PETROLEUMSTILSYNET

Report	
Report title Investigation of fractured coiled tubing on Gullfaks C	Activity number 001050090

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☑ Public	☐ Restricted	☐ Strictly confidential
☐ Not publicly available	☐ Confidential	

Involved	
Team T1	Approved by/date Kjell M Auflem/12 October 2023
[redacted]	[redacted]

Image 1 - Gullfaks C (source: Equinor).

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1 Summary

A well-control incident which involved the fracturing of coiled tubing (CT) – classified as a DSHA 3 – occurred during a well intervention activity on 25 January 2023 on Equinor's Gullfaks C facility. The Petroleum Safety Authority Norway (PSA) decided on 1 February 2023 to investigate the incident.

A well clean-up was being conducted using CT at the time of the incident, following an unsuccessful fracturing operation which left the whole wellbore filled with gel containing proppants. While circulating through the CT, the latter fractured at the surface. Further fractures occurred at the reel and injector head during the following hours. When the CT in the well fractured, the blind shear ram in the CT BOP was activated to shut in the well and restore the primary barrier.

Had the string parted with personnel close to the CT reel, energy in the form of released bending moment could have led to them being struck and injured.

The direct cause of the incident was sulphide stress cracking (SSC) induced by H_2S, which most probably resulted from a chemical reaction between oxygen scavenger, citric acid and iron from the inner surface of the CT. The material quality selected for the CT was vulnerable to H_2S exposure. Combined with mechanical stresses, this gave rise to the incident.

Oxygen scavenger, which was added directly to the fluid flow with the citric acid solution, can form toxic gases and has limited effect when mixed with acidic solutions.

The combination and sequence of additives were most probably decisive for the incident. Changes related to responsibility for planning and execution and inadequate communication of risk probably contributed to its occurrence.

Two nonconformities and two improvement points have been identified.

2 The PSA investigation

2.1 The PSA's investigation team

The PSA's investigation team comprised the following participants.

[redacted]	F-Drilling and well technology (investigation leader)
	F-Drilling and well technology
	F-Drilling and well technology
	F-Occupational health and safety

[redacted] F-Structural integrity
F-Structural integrity

2.2 Mandate

The following mandate was adopted for the investigation team.

a. *Clarify the incident's scope and course of events (with the aid of a systematic review which typically describes the time line and events)*
b. *Assess the actual and potential consequences*
   1. *harm caused to people, material assets and the environment*
   2. *potential harm to people, material assets and the environment*
c. *Assess direct and underlying causes*
d. *Identify nonconformities and improvement points related to the regulations (and internal requirements)*
e. *Discuss and describe possible uncertainties/unclear aspects*
f. *Discuss barriers which have functioned (in other words, those which have helped to prevent a hazard from developing into an accident, or which have reduced the consequences of an accident)*
g. *Assess the player's own investigation report*
h. *Prepare a report and a covering letter (possibly with proposals for the use of reactions) in accordance with the template*
i. *Recommend – and normally contribute to – further follow-up*

And, in addition:

1. assess possible deficiencies related to management preconditions for technical and operational integrity during the operation
2. assess why the decision basis appears to have been inadequate when the choice of CT for this activity was made
3. assess the roles of the planning and operation centres in preparing and following up the activity
4. assess conditions across other relevant incidents in Equinor (and at other companies) with similar identified causal factors (such as the incident on Martin Linge with a similar set of causes).

The incident occurred on 25 January 2023 and was normalised on 3 February 2023.

The PSA investigation team travelled out to Gullfaks C on Tuesday 14 February 2023, returning to land on Thursday 16 February 2023. Equinor's investigation group was offshore during the same period.

Inspections by the team took place in areas relevant to the incident and seven interviews were conducted on the facility. Up to the end of May, a further 21 interviews took place with personnel at Equinor's premises in Bergen, the PSA's offices in Stavanger and via Teams. People from all the companies involved were interviewed.

The investigation team has chosen to utilise the Step methodology to systematise the course of events and underlying causes. This choice was dictated by a complex player picture with many interfaces.

3 Abbreviations

Abbreviation	Description
BH	Baker Hughes
BHA	Bottom hole assembly
B282	Chemical for reducing hydraulic friction
CT	Coiled tubing
CT BOP	Blowout preventer for CT operations, comprising blind shear, pipe and slip rams
DFIT	Dynamic formation integrity test
DOP	Detailed operating procedure
Gooseneck	Transition piece which converts the CT from vertical above the injector head to (almost) horizontal before spooling on the reel
H^+	Hydrogen ion
H_2	Hydrogen gas
H_2S	Hydrogen sulphide
HE	Hydrogen embrittlement
Headspace	Air pocket over the fluid in a sample bottle
HIC	Hydrogen-induced cracking
HRC	Hardness Rockwell C
HSLA	High strength, low alloy steel
KSI	Kilopound per square inch
M296	Chemical for reducing friction between metals
MEG	Monoethylene glycol
MPa	Megapascal
NOV	National Oil Varco – supplier of the CT BOP
pH	Unit of acidity in fluids (scale: 0-14)
POOH	Pull out of hole
ppm	Parts per million
Pressure-out	In fracturing operations, where pressure rises to the maximum operational level before all proppants are forced into the formation
Proppants	Fracturing sand
PSA	Petroleum Safety Authority Norway
SLB	Oil service company
SCC	Stress corrosion cracking

SSC	Sulphide stress cracking
Swab valve	Topmost valve on an Xmas tree
Wiper trip	Simultaneously pulling out and circulating in a well to clean out loose materials and/or check downhole status
XT	Xmas tree – assembly of valves on the well

4 Background information

While well C-21 (Nøkken) was being cleaned up after fracturing, a well-control incident occurred on Equinor's Gullfaks C facility on 25 January 2023.

A fracture in the CT was observed at 06.56 during the hand-over between night and day shifts. The check valves in the BHA held firm against the well and the primary barrier loop was intact. During the hours which followed, six different fractures were observed in the CT on the surface.

Wellhead pressure fell at 15.40, at the same time as fluid from the CT flowed out over the reel. This was assessed as a fracture in the CT above the check valves in the BHA. The crew closed the slip and pipe rams at 15.42. A further fracture occurred at the gooseneck at 15.44. The well was secured at 15.52 by activating the CT BOP blind shear ram, which forms part of the primary barrier system.

Other well operations were halted and the area cordoned off.

Image 2 - CT with fractures (source: Equinor).

4.1 Description of the facility and organisation

Well C-21 was planned as a gas and condensate producer drilled from Gullfaks C to the Nøkken deposit, which lies east of Gullfaks at a horizontal distance of 6 500 metres from the facility.

The 34/11-2 S discovery well was drilled in 1996 and lies in production licence 193 GS. Located in nearby PL 050, Gullfaks has been developed with three integrated production, drilling and quarters platforms (A, B and C) as well as various subsea installations.

Gullfaks produces oil from Middle Jurassic sands in the Brent Group, Lower Jurassic and Upper Triassic sands in the Statfjord Group, and the Cook and Lunde formation. Nøkken and C-21 produce from both upper and lower parts of Brent. No communication has been proven between Nøkken and other Gullfaks wells.

