FROM PRE-SCREENING TO MONITORING OF PLUGGED AND ABANDONED MARINE EXPLORATION WELLS - ENABLING REUSE OF RESERVOIRS FOR CO2 STORAGE THROUGH GEOPHYSICAL MONITORING

Benjamin Emmel[1*], Simone Zonetti[2], Anouar Romdhane[1], Bastien Dupuy[1], Malin Torsæter[1]

[1] SINTEF Industry, Applied Geoscience Group, Trondheim, Norway

[2] SINTEF Digital, Applied Optics Group, Oslo, Norway

* Corresponding author e-mail: Benjaminudo.emmel@sintef.no

Decommissioning of platforms and permanent plugging and abandonment (P&A) of oil and gas wells is a major future financial challenge for oil producing countries. This is especially true for offshore wells in deep water, where heavy-duty drilling rigs with high day rates need to be applied for well closure. Even if well monitoring is typically not done after abandonment, this is an emerging topic – which is crucial to enable reuse of reservoirs for e.g., CO_2 or hydrogen storage. With this respect, it is important to find new cost-efficient ways of monitoring plugged offshore wells, where in-situ gas measurements, satellite- and/or air- based monitoring techniques are difficult to implement or not possible. In the present paper, we propose the first steps for a data-based, *geophysical monitoring strategy for permanently plugged wells*. The foundation is a detailed analysis of documents provided by operators towards the Norwegian authorities. Based on these open-access data, we construct numerical wells and simulate/evaluate the geophysical response of the different well barrier materials. The data can be used for future field reuse/monitoring campaigns to detect missing or damaged cement barriers in abandoned oil and gas wells. This will broaden the available sites for future large-scale CO_2 storage.

Keywords: *CO_2 storage, Well integrity, Plugging and Abandonment (P&A), Numerical simulations, Geophysical monitoring, CSEM*

1. Introduction

The decommissioning and permanent plugging and abandoning of wells is an *eternal* legacy of energy companies working in the North Sea. Post-abandonment monitoring is typically not performed but is an important topic if the reservoir is to be qualified for re-use as e.g., a CO_2 storage site. Since 1966, more than 750 wildcat wells have been drilled only in the Norwegian part of the North Sea. Some of these wells might pose an environmental risk by representing potential leakage paths for gases towards the seafloor, the water column, and maybe into the atmosphere [1]. Leakage along wells can occur through or along the cement plug placed within the wellbore or through/along the annular cement outside the casing pipe. Both the cement matrix and the cement-rock and cement-steel interfaces are potential leakage paths [2]. Plugging and abandonment (P&A) procedures aim at preventing such integrity failures with an *eternal* prospective by filling carefully selected discrete sections of the well with cement (cement plugging) [3]. However, as indicated by a few scientific cruises targeting decommissioned exploration wells, these locations show gas leakages from the subsurface to the seafloor [4][5][6]. As there are strict requirements for P&A on the Norwegian Continental Shelf since the start of oil and gas production, the wells are always plugged with cement – and the leak are thus most likely connected to degradation of barriers over time. Both steel and cement are materials known to deteriorate over time in subsurface environment, as is also the bonding between them[7][8].

Current strategies for well integrity assessments are based on cased logging tools, requiring entry and access into the wellbore. This makes the monitoring of temporarily and permanently P&Aed wells costly and challenging. To our knowledge, no reliable methods for non-invasive (tophole) well integrity monitoring for plugged wells have been published in scientific literature, even though some recent studies and industry workshops have pointed out the urgent need for developing such methods – especially for reservoir re-use for CO_2 storage purposes.

Our approach is to develop such a technique through the combination of knowledge on well construction, material degradation over time and non-invasive subsurface imaging. In this context, geophysical techniques offer the potential to represent a more continuous and cost-efficient alternative to in-situ gas measurements on the seafloor, allowing early prevention and mitigation of well barrier degradation. However, before entering a geophysical monitoring stage, a good overview of the P&A status and associated well architecture, and subsurface geology is necessary. This can be achieved by evaluating old drilling operation reports and by identifying critical parameters such as parameters from drilling (e.g. drilling induced damage to the rock formation), the success of primary well cementing, any pressure/integrity testing performed on barriers during the wells' operative lifetime, information on build-up of sustained casing pressure over time in the well, and the general subsurface conditions in the well (to estimate the degree of material degradation). All this data can be extracted from publicly available well completion reports and the webpage of the Norwegian Petroleum Directorate (NPD). After the pre-screening results are evaluated, specific wells can be selected for a detailed geophysical analysis based, in a first stage, on numerical but realistic models. Comparisons with laboratory and field experiments can be performed afterwards.

