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Final report - Rock salt stimulation feasibility for well abandonment

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Contents

1 Project information

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Topsector Energy, TKI Nieuw Gas:
Program line Geo Energy – Research theme: Decommissioning and Abandonment

Project duration:
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Project partners:
TNO (coordinator), University of Utrecht, EBN, Total, Shell, Oranje Nassau Energie, Neptune, Nouryon

2 Technical reporting

2.1 Management Summary

An increasing number of oil and gas fields will reach the end of economic hydrocarbon production in the coming decades. For most offshore oil & gas fields in the Netherlands, cessation of production is expected to occur in the next 1-2 decades. Accelerated decommissioning of infrastructure will be a major issue associated with the end of field life of onshore and offshore assets, with both technical and economic challenges. More efficient well plugging and abandonment methodologies can aid in tackling technical challenges, reduce costs of decommissioning and provide reliable long-term containment.

The aim of the project was to investigate the potential options for Zechstein rocksalt stimulation, through experimental verification, and to provide a concept design for a pilot test in order to enable implementation of the most promising technique (in case the stimulation options can already be applied in the field).

Stimulation might be required under circumstances where the rocksalt does not close the wellbore fast enough and could boost the development and implementation of this natural sealing methodology.

The research included four different studies relevant to proof the feasibility of rocksalt as a wellbore sealing and P&A plugging material:

1. A chemical approach for salt stimulation using a saturated brine and crystallization by the evaporation of water and using an antisolvent
2. Investigation of the creep behaviour and porosity-permeability evolution in Zechstein rocksalt during borehole closure
3. Accelerated natural sealing of abandoned wells by local heating of well system and salt creep through perforated casing and cement
4. Well inspection of Hengelo Z-1 as preparation for a downhole rocksalt creep-test

The key messages from the studies are:

- It was shown that the chosen chemical stimulation approach using an evaporation-concept can generally form solid to rock-hard salt plugs. However, these concepts are generally at a low TRL level. The small-scale lab tests showed that a certain development time would be required to get to a field application which conflicts with need of having P&A materials available within the next 3-5 years. Also, the placement and required handling of various fluids on site seem to be a challenge for field application of the investigated concept.
- Unconfined and triaxially confined compression experiments used to investigate the effect of fluid on the mechanical behaviour and permeability evolution of (damaged) rocksalt showed, a rapid acceleration in creep rate upon injection of saturated brine, accompanied by a decrease in flow strength. Long-term permeability measurements showed that damaged rocksalt, saturated with brine, gradually became less permeable with time.
- The analysis of rocksalt properties conducted to investigate the feasibility to form salt plugs through perforations suggests that a permanent, impermeable and continuous seal may be formed that connects salt formation to a (rocksalt)

well plug at timescales relevant for well decommissioning. However, it has to be demonstrated that natural sealing and stimulated salt creep through perforations lead to a sealing barrier under configurations and conditions relevant to real wells.
- The well inspection of Hengelo Z-1 revealed that there is no showstopper and that can generally be used for the envisaged downhole salt creep test. However, it requires some unforeseen workover, e.g. to remove a detected bridge, to be fit for the field trial, which will be performed in the further preparation of the downhole test.

As a result of the above a dedicated field test design for an “enhanced” salt creep test appears to be impossible and immature at this stage of development of the investigated stimulation options. Small- and large-scale test under in-situ conditions are suggested as next step towards a field trial which could also combine different stimulation concepts studied (e.g. chemically/thermally stimulated creep through perforations).The use of temperature and/or saturated brine to enhance the creep process in the Hengelo Z-1 test will be part of the design discussion of the field trial preparation. If applied, the simulation should not put more risk on the already challenging downhole test operation and has to be accepted beforehand by the well owner Nouryon.

““Het project is uitgevoerd met subsidie van het Ministerie van Economische Zaken, Nationale regelingen EZ-subsidies, Topsector Energie uitgevoerd door Rijksdienst voor Ondernemend Nederland.”

2.2 Introduction, motivation and scope

The abandonment of thousands of wells in NL in the near future requires cost-efficient and reliable solutions. Reducing P&A costs and increasing long term safety could be achieved by developing new methods for well plugging and annular zonal isolation based on the use of natural sealing formations. Rocksalt is particularly attractive because of its ductility, ability to creep and self-healing/sealing behavior. The advantage of restoring the original caprock is its very low permeability, proven long-term sealing capacity and chemical stability. Many evaporites, even when ductile and principally suited for natural formation sealing might creep (causing wellbore convergence and closure) too slow for the application within P&A operations, particularly at shallow depths above 2000 m.