The well was completed with a 4 ½-inch liner through the reservoir and 4 ½- x 5 ½-inch production tubing.

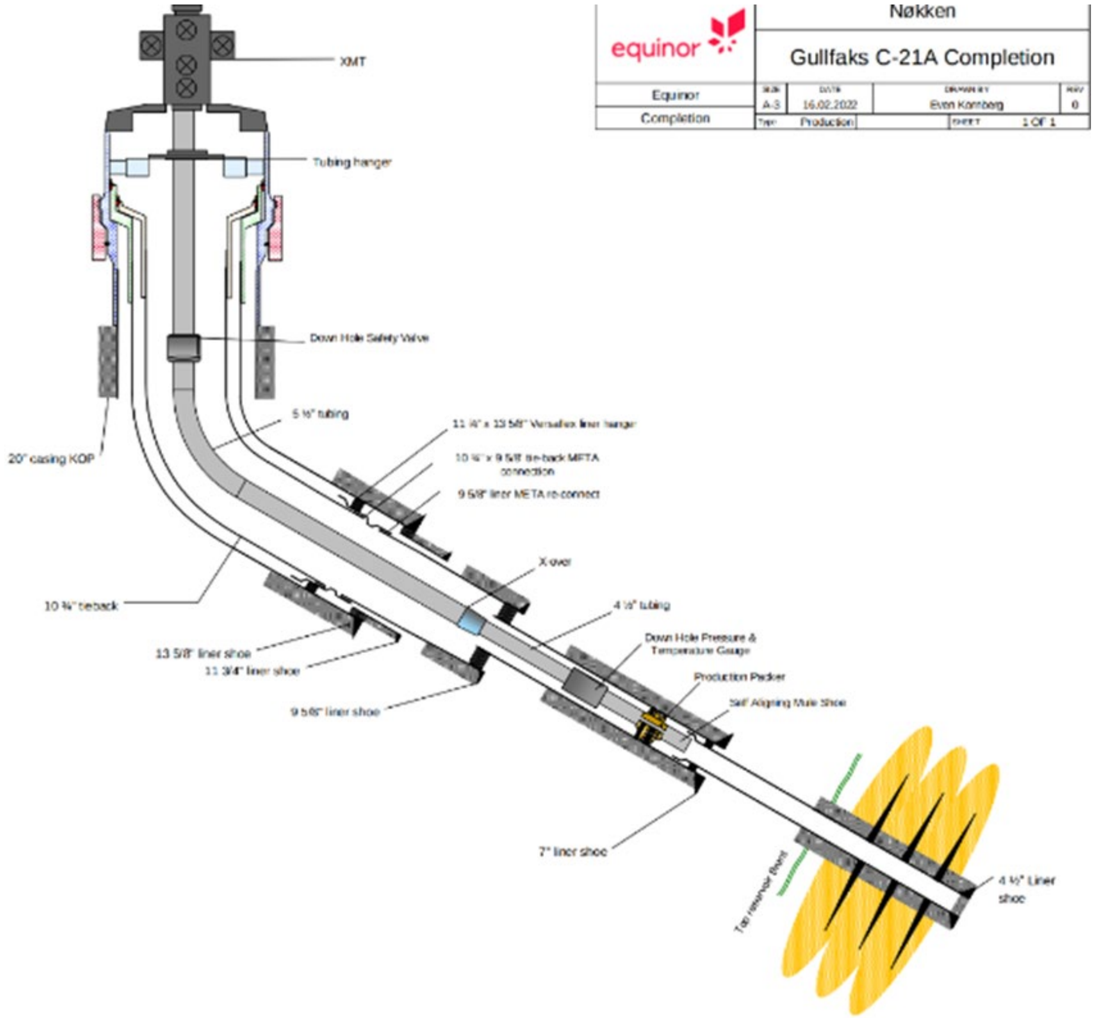


Figure 1 - Well diagram for C-21 A (Nøkken).

Equinor is operator of PL 193 GS Nøkken with a 70 per cent holding and with Petoro as partner holding 30 per cent.

Baker Hughes (BH) had the contract to provide stimulation services to Equinor for this work. The company pulled out of stimulation services in Norway during 2022 and Stimwell was chosen as the new provider. In addition to Equinor, several contractors were involved with the well stimulation activity on Nøkken. Stimwell had a vessel with tank and pump capacity, and supplied proppants in gel via hoses running from ship to platform.

SLB CT provided CT services related both to perforation work and well clean-up after stimulation, SLB Testing provided surface equipment for separating surplus proppants from clean-up fluids, and SLB Pumping was responsible for delivering chemicals pumped into the well as well as the required pumps. Resources from Archer, the drilling contractor on Gullfaks, were also utilised since the rig's tanks and pumps were utilised by the intervention group.

4.2 Description of CT rig-up

The CT equipment was rigged up on the pipe deck, skid beams and hatch deck. Well control equipment with BOPs and lubricators was positioned vertically up from the well. An access bridge was installed across the skid beams with an access tower for the CT injector head and deployment of tool strings in the well. The CT reel, control cabin, fluid pumps and power supply were placed on the pipe deck, with the return system – comprising choke manifold, sand cyclones and return lines – on the hatch deck. Completion tank 28 was used to deliver fluid for pumping through the CT. This largely comprised untreated seawater from the water injection facility on Gullfaks C.