In this contribution, we report a strategy for how to proceed from pre-screening of available data reported to the NPD towards the building of numerical well models for assessing the sensitivity of selected geophysical techniques to well integrity issues.

In the future European green energy network Norway has a crucial role to store CO_2 or hydrogen in depleted gas and oil reservoirs. A monitoring strategy for abandoned wells as one of the major risks for gas leakage [9][10] will be one of the key aspects to de-risk environmental pollution and guarantee safe sub-surface future energy storage. Such a strategy will help to apply new, cost-effective P&A methods developed at SINTEF Industry, such as using shale as a natural barrier [11] or repairing damaged cement by electrochemical enhancement of mineral growth [12].

2. Methods and results

In this paper, we present two methods. We start with the pre-screening of data reported to the Norwegian authorities. Based on this public data-set we show how to build realistic numerical models and examples of geophysical numerical modelling that is part of an underway sensitivity analysis.

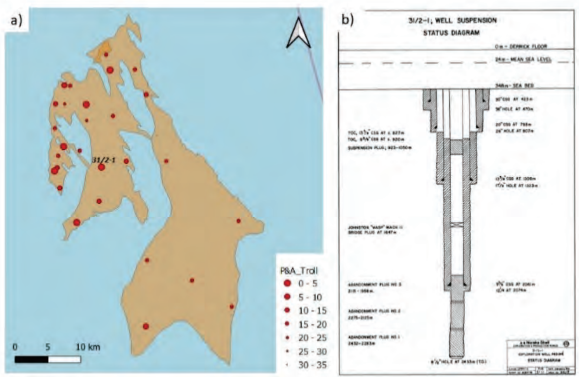

Figure 1: a) Map showing locations and P&A evaluation scores for exploration wells (red dots) from the Troll gas and oil field (brownish area). b) Decommissioning and P&A plan for well 31/2-1 showing the planned outer cement framing and the position of a "suspension" plug (923-1050 m) and three abandonment plugs between 2283 m and 1958 m. The grey shaded area should represent volume filled by cement.

2.1 Pre screening (evaluation of available data)

Well decommissioning data provided by the NPD are analysed with respect to their availability, plausibility, and to conformance to the present P&A regulations offshore Norway [7]. Based on twelve criteria a final P&A score for 31 exploration wells in the Troll area was established (Fig. 1a) and interpreted in a Geographic Information System (GIS) environment [13]. A few of the evaluation criteria will be explained with the example of exploration well 31/2-1 (Fig 1a) which was drilled in 1979 to a total vertical depth of 2433 m and discovered oil in the sandstones of the Sognefjord Formation.

The evaluation results are given in Table 1. The first 4 criteria *sc_status* (e.g., P&A, suspended, junked etc.), *sc_entryYear* (before or after 2004), *sc_plugged_sa, sc_plugged_ab* relate to data given from NPD in their wellbore GIS shape-file *wlb.Point.zip* [14]. Criteria *sc_report, sc_cs_ver, sc_plug_len, sc_pl_ver, sc_mill, sc_ind_leak* are explained in the description of Table 1, *sc_plug_job* and *sc_cem_job* are explained more detailed in the following.

Table 1: Pre-screening evaluation results for well 31/2-1 and short description of the evaluation criteria. The pre-screening score is far below average of exploration wells from the Troll gas and oil field and thus a further investigation is necessary.

Criteria	Score	Max	Description
sc_status	1	3	Status descriptions for exploration wells from NPD
sc_entryYear	0	1	Year of drilling related to regulations
sc_plugged_da	0	1	Reporting of plugging operation to the authorities
sc_plugged_ab	0	1	Finishing date reported to the authorities
sc_report	2	3	Report quality
sc_cem_job	3,00	3	Casing cement job evaluation
sc_cs_ver	1	3	Casing cement job verification
sc_plug_job	-6	6	Abandonment, reservoir and surface plug
sc_plug_len	2,80	3	In the NNS the required plug length is 100 m
sc_pl_ver	0	3	Tagging or weight testing of plugs?
sc_mill	0	1	Milling of casing to improve cement integrity
sc_ind_leak	1	2	Leakage indicated by secondary measurements
sc_total	4,80	30,00	

In the casing cement job evaluation (*sc_cem_job*), we investigate the volumes of the drilled hole used cement along the full length of the wellbore (including cement used for well lead, tail and shoe, without add-ons). We assume a cylindric shape of the borehole and the casing. The volume between the open borehole and the casing was calculated by subtracting the casing volume from the open borehole volume. The *sc_cem_job* score (between 0 and 3) is obtained by adding the individual scores for every casing interval and by normalization. For well 31/2-1, the cement job is sufficient for all four casing intervals and thus a score of 3 is given (Fig. 2a, Tab.1).