The aim of the project was to investigate the potential options for Zechstein rocksalt stimulation, through experimental verification, and to provide a concept design for a pilot test in order to enable implementation of the most promising technique. The project is aimed at oil, gas, geothermal wells and salt producers in the Netherlands that are faced with decommissioning wells that transect, or operate in, Zechstein rocksalt formations. Zechstein rocksalt overlies a high proportion of Dutch gas fields, many of which will be decommissioned in the coming decades, both on- and off-shore. Moreover, the Dutch salt mining industry is one of the largest in the EU, with many wells to be decommissioned or re-used for energy storage in solution-mined caverns, which will likely be needed even more in the near future.

Rocksalt creep strain rates that govern convergence strongly depend on differential pressure in the wellbore, environmental temperature and mineralogical composition of the salt. Previous studies showed that the wellbore closure times can vary in a wide range, from a few hours for potassium (K/Mg) squeezing salts to a few years for halite at shallow depths of ~1 km[1,2,3]. The range of predicted wellbore closure times for rocksalt is too wide and closure times of several years are likely too long to be practicable for well plugging by (some) ductile natural formation. The project proposed here aims to investigate the feasibility of using different salt stimulation techniques to control and enhance the formation of a natural formation plug in Zechstein rocksalt for well P&A. Increasing the creep strain rate by stimulation will offer a major step forward when using natural rocksalt as the sealing plug.

Research objectives

- Review and evaluate available techniques for Zechstein rocksalt stimulation potentially suitable for P&A of wells penetrating Zechstein rock salt formations.
- Investigate the feasibility of using identified techniques for stimulating salt convergence in open wellbores and wellbores filled with the native Zechstein rocksalt material, with and without additives.
- Develop concept solutions for applying identified Zechstein rocksalt stimulation techniques in downhole conditions.

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[1] Orlic, B. and Buijze, L.. 2014. Numerical modeling of wellbore closure by the creep of salt caprocks. In Proceedings of the 48th US Rock Mechanics/Geomechanics Symposium, Minneapolis. ARMA paper 14-7499.

[2] Orlic B. and Wollenweber J. 2017. D 1.1.1 Baseline geomechanical modelling -"TKI Downhole Lab" project deliverable report, TNO 2017 R10502

[3] Hou, M.Z., Wundram, L., Meyer, R., Schmidt, M., Schmitz, S. and Were, P. 2012. Development of a long-term wellbore sealing concept based on numerical simulations and in-situ-testing in the Altmark natural gas field. Environmental Earth Sciences, 67 (2), 395-409

2.3 Project structure and execution

To address the defined research questions the following key activities were conducted:

- Identify functional and operational requirements for well plugging with rocksalt
- Review of techniques and methods for creating rocksalt plugs
- Design of laboratory experiments and test program
- Perform dedicated lab experiment and investigate the creep behavior and porosity-permeability evolution in evaporites as well as test options for enhancement of wellbore closure process
- Investigate if a downhole salt creep test can be performed at a potential Nouryon test well Hengelo Z-1 including re-entering and logging operations to find out about the current state of the well and if workover is required to conduct a downhole creep test (in a follow-up project).

The research was structured and is reported in four separated studies relevant to proof the feasibility of rocksalt as a wellbore sealing and P&A plugging material:

1. A chemical approach for salt stimulation using a saturated brine and crystallization by the evaporation of water and using an antisolvent
2. Investigation of the creep behaviour and porosity-permeability evolution in Zechstein rocksalt during borehole closure
3. Accelerated natural sealing of abandoned wells by local heating of well system and salt creep through perforated casing and cement
4. Well inspection of Hengelo Z-1 as preparation for a downhole rocksalt creep-test

The project had a duration of 30 months and was conducted from May 1st 2018 to November 1st 2020 together with the industry partners EBN, Shell, Total, Nouryon, Neptune and Oranje Nassau Energie.

During the project no major problems occur, However the original project duration had to be extended due to organizational reasons and to account for lockdowns due to the COvid-19 pandemic in 2020 which delayed lab and field work.