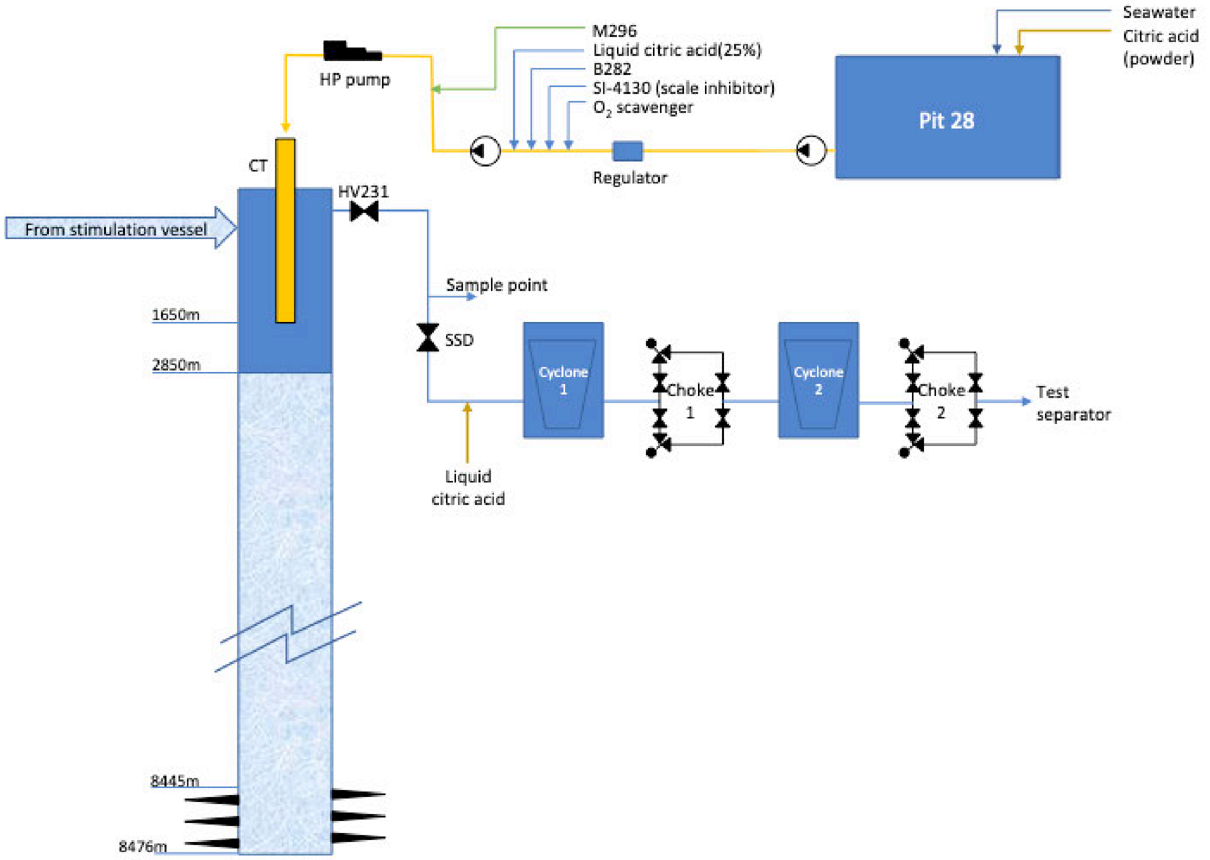


Figure 2 - Simplified circulation diagram for cleaning out proppants.

4.3 CT operations

CT is a continuous tube coiled on a reel. It is run down and pulled out using an injector head installed vertically above the well. BOPs and sealing against air are arranged in such a way that CT can be used on live wells. This system is well suited for cleaning out wells because circulation can continue uninterruptedly while operating downhole, which prevents particles in motion precipitating from the fluid flow.

HSLA steel is used to manufacture CT. The Gullfaks C-21A operation utilised a CT with an external diameter of 2 3/8-inches and a yield strength of 130 000 psi. The tube wall had a tapered design, with thickness increasing from 0.145 inches (lower end) to 0.204 inches (upper end). An 0.125-inch Inconel tube housing power and fibreoptics ran the whole length of the CT for passing energy and signals to equipment in the BHA.

During operation, two opposed chains of crescent-shaped friction blocks are pressed by the injector head against the CT to move it from the reel and down the well. This subjects the CT to bending moments when it is uncoiled from the reel, when it is bent over the gooseneck and when it is straightened between the injector-head chains. This process is reversed when pulling the CT from the well. Image 3 illustrates how the CT was rigged up on Gullfaks C. The CT undergoes plastic deformation in each bending and straightening sequence, and the fatigue stress gradually increases. Down the well, the CT is exposed to compression and tensile stresses. HSLA steel is particularly vulnerable to corrosion in an acidic environment. See section 4.7.

Image 3 - CT rig-up.

4.4 Fracturing

To increase its output, well 34/10-C-21A was to be stimulated by the use of hydraulic fracturing. This operation involves pumping viscous fluid with added proppants down the well at a high pump rate. When the injection force exceeds stresses in the reservoir rock, cracks are opened in the latter and filled with injected fluid and proppants. The pressure is then reduced, and the proppants keep the cracks open so that flow from reservoir to well improves.

Any proppants not forced into the formation must be cleaned out before the well can be brought back on stream. Excess proppants can be washed out using CT.

4.5 Chemicals

Various chemicals are utilised, depending on the requirements and properties/ challenges involved in the relevant fracturing operation. Table 1 presents the various substances which might be used and their function.

Table 1: Overview of chemicals used in fracturing operations.

Chemical	Purpose
Proppant	Spherical particles driven into cracks in the reservoir rock to increase drainage to the well
Gel	Carrier fluid for proppants
Biocide	Added in various phases to eliminate bacterial growth which can contribute to H_2S development and scale
Scale inhibitor	Added to avoid scale build-up in the well
Corrosion inhibitor	Added to protect CT, for example, from corrosion
Oxygen scavenger	Used to remove oxygen from seawater, for example, to avoid oxidation of CT, etc
H_2S scavenger	Added prophylactically or with H_2S challenges in the well. Reacts with and reduces/eliminates H_2S
Friction reducer	Added to reduce pressure challenges and friction between CT and casing and/or CT and fluids
Acid (citric acid)	Used to break down carrier fluid/gel when cleaning up the well after fracturing
MEG (monoethylene glycol)	Added to avoid hydrate formation/ice plugs

4.6 Information on H_2S

H_2S is a highly toxic, colourless and flammable gas which is somewhat heavier than air. At low concentrations, it smells strongly of rotten eggs. It is not only very toxic but also extremely corrosive. In the petroleum industry, its development is usually related to sulphate-reducing bacteria which anaerobically break down organic materials containing sulphur to produce H_2S. The potential to develop H_2S relates to tanks and volumes of organic materials lying static in water without access to oxygen, which can also arise in reservoirs. In nature, therefore, H_2S may develop in marshes and swamps and is known then as marsh, swamp or bog gas.

H_2S can also develop as a result of chemical reactions.

4.6.1 Health hazard

The threshold for smelling H_2S is very low, and far below the levels where symptoms of health effects resulting from exposure are registered. At low levels, the smell is unpleasantly reminiscent of rotten eggs. This changes somewhat at higher levels. At

H_2S levels of 100 parts per million (ppm), the sense of smell will cease to function. Above that concentration, breathing H_2S will be acutely toxic. Experience from exposure incidents and reports has contributed to knowledge of the symptoms and health hazards associated with exposure to various concentrations of the gas in the air. These are presented in table 2 below.

Table 2: Overview of symptoms and health hazards from exposure to various concentrations of H_2S.

Concentration (ppm)	Symptoms/health effects
0.00011-0.00033	Background levels
0.01-1.5	Smell threshold (when most people can detect the rotten-egg smell). This becomes more unpleasant at three-five ppm. Over 30 ppm, it is described as sweet or sickly sweet.
2-5	Long-term exposure can cause nausea, watery eyes, headache, sleep problems, and respiratory problems for individual asthmatics.
20	Listlessness, appetite loss, headache, irritability, memory loss and dizziness.
50-100	Visual impairment and respiratory irritation after an hour. Can cause digestive problems and appetite loss.
100	Coughing, eye irritation, loss of smell after two to 25 minutes. Changes to breathing frequency, listlessness after 15-30 minutes, throat irritation after an hour. Symptoms increase in seriousness within a few hours. Death can occur after 48 hours.
100-150	Sense of smell lost.
200-300	Serious eye and respiratory irritation after one hour. Lung oedema can occur with lengthy exposure.
500-700	Dizziness, collapse within five minutes. Serious eye damage within 30 minutes. Death after 30-60 minutes.
700-1 000	Swift loss of consciousness. Rapid, "knockdown" within one-two breaths, respiratory failure within minutes, death in a few minutes.
1 000-2 000	Acute threat of death.