We evaluate three plug types in the *sc_plug_job* criteria. These are from the deepest to the shallowest wellbore depth: (i) Abandonment plug: this well barrier should protect against any potential source of inflow within permeable zones. The cementing job consists in filling the deepest parts of the wellbore, including sometimes open hole sections (with no casing). (ii) Reservoir plug: added if a potential source of inflow or if the reservoir is exposed (hydrocarbons present). (iii) Environmental plug: this well barrier should isolate the surface/seabed from any potential source of inflow from the wellbore.

In the *sc_plug_job* evaluation, we mainly consider two criteria. At first, we check if all plugs are available and in the correct position, e.g., if the reservoir plug is correctly placed according to the present regulations and regional geological knowledge (e.g., top of a reservoir unit). Figure 2b shows the plug locations along the well 31/2-1. Environmental plug and reservoir plug are missing or placed incorrectly. The cement volume calculations for the abandonment plugs indicated insufficient used cement volumes for the anticipated plug lengths resulting in a *sc_plug_job* score corresponding to -6 (Tab. 1), indicating that the plugs are not placed in the right position and/or the amount of used cement was insufficient. The resulting total score of well 31/2-1 is 4.8 (Tab. 1) which is below the average score for exploration wells from the Troll gas and oil field. A further monitoring/examination of this well is therefore recommended.

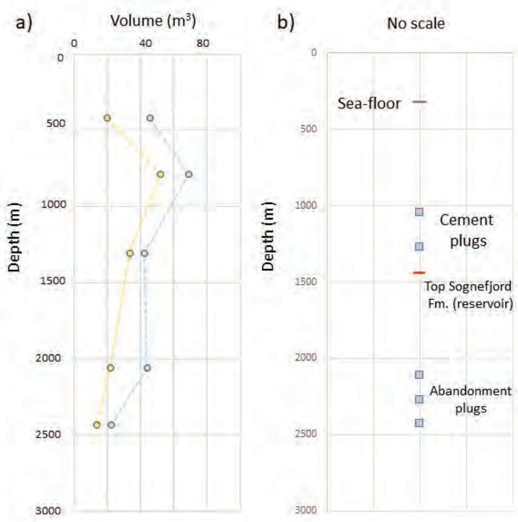

Figure 2: Graphic representation of the casing cement job and the plug position for well 31/2-1. a) The dashed yellow line indicates the volume between the open hole and the casing which should be filled by cement. The dashed blue line is the volume of cement used between every of the 4 casing intervals. b) Schematic illustration of plug positioning in relation to the top of the reservoir and the seafloor (the plug length is not considered in the figure). In this case, the cement plugs (this work was done 1979) are not positioned according to the regulations from 2004 [7].

2.2 Numerical model set-up

The data of well 31/2-1 is used to build a numerical model to simulate electromagnetic (EM) responses using the finite element method (FEM) software COMSOL Multiphysics® v. 5.5 [15].

The cylindrical well element, radially layered to accommodate different wellbore and casing sizes, is enclosed in a large cylindrical domain with a radius larger than 500 m. The whole geometry is also layered horizontally, following the size changes in the well and the location of the plugs, with the inclusion of a water layer and an air layer at the top, and additional 400 m of rock formation below the well. Furthermore, the modelling domain is surrounded by absorbers to simulate infinitely large systems and avoid the generation of data due to the use of a limited bounded simulation domain. The geometry of the well (not to scale) is given in Figure 3.

