROGRESS AND METHOD ADOPTED IN PROJECT EXECUTION

Timeline	Conditions	Activities	Deliverables	Status
Phase 1 / Stage 1	Project objectives. Existing products/services. Stakeholder preferences.	Populate QFD quality house. Literature review. Industry needs and knowledge gaps.	Project plan Product description	Closing
Phase 2 / Stage 2	Stakeholder preferences (needs, benefits/value and priorities).	Populate QFD quality house. Concept evaluations	Product requirements	Ongoing
Phase 3 / Stage 3	Product requirements; dimensions, materials, instrumentation, ...	Populate QFD quality house. Concept development and selection.	Product design	-
Phase 4 / Stage 4	Product design	Populate QFD quality house. Prototyping and testing.	Product specification	-

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TABLE 4. THE QUALITY HOUSE POPULATED IN PRODUCT DESCRIPTION STAGE 1

Product description Preference elicitation		Maximum cell length	Minimum cell length	Maximum cell OD	Minimum cell ID	Maximum cell weight	Pressure rating	Temperature rating	Free pipe section length	Shale element section length	Vibration/resonance, Hz	Internal pressure, MPa	External pressure , MPa	Hydraulic pressure, MPa	Inner casing system fluids	Shale element system fluids	Shale stress system (hydraulic) fluids	**“Voice of business”** *Improve the quality of decisions made based on use of cement evaluation technologies in regards to NCS shale forming an acceptable annulus barrier.*
Existing/Emerging technologies	Priority																	Evaluation remarks
Acoustic CBL/VDL technologies	2	(3)	(6)	(3)	(6)	(3)	(3)	(3)	(3)	(6)	(1)	(6)	(1)	(6)	(3)	(6)	(1)	3-5ft (1.5m) TR plus excess length of tool. OD <7 inches (18cm). Vast experience database wrt. use and interpretations. Sensitive to thin cemen sheets, tool eccentering and lack of a proper 'shear-bond'. Limited resolving power. Works historically well for casing to cement micro-annulus detection (1000psi rule).
Ultrasonic pulse-echo technology	4	(1)	(1)	(3)	(6)	(1)	(1)	(3)	(1)	(1)	(3)	(1)	(3)	(3)	(3)	(6)	(1)	<1 ft TR plus excess length of tool. OD <7 inches (18cm). Vast experience database wrt. use and interpretations. Works historically well for casing wall thickness evaluations. Sensitive to large diameter and thick pipe, gas, and porous mediums that may have same impedance signature as water and free pipe.
Electromagnetic acoustic technology	3	(3)	(6)	(3)	(6)	(3)	(1)	(3)	(1)	(6)	(6)	(1)	(3)	(6)	(3)	(6)	(1)	<3-5ft TR plus excess length of tool. OD <7 inches (18cm). Limited experience database wrt. field use and interpretations (value added). Log concerns could be interference from magnetic particles and debris in well. Focus on behaviour of sonic shear wave in annulus isolation introduced by electro-magnetic principles.
Ultrasonic flexural technology	3	(3)	(6)	(3)	(6)	(3)	(1)	(3)	(1)	(6)	(6)	(1)	(3)	(6)	(3)	(6)	(1)	3-5ft TR plus excess length of tool. OD <7 inches (18cm).Limited experience database wrt. field use and interpretations (value added). Focus on behaviour of flexural ('bending'/'resonance') wave introduced in the casing by ultrasound.
X-ray scattering technologies	1	(6)	(6)	(3)	(6)	(6)	(1)	(1)	(1)	(6)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	New technology. No experience database wrt. field use and interpretations (value added). Ca. 3m (12ft) TR section plus excess length. OD <7 inches (18cm). Focus on scattering patterens of X-rays. May have very different requirements compared to the sonic tools.
Product description (rank)		2	3	2	4	2	1	2	1	3	3	1	2	3	2	4	1	Rounding up the normalised weighted averages.
Important to service providers	Free pipe calibration is mostly desirable for CBL/VDL. Onboard sonic CET calibration made for eccentering, receiver sensitivity, well fluid properties and temperature effects (inner casing fluids). Other factors mentioned (Petrowiki.org): Surface roughness of caing (cement residues, oxidation, wear, …), annuli fluid attenuation and free gas. Most challenging logging condition is light weight cement (*or similar*) where cement log response look virtually same for free and cemented pipe. Do not depend on a single set of data, like compressive strength or acoustic impedance, for interpretation Benge, 2016)). Newer tools provide higher resolution, but formation signal is not so visible as with CBL/VDL (less penetration).																	
Important to operators	Note general NCS caprock requirements: (i) Must be a low permeability formation, which may be verified by formation evaluation logs combined with analysis of drill cuttings. (ii) Must have sufficient formation integrity (strength), which may be verified by earth stress model calculations combined with formation integrity tests. (iii) Must be cross-sectional and cover a sufficient length interval, which may be verified with pressure testing or logging tools. Important that calibration emulate in-situ conditions vs. tool technology as closely as possible, minimum focus on todays promising NCS creeping shale formations. Aim could be to verify “10 out of 10 times” if false-positive result wrt. existence of hydraulic isolation, say, for example that this means pressure integrity equivalent to passing a ISO V0 leak qualification test. Note: Not necessarily a need to verify “10-out-of-10” false-negatives. I.e. allow sometimes the 'waste' of a good barrier. Should be able to relate CET interpretations to degree of hydraulic isolation.																	
Important to researchers	Important all major cell parameters are controllable. Preferably made independently changeable, but as a minimum measureable within limited tolerances. Desirable that parameters can be related to in-situ flowrate estimation uncertainty (Poiseuille/Darcy/Bernoulli). Smaller setups preferred, these are generally cheaper to manufacture/replicate, use/reproduce and to upkeep.																	
Important to the authorities	Important all relevant CET technologies are considered together with key P&A phase safety factors. Principles for barrier management on NCS advocate the use of risk assessment before an evaluation of the number and location of barriers required to maintain an acceptable risk level for the activities. Risk may be defined as plus's / delta's and uncertainties associated with CET conclusions produced.																	
Units		m	m	mm	mm	tons	MPa	DegC	m	m	kHz	MPa	MPa	MPa				
Representative in-situ values		>30	>30	NA	212.8 (drift)	NA	34.5	60 – 120	TBA	>30	TBA	TBA	TBA	TBA	WBM, OBM, SBM	Pore fluids	NA	Common NCS casing, 9 5/8” (244.5mm) / 9 7/8” (250.8mm)-53.5# / 62.8# (13.8mm / 15.9mm wt) by 12.25” (311mm) nominal hole, >30m required formation barrier at typical NCS shale 1500-2500m depths, CET made for logging 9 5/8” casing.

Legends: 1 = Low priority/importance, 2, 3, 4 = High priority/importance. (1) = Weak relationship, (3) = Medium relationship, (6) = Strong relationship

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