Due to unexpected events and the staff situation at Nouryon as result of the Covid-19 pandemic situation in summer 2020, more subcontracting was needed to perform the well inspections. This in particular concerned the well inspection planning, preparation work on the well and the measurements themselves. Conclusively all technical activities could be performed as initially proposed and the objectives were met.

All changes were made in agreement with the partners and TKI Nieuw Gas. The overall project budget or scope was not affected. Two deliverable reports have been submitted on time at the agreed dates that outline the approaches and results in detail.

2.4 Results and conclusions

2.4.1 Chemical stimulation feasibility

The proposed concept is loading of the wellbore with saturated brine through a coil (Figure 1), followed by the addition of an anti-solvent as a precipitating agent for salt. This way a salt cake layer can be deposited. These steps can be repeated again to deposit the salt cake layer by layer while lifting the coil stepwise to create a plug.

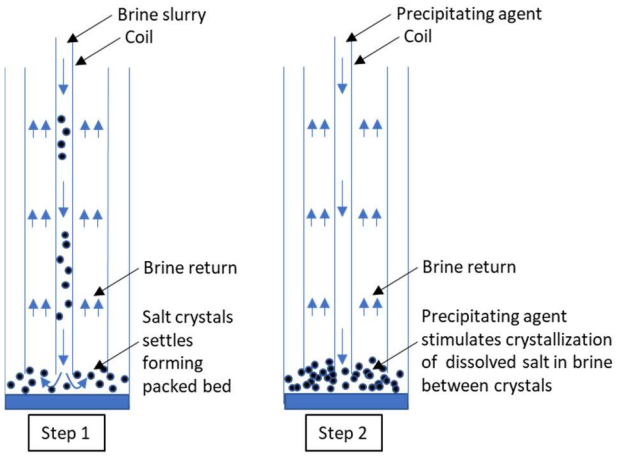

Figure 1 Conceptual sketch formation of salt plug by brine slurry feeding and addition of precipitating agent

The lab testing revealed that sodium chloride and potassium chloride and mixtures of these two salts form reasonably hard cakes under laboratory conditions (atmospheric pressure, 60°C and allowing evaporation). The addition of dry silica aids the formation of cakes to a limited extent. Calcium chloride dissolves exothermally and forms chunky pieces of cake. It should be noted that the formed plugs can also be dissolved again (and with that lose the function of plug formation) upon exposure to water.

Under downhole target conditions, i.e. super-ambient pressure, temperatures from 60°C upwards and hence limited possibilities for evaporation, the formation of the same plugs may be more challenging.

The concept of using an anti-solvent to induce the formation of cakes did not result in the formation of cakes under laboratory conditions. Under wellbore conditions the cake formation process is also considered to be challenging.

The gypsum reaction of calcium chloride and sodium sulphate resulted in rock hard cakes. The reaction temperature of the gypsum formation process is crucial, considering the wellbore conditions. Under laboratory conditions at temperatures above 60°C no cakes were seen to form, unless the molar ratio of sodium sulphate to calcium chloride exceeded a certain threshold.

Initial permeation experiments resulted in mixed results. With the salt plugs no representative permeation experiment could be executed due to cracking of the sanded salt cakes. This may be resolved by better distributing the force upon

closing of permeation vessel over a larger circumferential surface area. With the sanded gypsum cakes it was found that the cores of the samples were still wet and hence the samples gave way at a pressure of roughly 10 bar which is remarkable for a few cm plug. Enhanced drying of the samples could even enhance the sealing capacity, aside from increasing the thickness of the plugs.

The formed salt plugs were found to adhere well to slate and steel, and weakly to cement. The gypsum plugs were found not to adhere well to steel, but well to slate and cement. Generically, the gypsum cakes were seen to more strongly adhere to the wellbore materials than the salt cakes.

2.4.2 Investigation of the creep behaviour and porosity-permeability evolution in Zechstein rocksalt during borehole closure

We performed room temperature, unconfined and triaxially confined compression experiments to investigate the effect of fluid on the mechanical behaviour and permeability evolution of (damaged) rocksalt. The experiments were performed on Leine Steinsalz samples, obtained from the Zechstein 3 formation.