Electrochemical sensors are often used to monitor airborne H_2S levels. They are small, light and easy to carry by potentially exposed personnel. Such units are equipped with an alarm function which provides both audible and visual warnings when levels exceed a specified threshold value. They are limited to detecting concentrations up to

200-500 ppm, and other kinds of equipment must be used to monitor higher levels. Colorimetric methods, such as a Dräger tube where an exposed medium gives a colour response related to the level present, can measure concentrations in the air of up to 40 per cent H_2S.

Regulations on action and threshold values from the Norwegian Labour Inspection Authority set exposure limits for H_2S on the basis of an eight-hour working day. Section 36 of the activities regulations specifies that these values must be corrected by a safety factor of 0.6 for a working period of 12 hours. Table 3 presents an overview of threshold values for H_2S.

Table 3: Overview of threshold values for H_2S

	8-hour shift	**12-hour shift**
Threshold value	5 ppm	3 ppm
Ceiling value*	10 ppm	10 ppm

* The ceiling value is the maximum airborne concentration of a chemical agent which a worker may be exposed to at any given time.

4.7 Hydrogen-assisted fracture

Hydrogen embrittlement (HE) is a characteristic change in the mechanical properties of certain metals, particularly steel, in the internal presence of free atomic hydrogen. HE occurs at low hydrogen concentrations. Small quantities may be present after production of the material, added during fabrication (from welding, for example) or introduced by other exposure to hydrogen while the material is in use.

Atomised hydrogen can occur, for example, through corrosion processes, splitting of water, or the presence of H_2S. Hydrogen reduction depends on an adequate supply of hydrogen ions (H^+). In solutions with low pH values (lower than 3.5), the H^+ concentration is basically high and the reaction can occur spontaneously.

H_2S which comes into contact with metals forms metal sulphide and hydrogen gas (H_2). The sulphide ions can disrupt the recombination of hydrogen atoms into H_2 gas, thereby promoting the diffusion of atomised hydrogen into the material and leading to HE. This can result in hydrogen-induced cracking (HIC) or cracks caused by sulphide stress cracking (SSC) or stress corrosion cracking (SCC).

SSC is considered to be a corrosion-driven form of HE, and three factors must occur simultaneously for it to arise. These are often illustrated as in figure 3.

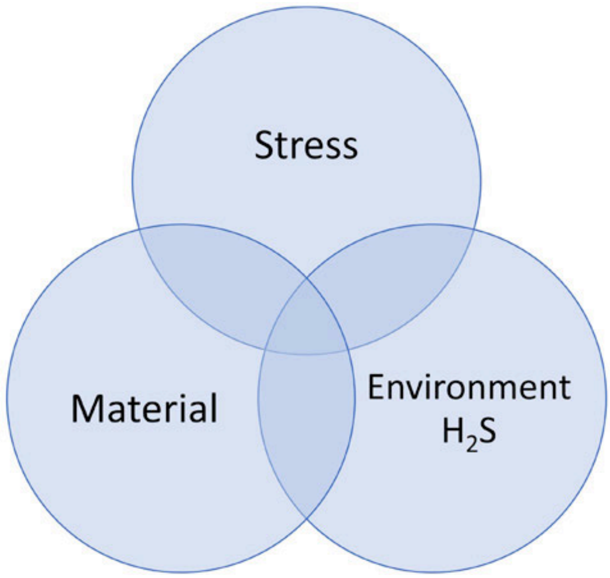


Figure 3: Preconditions for SSC.

HSLA steel is often used in CT operations. Such materials not infrequently have a minimum yield strength of 130 ksi (896 MPa) with a hardness above 36 HRC.

The CT is subjected to high loads in well operations, stresses are present, and the material may be bent beyond its yield strength so that it experiences permanent deformation with a consequent threat of fatigue.

Enhanced mechanical properties help to make this type of material vulnerable to hydrogen-induced cracking and SSC. According to ISO 15156, a recognised standard on material selection for H_2S environments in oil and gas production, hardness plays an important role in determining the sensitivity of the material to SSC. The standard specifies a maximum hardness of 22 HRC when using HSLA steel where H_2S might be encountered. In addition to the partial pressure of H_2S, several factors influence SSC aggressiveness in the environment – including pH and temperature. For details, see figure 1 in ISO 15156-2 and other sources.

4.8 Similar incidents

An incident occurred on Martin Linge on 25 January 2017 involving leakage from a CT string during extraction from well A09. The string later developed fractures at several points which resemble those observed in the Gullfaks C incident. Both strings had similar material properties (QT1300 and Duracoil 130 respectively), with a strength of 896 MPa (130 ksi). Furthermore, acid was injected through the CT in both operations. Laboratory analysis concluded that the leak was a result of HE. The source of the hydrogen could have been external H_2S and/or a microwash containing acetic acid.

Total was the operator and BH the contractor during the incident. Statoil/Equinor was a partner in Martin Linge. An investigation of the incident was initiated by Total on 7 April 2017, 2.5 months after the incident. Lessons learned by the industry from what happened have been limited, with the report not made public and no formal forum for learning about intervention incidents.

5 Course of events

5.1 Position before the incident

The lowest interval of the 4 ½-inch liner was perforated with perforating guns on 2 January 2023. This was followed by a mini-fracturing with subsequent pressure-out on 5 January 2023. During fracturing, proppants in gel were pumped from tanks on Stimwell's *Island Patriot* vessel directly down the production string in the well. Cleaning out after the mini-fracturing began on 7 January 2023 using CT. This work was conducted with seawater, oxygen scavenger and friction reducers (B282 and M296). Citric acid was added on the return side during this clean-up to break down polymers in the gel before further treatment in cyclones.

A further mini-fracturing was conducted on 17 January 2023. This went as planned and required no subsequent clean-up. The main fracturing operation began on 20 January 2023. Problems again arose relating to excessive pump pressure as a result of friction, and a pressure-out occurred almost as soon as work had begun to flush out proppants with clear fluid. The well became completely filled with gel containing proppants because pumping could no longer continue.

The subsequent clean-out began on 21 January 2023 through CT, using seawater, 0.2 per cent citric acid and oxygen scavenger. The citric acid concentration was later increased to 0.4 per cent. See figure 2. The B282 chemical was used to reduce fluid friction.

Clean-up work was interrupted on 24 January 2023 when the CT had to be pulled from the well for routine BOP testing. Washing had then reached a depth of 1 900 metres. The clean-up continued after the test and had reached 2 850 metres on 25 January 2023. To ensure good cleaning within the pressure limitations for well and equipment, a wiper trip was conducted from 2 850 metres back to 1 650 metres. The first hole in the CT was discovered during pumping (bottom-up) at the latter depth.

5.2 Position during the incident

An unused CT manufactured in Duracoil 130 was used for the downhole work. The string was designed for this operation in order to have sufficient strength and pump capacity available.