A transmitter antenna is implemented as a perfect dipole of arbitrary length and can be placed anywhere in the simulation domain with any orientation. Taking advantage of field symmetry, simulations of radial and tangential polarisations allow to reduce computational requirements by half. Materials are characterized by their conductivity and relative permittivity and are considered, in first approximation, to be independent from the frequency of EM radiation. Formation properties are taken to be isotropic but vary with depth. The model is meshed using a triangular mesh on the seafloor surface, with element size adapted to provide sufficient local refinements in the proximity of the well, surrounded by a mapped mesh on the corresponding absorbing boundary. The resulting surface mesh is then swept along the vertical direction (Fig. 4).

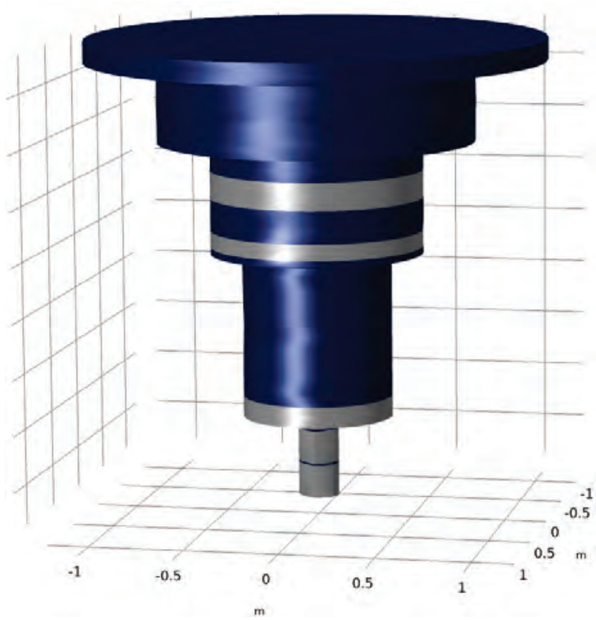

Figure 3: Visualization of the well structure implemented in COMSOL Multiphysics® [15], not to scale. Dark blue areas represent the well casing, grey areas the cement plugs.

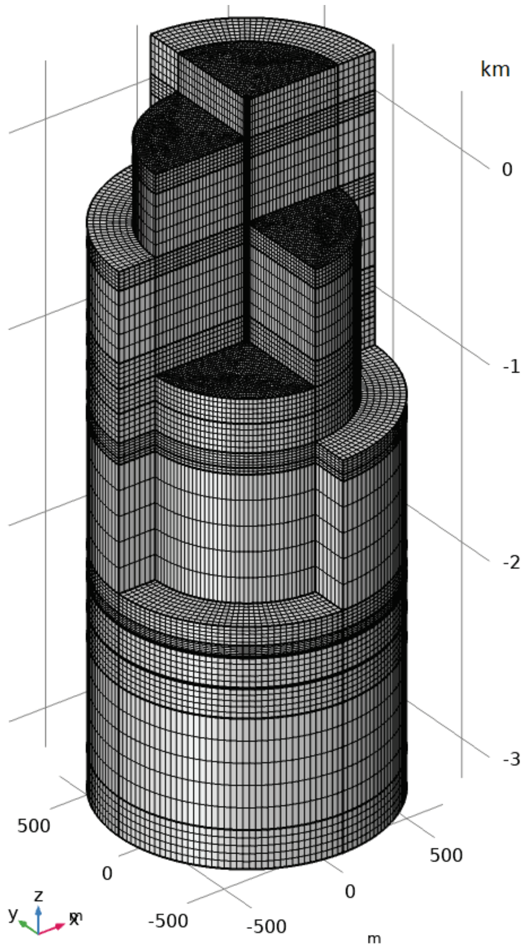

Figure 4: Example of a possible discretization of the FEM model, with a dense triangular mesh on the horizontal internal surfaces, mapped mesh on the absorbing layer, and swept mesh in the vertical direction.

2.3 Geophysical monitoring techniques

Taking advantage of a dedicated implementation of low frequency EM, including effective formulations for thin electrical layers, it was possible to study the response of well components to external EM fields, both for the purpose of well detection and well monitoring. Results from the numerical models can be used as benchmark models in a realistic field scale well integrity monitoring study.

A 40 m long horizontal dipole emitter located 30 m below the sea surface at a radial distance of 100 m from the wellbore, is considered with a frequency corresponding to 1 Hz. We derive the corresponding electric field in the simulation domain and extract the solution at the seafloor surface. Figure 5 shows an example of the resulting data where the gain in dB, calculated as 20*log10 (scattered field / background field) for the horizontal component of the electric field, is displayed. The background and scattered fields correspond to the cases where no well is considered in the simulation domain and where a well geometry including plug is added, respectively. The result highlights the field patterns that can be observed with finite measurements of the electric field at the seafloor (CSEM receivers). It is also indicative of spatially variable sensitivity that one might expect. Similar patterns can be derived for different orientations of the dipole emitter with respect to the wellbore location.