1. The dry stress-relaxation stage of the dilated rocksalt is characterized by dislocation creep where the strain rate is strongly dependent on the applied stress (i.e. high stress dependency). This behaviour can be described using a conventional power law creep equation with stress exponents (*n*-values) in the range of 35-40 at the start of the experiment, which decreases to ~15 towards the end of the stress relaxation stage, suggesting dislocation glide is the dominant deformation mechanism operating during dry deformation.
2. Upon injection of saturated brine, there is a rapid acceleration in creep rate, accompanied by a decrease in flow strength, as observed during the wet stress relaxation stage. As the sample relaxes, the stress exponent *n* decreased from ~15-18 to ~2-4, meaning the strain rate became less sensitive to the imposed differential stress. The effect of saturated brine on the mechanical behaviour of damaged rocksalt is likely related to a combination of microcracking reducing the average grain size, further enhanced by subcritical crack growth in the presence of fluid, and fluid-assisted dynamic recrystallization leading to contact stress enhancement and an increased contribution of grain size sensitive processes like pressure solution.
3. Long-term permeability measurements showed that damaged rocksalt, with an initial gas permeability of $1.4 \cdot 10^{-17}$ m^2, placed under confinement (8-11 MPa effective confining pressure) and saturated with brine, gradually became less permeable with time. After 75 days under confinement, brine permeability had decreased to $3.4 \cdot 10^{-20}$ ($\pm$ $2.5 \cdot 10^{-20}$) m^2. This could have been a result of slow, time-dependent creep of the sample and/or slow, diffusive mass transfer processes leading to crack healing and/or dynamic recrystallisation.
4. Based on our long-term brine permeability measurements, natural permeabilities of 10^{-21} m^2 or lower could be reached in six months to two years at the experimental conditions used in this study (11 MPa effective confining pressure, 2 MPa brine fluid pressure, room temperature). At elevated pressure and temperature conditions, relevant for realistic in-situ conditions at > 1-1.5 km depth, this permeability could be achieved quicker.

However, this needs to supported by additional experimental work and a microphysical model.

5. Strain rate equations describing the effect of fluids should include the effect of contact stress enhancement caused by dilation and the impact of grain size reduction on pressure solution. This can be done through a combined strain rate equation of the form $\dot{\varepsilon} = A\left(\frac{1}{1-\varphi}\sigma\right)^m + B\left(\frac{1}{1-\varphi}\sigma\right)d^{*-p}$, where d^* is the reduced grain size, φ is the dilated porosity, A and B are temperature-dependent constants, and m and p are processes-dependent stress exponents. More research is needed to come up with these physics-based strain rate equations.
6. To be able to accurately predict the permeability evolution and time until sealing of damage zones in converging wellbores, whether open hole or plugged with granular salt or a salt plug, strain rate equations, able to predict the evolution of sample porosity, need to be combined with percolation theory-based models for damaged rocksalt.

2.4.3 Accelerated natural sealing of abandoned wells by local heating of well system and salt creep through perforated casing & cement

In this study, the option to plug wells using natural sealing of accelerated salt creep through well perforations has been investigated (Figure 2). Focus was on the analysis of processes, factors and conditions leading to the formation of a permanent, impermeable and continuous seal that connects salt formation to well plug at timescales relevant for well decommissioning. Rocksalt-bearing evaporite formations are present over large parts of the northern onshore and offshore in the Netherlands, acting as caprock for many oil and gas reservoirs. For these areas, natural sealing of wells by salt creep may be an attractive option as it has the potential to be both technically advantageous and cost effective.