The desired volume of gel and proppants was not squeezed out into the formation during the fracturing operation, which meant the well became filled with this mixture. Equinor revised the procedure for washing out proppants on 21 January 2023, and a detailed operating procedure (DOP) was established with participation by all the players for washing out proppants in two steps:

- to 1 000 metres in order to re-establish the well barriers
- along the whole well length.

This operation was originally planned to wash out small quantities of proppants and gel. When the well then filled with proppants, insufficient citric acid was available for the volume needing to be cleaned out. The DOP drawn up on 21 January 2023 specified that 0.2 per cent citric acid should be injected continuously through the CT. Since not enough of it was available, it was decided to utilise citric acid in dry form which would be blended using the mixing and completion tanks in the Gullfaks C drilling facility. Oxygen scavenger chemicals and a hydraulic friction reducer (B282) were added to the mix downstream between the tank and the high-pressure pump. See figure 2. A mechanical friction reducer (M296) was left out because it had been identified as a potential source of separation problems in the cyclone on the return side.

After washing down to 2 850 metres, the CT was pulled back to 1 650 metres as part of effective well cleaning. While stationary at this depth and circulating, it experienced fracturing on the reel located on the pipe deck.

5.3 Immediately after the incident

Closing the slip and pipe rams on the CT BOP secured the well. The integrity of the CT remaining in the well was verified by testing the check valves in the BHA. Several more tubing fractures occurred on the reel and the gooseneck. After a few hours, a fall in well pressure and an outflow from the CT from fractures on the reel were observed. This was interpreted as a failure of either the check valves in the CT BHA or of the CT downhole. The CT BOP shear ram was then activated, cutting the CT and restoring the primary barrier in the well.

Measurements of H_2S were conducted during this period. See section 6.1.

Level 3 H_2S emergency response for H_2S was established from 28 January 2023. Maersk was mobilised and conducted regular measurements of fluids and the air.

The integrity of the CT which hung from the CT slip ram in the well was regularly checked by cautiously attempting to close a manual gate valve in the riser. On 1 February 2023, confirmation was obtained that the CT had separated and fallen down the well. The latter was then shut down in accordance with the regulations, using swab, manual and hydraulic master valves and the downhole safety valve.

5.4 Timeline

Date	Time	Activity	Depth [m]
05.12.2022		CT rigging up	0
21.12.2022		Run #1 – operating run (venturi)	8 476
31.12.2022		Run #2 – perforation	
01.01.2023	16.23	Perforation 1	8 450
01.01.2023	16.47	Perforation 2	8 442
01.01.2023	21.41	DFIT (pumped through CT to fracture the formation)	8 412
02.1.2023	03.16	POOH, incl Rosen CT inspection	8 412
05.1.2023	17.06	Start mini-fracturing – formation plugged	
07.1.2023	04.24	Run #3 – well clean-up	8 460
17.1.2023	22.10	Mini-fracturing – 20 bbl/min	
20.1.2023	21.26	Main fracturing commenced	
20.1.2023	23.10	Pressure-out above XT	
21.1.2023	21.28	Run #4 – well clean-out to 1 000 metres (0.2 per cent citric acid)	
23.1.2023	04.24	Run #5 – main well clean-out	
23.1.2023	14.28	Increased citric acid concentration to 0.4 per cent	1 650
23.1.2023	18.30	Started POOH (for BOP function test)	1 900
24.1.2023	08.41	Run #6 – well clean-out continued	
25.1.2023	03.51	Wiper trip	2 850
25.1.2023	06.56	CT fracture on reel	1 650
25.1.2023	07.11	BHA check valve verified, well secured	1 650
25.1.2023	10.45	New CT fracture on reel	
25.1.2023	11.20	CT fracture on reel	
25.1.2023	12.06	CT fracture on reel	
25.1.2023	12.49	CT fracture on reel	
25.1.2023	15.10	CT fracture on reel	
25.1.2023	15.40	CT fracture on reel – flow from CT	
25.1.2023	15.42	Pipe and slip rams closed on CT BOP	
25.1.2023	15.44	CT fracture on gooseneck	
25.1.2023	15.52	Flow from CT on gooseneck – closed blind shear ram on CT BOP, well secured	
27.1.2023	00.00	Implemented level 3 H_2S emergency response	
27.1.2023	23.07	Initiated displacement of MEG with H_2S scavenger downhole	
1.2.2023	23.16	Swab valve closed (CT had separated and fallen further down the well)	
2.2.2023	21.36	Lower master valve closed	
2.2.2023	22.34	Closed and tested hydraulic master valve – OK	
3.2.2023	02.45	Closed and tested downhole safety valve, 30 minutes – OK	

5.5 Tests and analyses conducted

5.5.1 Material testing

Equinor and SLB independently commissioned a number of tests of the CT which failed. Samples were taken from various parts of the tube which had been in contact with injection fluids.

The Duracoil 130 CT used in the operation was manufactured from an HSLA steel which, as mentioned above, is vulnerable to HE. See section 4.7. The manufacturer has specified the following mechanical properties for this type of CT:

- minimum yield strength: 896 MPa/130 ksi
- minimum tensile strength: 951 MPa/138 ksi
- maximum hardness: 40 HRC

Both reports determined that the mechanical properties, chemical composition and microstructure of the material accorded with the information in the certificate from the manufacturer.

The tests showed that the corrosion layer inside the CT included sulphur, chlorine and oxygen – elements which are corrosive in themselves, but also normal corrosion products in low-allow steel. Traces of H_2S were also found.

Intergranular brittle fracturing had developed from the internal wall of the CT and propagated outwards. Together with findings of sulphur and H_2S, this supports the view that HE is the failure mechanism. The test reports conclude that SSC, a corrosion-driven form of HE, is very likely to be the cause of the CT fractures.

The finding of H_2S is confirmed by analyses of the chemical mixtures used during the operation.

5.5.2 Chemical analyses

On behalf of Equinor, Stimwell requested analyses of the chemical mixtures used during the CT operation in order to determine whether these could form H_2S.

Samples of the gel were taken both before and after the incident, and these were analysed for their total content of bacteria and of sulphate-reducing bacteria (SRB). The results indicated that the H_2S is unlikely to have been formed by bacterial action.

In addition, a number of simplified laboratory tests were conducted after the incident with various chemical and fluid mixtures corresponding to those used during the CT operation.

According to the analyses. H_2S can form quickly and in high concentrations when oxygen scavenger, iron and/or B282 are mixed in seawater where citric acid has already been added. The laboratory investigations appear to suggest that the potential for forming H_2S increases with higher concentrations of citric acid and oxygen scavenger. The actual chemical reaction which gave rise to H_2S has not been identified.

6 Potential of the incident

6.1 Actual consequences

About 1 000 ppm of H_2S was measured in samples taken from the well return flow (measured in the sample bottle). Rotten-egg/H_2S-like odour was also reported when handling proppants cleaned from the well. Personnel on deck were exposed to hydrogen sulphide (H_2S) during waste treatment of returned fluids. Estimating the degree of exposure is challenging, but it cannot be ruled out that this might have exceeded the ceiling value.

The incident had no consequences for the natural environment.