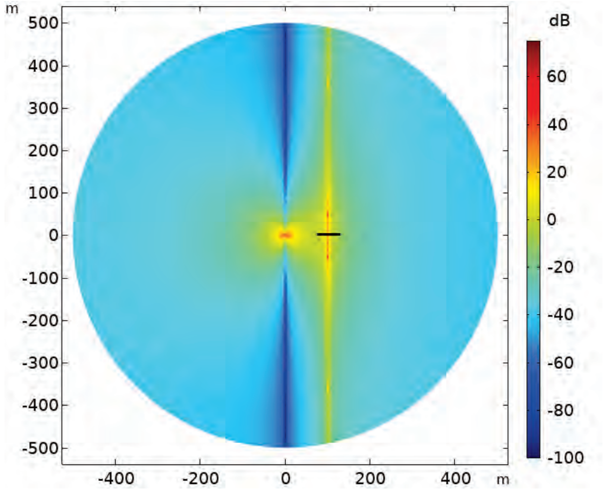

Figure 5: Example of electric field gain (x component) on the seafloor surface of the FEM model. The well is at the center of the plot. The position of the 40 m long dipole antenna relative to the sea-floor plane is pictured as a black line, 100 m away from the wellbore.

3. Discussion and conclusion

Potential leakage pathways for stored and/or natural subsurface gases can be geological (e.g., through fractures, faults, or due to caprock failure) or man-made, with the latter mainly due to leakage along deep active or abandoned wells [16]. Wells can form a direct connection between deep gas and oil reservoirs or CO_2, hydrogen storage units with the seafloor by-passing all geological sealing caprock units. The European CO_2 storage community expects a low risk due to leakage along active and onshore wells because they can be monitored very effectively through geochemical and geophysical methods [16] and observed leakage might be restricted to a few incidences [4][6]. There is, however, little information on leakage from abandoned offshore wells, which can be more severe – and uncertainty about these wells can typically jeopardize the use of a reservoir for CO_2 storage purposes. However, leakage along wells with emission of greenhouse gases must be treated as a global problem including countries with limited federal regulations [17] and cost-effective monitoring strategies are needed to be implemented as soon as possible.

Here, we propose a strategy which starts with the evaluation of documents provided by the drilling operating companies towards the Norwegian authorities. Every exploration well is unique when it comes to the design and the interaction with the surrounding geological units. The level of details in the available well documentation can vary significantly. Pre-screening criteria's are e.g.: (i) the date of drilling, P&A work, number of plugs, and quality of the cementing work are considered in our study. The obtained results suggest higher scores for the wells drilled after 2004, date of the first regulations for P&A on the Norwegian continental shelf [7], compared to the wells drilled before that date.

Here, we can assume that federal regulations have improved on average the quality of P&A work.

(ii) For the plugging, most industry standards only require isolation for zones with flow potential. This means, that for an exploration well one plug isolating a hydrocarbon reservoir might be sufficient. However, in our evaluation we include three plug types (1) abandonment, (2) reservoir and (3) surface plug considering the future usage of a depleted reservoir as a potential CO_2/hydrogen storage place. (iii) The quality of the cement work is evaluated by simplified volumetric calculations using the data given in the reports. Temperature, pressure and add-ons volumes are neglected in the volume calculations.

For the geophysical modelling, a further understanding of the sensitivity of EM measurements as function of frequency, data noise, and the orientation of the dipole emitters and receivers is required. A first practical application of such measurements consists in finding the exact location of the wells in the subsurface. If casing is still present, EM signals will be very sensitive, and should help locate accurately the wells. Another application consists in identifying and verifying the location and thickness of cement plugs. Finally, we foresee possible use of EM signals in a 4D context where the objective is to provide alerts about possible integrity issues (e.g., casing discontinuity due to corrosion). For these possible applications, EM signals must be recorded and processed to extract the relevant information (e.g., using inversion) out of the raw data. Future work will also include seismic modelling and would be the basis for the design of tailored acquisition layouts capable of detecting old P&Aed wells and in a later stage providing useful information about wellbore integrity status.

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