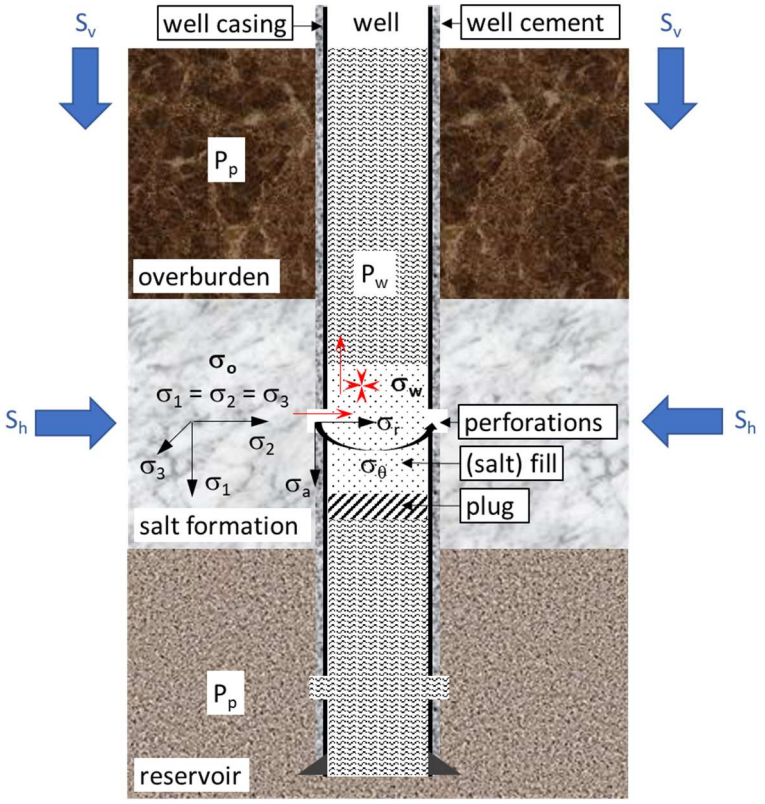

Figure 2. Schematic diagram illustrating the concept of natural sealing by stimulated salt creep for plugging of wells (NSSSCPW). A well section is perforated at the depth of a salt formation. Difference in stress states outside (σ_o) and inside (σ_w) the well drives salt creep through perforations and compaction of the salt fill. Natural sealing is successful if a permanent, impermeable and continuous seal has formed that connects salt formation to well plug. If salt is not fractured or subject to dilatant deformation, permeability in the salt barrier is expected to be very low (typically ~10^{-20} m^2 or 10 nD)

This study provides a first evaluation of well plugging based on accelerated natural sealing by stimulated salt creep. It consists of (1) an analysis of processes and mechanisms controlling natural sealing by stimulated salt creep, (2) insights from experimental, modelling and field studies on salt creep processes, flow properties and proof of concept in case studies, and (3) development of an experimental setup consisting of scaled down well system that can allows salt creep, convergence and in/along well permeability to be quantified at in situ pressure, stress and temperature conditions.

The analysis of rocksalt properties suggests that a permanent, impermeable and continuous seal may be formed that connects salt formation to well plug at timescales relevant for well decommissioning. However, it has to be demonstrated that natural sealing and stimulated salt creep lead to a sealing barrier under configurations and conditions relevant to real wells. The experimental setup of a scaled down well system allows proof of concept to be demonstrated and optimum conditions for sealing barrier formation to be assessed.

The experimental setup has been tested but need some modifications to be used for evaluation of formation and properties of self-sealing continuous sealing barrier consisting of rocksalt. Future work will focus on modifying the setup so it can be used to evaluate properties of the sealing barrier at different conditions relevant for

conditions in real wells. The setup will be used to derive data on salt creep, convergence and in/along well permeability at in situ pressure, stress and temperature conditions.

2.4.4 Results of workover on Hengelo Z-1 well

Hengelo-1 (HEN-01) is a relatively deep salt well which is no longer producing. Production was ceased in the year 2000 and the well was temporarily shut-in. The well is going to be used for an investigation into the behaviour of the Zechstein salt regarding creep closure in drilled wells. Before this investigation can start two workovers need to take place.

The first workover is rig-less and the objective was to run various e-line tools to ensure access to the top of the cavern, to verify the condition of the 9 5/8 inch casing and 7 inch liner for damage, metal loss, deformation and to evaluate the cement bond behind the liner and casing. To inspect any damage of the casing, liner and possible obstructions a camera run was planned to aid the interpretation of the data. The camera run would determine the accessibility of the 7 inch liner for any wireline tools and to verify the liner centralisation in the 9 5/8 inch casing.

The study provided findings and conclusions from the first workover and provided recommendations for the second workover on HEN-01 which will take place in 2021 (detailed information is classified). The workover activities included:

- Wellhead pressure observation
- Downhole camera run using an EV CAM deployed on SOCON's wireline truck
- Casing and cement bond inspection using Archer's SPACE Vernier tool and the Radial Bond Tool (RBT) deployed on SOCON's wireline truck

Overall no showstopper could be identified to use the well for a downhole rocksalt creep test in a follow-up project.