A total of 1 600 metres of 2 3/8-inch CT was left in the well, along with proppants and gel from 2 850 metres to the total depth of 8 558 metres. Removing this will be challenging and time-consuming.

The incident has resulted in substantial financial loss through postponed, and possibly lost, production. In addition come losses resulting from extra work as well as costs incurred with damaged equipment.

6.2 Potential consequences

When personnel detected the first hole in the CT, steps were taken to mark its position using spray paint. No suspicion had arisen at this point that the tube was weakened from the inside and that it would fracture. Had the string broken with personnel next to the CT reel, energy in the form of released bending moment could have led to them being struck and injured. Once several fractures were observed in the CT, it was decided to cordon off the area and to secure the CT on the reel with the aid of transverse beams.

Personnel working around the reel on deck could have been exposed to H_2S, creating a risk to their health.

7 Direct and underlying causes

7.1 Direct causes

The direct cause of the CT fractures was SSC induced by H_2S. The latter most probably arose from a chemical reaction between the oxygen scavenger and citric acid being pumped down the CT plus iron in the latter – see section 5.5 – combined with a material vulnerable to cracking and mechanical stresses.

7.2 Underlying causes

7.2.1 Contributors to risk

7.2.1.1 Mixing of chemicals

The fluid system used to wash out proppants and gel was composed by taking filtered seawater from the Gullfaks C seawater system for blending in the drilling module's mixing and completion tanks. Citric acid in powder form was then added to achieve the desired concentration. Oxygen scavenger was injected in the pump line with ready-mixed citric acid upstream of the CT inlet. Chemicals for reducing hydraulic friction were also injected into this line as required. The data sheet for the oxygen scavenger (Safe-Scav NA) states that the product is not compatible with acid and that mixing it into an acidic liquid can produce toxic gases (without specifying which). Interviews also confirmed that oxygen scavenger should not be mixed with acid.

The mixing procedure did not accord with the stated specifications for the products, and limited the effectiveness of the oxygen scavenger while potentially introducing toxic and corrosive compounds to the pump line.

7.2.1.2 Choice of materials and compatibility testing

The chosen material, Duracoil 130, had high strength but was vulnerable to environmental stresses, including changes to operating conditions. Adequate compatibility testing which could have identified undesirable interactions between chemicals and materials intended for use in the well was not performed.

Equinor's governing documentation does not include requirements for compatibility testing fluids to be used in wells along with third-party equipment such as CT.

7.2.1.3 Planning and change management

Planning of the well intervention activity in Gullfaks C-21A has been under way since 2016. From the start of detailed planning in 2018 and up to January 2022, BH participated as the supplier of stimulation services. In the latter month, it became clear that BH would withdraw its stimulation services from Norway, and the contract with Equinor was taken over by Stimwell in June 2022. This alteration involved technical, organisational and operational changes.

Stimwell's recommendations for cleaning up after the stimulation job on Nøkken differ from the plan drawn up by BH, SLB and Equinor. The original concept was to add corrosion inhibitor with the citric acid while cleaning the well with CT.

During the planning process involving Equinor, Stimwell and SLB, the decision was taken to pump a lower concentration of citric acid, at intervals, through the CT. On that basis, adding corrosion inhibitor to the fluid was found to be unnecessary.

Deciding to exclude corrosion inhibitor during the clean-out work was not followed up by an assessment of the associated risk, and no overview is available of the assumptions which underpinned this decision.

The pressure-out during the operation on 20 January 2023 presented challenges in breaking up the polymer bonds in the gel on the return side. Equinor and the players involved decided to add citric acid continuously on the supply side through the CT in order to increase the reaction time between gel and acid. Equinor's change log shows that this decision was not considered and risk-assessed.

As a result of the operational challenges posed in cleaning out proppants, decisions were taken which are subsequently thought to have been critical for the incident. Changes were made as a response to specific operational problems, but not risk-assessed in relation to previously identified limitations (for the material) or to each other.

Pressure-out is a known issue in proppant fracturing. Filling the well completely with proppants was a contributory factor for the incident. The plan for dealing with full pressure-out to the surface had not been completed nor verified before the operation.

7.2.2 Organisation and interfaces

Planning for drilling, completion and stimulation of Nøkken had been under way since 2016. Drilling the well as a sidetrack from C-21 began 2020. It was not until the autumn of 2022 that it was ready for intervention as part of proppant fracturing.

The project progressed from choice of concept to detailed planning in 2016-22. During this process, which included the Covid-19 pandemic, Equinor has undergone major organisational changes. It emerged from interviews that personnel involved with following up and planning the relevant operation, both in SLB and Equinor, were replaced several times along the road.

SLB was the main contractor for services which covered pumping, testing, CT and chemicals. Interviews by the PSA team revealed a lack of coordination in the company over activities, responsibilities and deliveries. No overall and joint review was conducted across all departments involved with the intervention activity which could have exposed issues related to fluid compatibility and material limitations.

Plans called for oxygen scavenger, friction-reduction chemicals and liquid citric acid to used during the operation. It became clear along the way that the quantity of acid required was greater than expected, and the decision was therefore taken to use more of this in powder form. Untreated seawater received from Equinor's operations department was added to it for mixing in the completion tanks. Since the oxygen content in the water contributes to an environment vulnerable to corrosion, plans called for the use of oxygen scavenger. It emerged from interviews and documentation that citric acid powder was added to the seawater before oxygen scavenger. According to the safety data sheet, toxic gas would form if the latter was mixed with acidic solutions, and this was considered inadvisable. That information was not grasped and applied by the parties involved. It emerged from interviews and document reviews that SLB had not adequately verified the compatibility of chemicals and materials which were delivered and taken into use. Nor were steps taken to ensure that the necessary information on the chemicals and precautions required was communicated to the executing team.

Made in 2019, the choice of CT material was governed by the length of the well and the requirements for material strength. The material's limitations in corrosion terms were identified and discussed when making this choice. Clean-out fluids were not selected until three years later. Close to the start of the operation, the fracturing contractor was changed from BH, the original provider, to Stimwell. The new recommendations from Stimwell reduced the concentration of added citric acid while corrosion inhibitor was excluded from the intervention programme.

These changes were not adequately considered by SLB and Equinor. Nor were they assessed in relation to the choice of material, which lay far in the past and was thereby left out of consideration.

The combination and pumping sequence of fluids and materials were critical for the incident. Changes related to responsibility for planning and execution, as well as organisational and administrative challenges with regard to communicating risk, probably contributed to allowing the incident to develop.

7.2.3 Capacity and expertise

It emerged from interviews that CT has been little used as an intervention method in Equinor during recent years, and that experience with this type of operation is limited in both the planning and operations centres responsible for the activity.

Both executing and managing personnel responsible for the operation in the planning centre arrived in the autumn of 2022. Key personnel at both the CT provider and Equinor were reshuffled as late as October that year, when a good deal of work still remained to be done before the activity programme could be signed off. It emerged from interviews that support for Equinor's planning centre was sought on several occasions, not only because of the workload but also in terms of experience, without this being followed up until late in the planning process.

Equinor's new staffing model involves a planning centre with dedicated engineering resources developing an activity programme to be taken over by the operations centre when the activity is to be implemented. This solution depends on adequate capacity and expertise being available in both centres, and on the documentation and plans delivered taking account of risk and uncertainty related to the activity.

It emerged from interviews that the model had not been applied because of the low level of CT experience in the company. The decision was therefore taken that the engineer responsible for planning should follow the well through both planning and operational phases. However, the person concerned was not released from duties related to planning new intervention jobs while supporting the operation.

The well has received a great deal of attention in Equinor, not only owing to its complexity but also because of its significance for the Gullfaks field's commercial life. Equinor has expert teams intended to support planning and operating centres with experience when the activity is particularly challenging. Despite the CT intervention method being little used in the company, adequate expert support has not been ensured for the planning centre.

7.2.4 Similar incidents

An incident on Martin Linge in 2017 has similarities with the Gullfaks C one, and lessons learnt from the earlier event could have helped to concentrate greater attention on pumping acid through low-alloy CT with high mechanical strength. Equinor was a partner in Martin Linge and had access to the report on this incident.

8 Emergency response

When the incident with CT fracturing occurred, personnel responded quickly and correctly to secure the well in accordance with procedure:

- closed the pipe and slip rams on the CT BOP following fracturing at the surface, tested check valves
- cordoned off the area
- cut the CT with the blind shear ram on the CT BOP when a fracture occurred downhole
- secured the CT on the reel.

Image 4 shows the tube stump recovered from the well after normalisation. The CT BOP blind shear ram has cut it off and left it with good opportunities for continued circulation via the CT BOP kill line.

Image 4 - Tube stump after being cut by the CT BOP.

9 Observations

The PSA’s observations fall generally into two categories.

- Nonconformities: this category embraces observations which the PSA believes to be a breach of the regulations.
- Improvement points: these relate to observations where deficiencies are seen, but insufficient information is available to establish a breach of the regulations.

10 Nonconformities

10.1 Planning the activity – Equinor

Nonconformity

When planning the intervention in well C-21 on Gullfaks C, Equinor had failed to ensure that important contributors to risk were kept under control – both individually and collectively.

Issues related to health, safety and the environment had not been addressed adequately and from every angle before decisions on the well intervention were taken.

Grounds
Given the combination of the chosen CT material and chemical additives in connection with the well clean-up, the risk of SSC and chemical reactions which could contribute to it was not kept under control, either individually or collectively.

Use was made of CT in high-strength steel, which is vulnerable to SSC. The limitations of this material with regard to corrosion were not identified and discussed at the time it was selected. When that choice was made and changes were implemented in the chemicals for the intervention programme, the limitations of the chosen material and the risk of corrosion and exposure harmful to health were not taken into account.

Equinor's TR 3532 management system includes requirements for testing the compatibility between fluids and its own well equipment, but these do not extend to third-party equipment which is not permanently installed downhole. The company was unable to present documentation on request concerning compatibility testing between fluids used in the well together with the CT (third-party equipment).

Changes were made to the project organisation during the planning process. See section 7.2.2. A number of alterations were also made to operational procedures for the well intervention. The original choice of clean-up chemicals was amended after the replacement of the stimulation provider. During the planning process involving Equinor, Stimwell and SLB, it was decided to pump a lower concentration of citric acid at intervals through the CT and that adding corrosion inhibitor to the fluid was not necessary. Equinor and the players involved then decided during the operation to add citric acid continuously on the supply side through the CT in order to increase reaction time between well fluid and acid. Equinor's change log shows that this decision was not considered and risk-assessed.

The mixing procedure for the chemicals did not accord with the recommendations in the safety data sheets. See nonconformity 10.2.

Changes were made as responses to specific operational problems, but not risk-assessed in relation to limitations (for the material) identified earlier or in relation to each other.

Requirements
Section 29, paragraph 1 of the activities regulations, see section 12, litera e of the facilities regulations
Section 11, paragraph 11 of the management regulations

10.2 Information and interface – SLB

Nonconformity

SLB had failed to ensure that necessary information related to compatibility and mixing procedures for chemicals used in the well intervention activity had been processed and communicated to relevant users.

Grounds

The choice of both chemicals and the mixing and pumping procedure affected the development of the incident. Various departments at SLB delivered chemicals used during the operation without coordinated control. It emerged from interviews that the properties of chemicals delivered by an SLB department were not reviewed and taken into account by the end-user department for these substances, and that little interaction and information flow occurs between the company’s various departments. This means that the necessary information – including the properties of the chemicals – was not communicated to relevant users.

The safety data sheet for the oxygen scavenger noted that hazardous gases could be generated by mixing it with acidic solutions, without specifying which these were. Nor did it state that mixing the chemical with such solutions would reduce its effectiveness.

Requirement
Section 15, paragraph 2 of the management regulations on information

11 Improvement points

11.1 Capacity and expertise – Equinor

Improvement point

Equinor does not appear to have made the resources needed for the well intervention activity available to the project organisation.

Grounds

The intervention activity on Gullfaks C was an extensive operation and attracted great attention in the company, both owing to its complexity and because of the well’s financial significance for the profitability of the Gullfaks field. Planning for the activity extended over a long period which, combined with organisational changes and replacements of personnel, made it challenging to maintain an overview while taking account of all contributors to risk. In this case, personnel from Equinor's planning centre had to continuing following up the well-intervention activity into the execution phase because the units lacked capacity related to CT operations. It emerged from interviews that personnel working on well intervention experienced a heavy workload and little access to expertise in specific disciplines, despite requests to provide support for the planning centre ahead of the activity.

Requirement
Section 12, paragraph 2 of the management regulations on planning

11.2 Inadequate learning from similar incidents – Equinor

Improvement point
Equinor does not appear to have made provision for applying experience acquired by it and others to improvement work.

Grounds
Similarities exist between the Martin Linge and Gullfaks C incidents, such as comparable CT material quality and use of acid when pumping through the CT. Equinor was a licensee in Martin Linge at the time of the 2017 incident, but its organisation for planning and executing the intervention activity in C-21A was unfamiliar with this event. Few opportunities for cross-company learning, in the form of industry fora or the like, exist between operators and suppliers in the well intervention field.

Requirement
Section 23, paragraph 3 of the management regulations on continuous improvement

12 Barriers which functioned

Action was taken in the wake of the incident to prevent harm to personnel and exposure to H_2S. See section 6.2. The well was secured as prescribed in the regulations by activating the blind shear ram on the CT BOP without unnecessary delay. See section 5.3.

13 Discussion of uncertainties

13.1 Samples taken from the return flow

Uncertainties exist related to analyses of return fluids after the incident. It is clear that H_2S measurements were made with these in the laboratory on Gullfaks C and that the results were discussed with experts in the land organisation. However, it is unclear how the samples were subsequently handled and taken care of. Results from these samples accordingly cannot be verified.

13.2 Determining the chemical reaction

Laboratory tests show that H_2S is formed when using the chemicals utilised in this incident, but the specific chemical reaction has not been identified.