2.5 Contribution to the TKI Nieuw Gas, program line Geo Energy Roadmap objectives, the TKI subsidy regulation and knowledge development

The project contributes in providing technology to use the natural sealing capacity to seal and abandon wellbores, which is an essential part of the TKI Nieuw Gas program line on Geo Energy and relevant for both, hydrocarbon and sustainable geoenergy operations such as geothermal or gas storage. It tackles a specific technological hurdle for the development of this application. Many evaporites, even when ductile and principally suited for natural formation sealing might "move" too slow for the application within P&A operations particularly in more shallow locations above 2000 m depth. Therefore, stimulation methods present a promising option to enable the application of natural formation sealing. The project helps to achieve specific objectives of the program line's research theme Decommissioning and Abandonment, which are in particular:

- Minimize negative effects of small-scale gas extraction on the environment and economics
- Re-use of existing infrastructure and integration with other energy activities in the North Sea.
- Development of sustainable and cost-efficient methods and techniques relating to integrity and state monitoring (pipelines,

wells, installations); closure of wells, platforms and finding useful use (decommissioning);
- Safety, reliability and integrity (offshore installations and pipelines).

Rocksalt and represent a high percentage (> 50%) of caprocks of small gas fields on- and offshore in NL, so the relevance and potential of the project is high. Natural sealing of abandoned wells is cheaper requiring substantial less energy and is in principle much more sustainable than engineered solutions and will reduce both the cost of decommissioning and associated CO_2 emissions[4,5]. Leakage of methane has a large greenhouse effect (>20x CO_2 effect) and CH_4 emissions from abandoned boreholes have been proven to present a significant but underestimated source of greenhouse gas emissions[6]. Effective borehole sealing significantly contributes to reducing greenhouse gas emissions and protecting the environment. This also applies to leakage of other gases and drilling fluids, such as H_2S, CO_2 or brine, for example.

Restoring the initial sealing caprock and the use of natural plugging materials like salt and clay provides a unique combination of benefits: the ecological footprint of the industry is minimized while at the same time increasing long-term safety is provided by using proven natural durable materials and this at lower costs. As such the project findings contribute to the roadmap of the TKI Nieuw Gas program line on Geo Energy and to the overall objectives of the subsidy regulation of the
the These are key objectives of the of the TKI subsidy regulation and major goals of the applicable subsidy regulation of the Dutch Ministry of Economic Affairs and Climate.

The innovative approach developed in this project, and in other recently finished and running research for the program line's research theme Decommissioning and Abandonment, will provide a unique competitive advantage of lower abandonment costs for national operators and service companies, and diminish the chance of unforeseen and costly future intervention operations including potential negative impact on the environment due to leakage.

2.6 Follow-up activities, spin-offs and exploitation

Based on the results of this project and related work in the program line on natural sealing for wellbores, the following spin-offs could be initiated to tackle remaining challenges and research questions with respect to the feasibility to use bentonites as wellbore seals. Both follow-up projects aim at demonstration of the sealing technology at large- and full-scale tests including using a rig and test well at the Rijswijk Centre for Sustainable Geoenergy (RCSG):

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[4] Fischer, H., Orlic, B., Geel, K., Pipilikaki, P., Wollenweber, J., 2016a. The phenomena of the ductile properties of shales and salts. "TKI Plugging wells by enhanced formation ductility – Deliverable report D3.1"; TNO report 2015 R11749

[5] Fischer, H., Orlic, B., Osinga, S., Hopmans, P., Wollenweber, J., Geel, K., 2016b. Options to initiate and enhance ductile properties of shale for well bore sealing. "TKI Plugging wells by enhanced formation ductility" - Deliverable report D5.1; TNO report 2016 R10970

[6] Kang et al. (2014). Direct measurements of methane emissions from abandoned oil and gas wells in Pennsylvania (doi:10.1073/pnas.1408315111)

Natural seals research and test well (with subsidy reference TKI2019-02-GE)
Natural Sealing Large-scale evaluation (with subsidy reference TKI2020-05-GE)

In the TKI DECOM 2020 project the actual downhole creep test in Nouryon's test well is envisaged.

The good progress in developing this alternative sealing technology led to an extension of the consortium of the program line Geo Energy's research them Decommissioning and Abandonment with Wintershall joining this theme.

As the project rather aimed at technology and patent development the work has not yet been published in journals, conferences or communicated to the press.

For further information on this project please contact the secretary of TNO's Applied Geoscience Group at secretariaat-aarde@tno.nl.

""Het project is uitgevoerd met subsidie van het Ministerie van Economische Zaken, Nationale regelingen EZ-subsidies, Topsector Energie uitgevoerd door Rijksdienst voor Ondernemend Nederland."