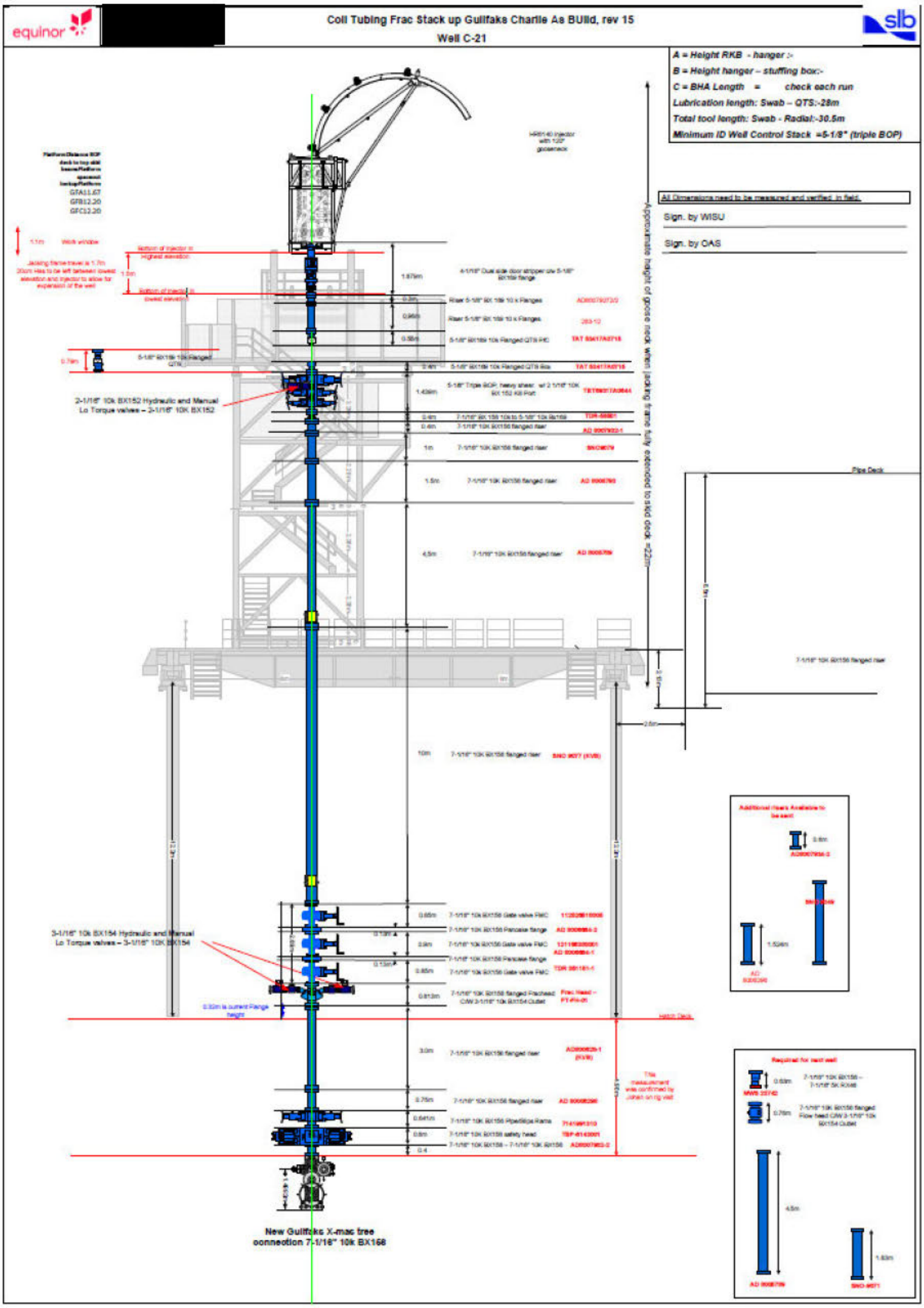
14 Assessment of the player's investigation report

Equinor conducted its own internal (level 3) investigation of the incident. The investigation team was drawn from both Equinor and SLB. Participants from the latter were two technical experts and the coordinating chief safety delegate. The investigation report appears to be extensive and thorough. Findings and proposed measures largely coincide with the results of the PSA's investigation.

15 Appendices

A: Rig-up on the well
B: Documents drawn on in the investigation

Appendix A – Rig-up on the well



Appendix B - Documents drawn on in the investigation

1 - Equinor PDP DW Org Chart.pdf
1 - Schlumberger Specification for Coiled Tubning_AJ_4880179_01.pdf
11 - TR3508 H2S Contingencies for drilling and well activites.pdf
13 - Tillegg til Beredskap på norsk sokkel - Gullfaks C.pdf
2 - Material Certification-10346.pdf
2 - POB 25.01.2023.pdf
20-VA05 er nå frigjort fra C-21 inntil videre..pdf
2733_34_11_2_S_COMPLETION_REPORT_AND_COMPLETION_LOG.pdf
3.1 - ACP CT Pipe_7528358_01 (1).pdf
3.2 - TFM_CoiLIMIT_Analysis_5435102_01_6083286_01.pdf
34_11-2S OD.pdf
4.1 - Equinor_Gullfaks_C-21A_17Jun2020_Rev.1 Jesus Campos.docx
4.2 - Equinor_Gullfaks_C-21A_19 October 2022_Rev.1.1 Jorge Pedro.docx
6 - 230051 Global Tubing- Failure Analysis on String 10346 Rev 1.pdf
9 - App. D Sikkerhetsstrategi for GFC.pdf
ARIS - DW400.pdf
ARIS - DW410.pdf
ARIS - DW411.pdf
ARIS - DW412.pdf
ARIS - DW413.pdf
ARIS - DW414.pdf
B - 3.1 - Well Concept Report RE-NOKKEN-00014 _01 - Final, with QA matrix.pdf
B - 3.2 - Nøkken DW Input Rank And Select Concept DW611_07.pdf
B - 3.3 - PM656-PMS-050-007_02 Design basis Nøkken.pdf
B - 4 - Well Drawing GF C-21 A Nøkken Final.pdf
B - 7.1 - DW602 - Activity program Drilling and Completion- 34_10_C-21A Nøkken.pdf
B - 7.2 - Amendment to Gullfaks C - C-21 A - Activity program_signed.pdf
B - 7.3 - RiskRegister Drilling planning.pdf
B - 7.4 - RiskRegister drilling Execution.pdf
B282.pdf
Best practice - Supplier information sheet_.xlsm
bilde av CUB og dræger 5600.jpg
Bilder perf assy. Perf run #1.pdf
BR-ELT.pdf
C-21_ Propanter på rømmen .pdf
C21A Investigation - Final-Released (Equinor).pdf
Cabsheet Equinor GFC1 .xlsm
CITRIC ACID.pdf
D21D.pdf
DailyAnalysisNOView (64).pdf
DailyAnalysisNOView (65).pdf
Dokumentasjon vedr brønnhendelse brønnkontrollhendelse Gransking - Equinor Gullfaks C - Brudd i CT streng 25012023.pdf
Dokumentliste.docx

Dræger Polytron 8000.pdf
DTI Report - 1.pdf
DTI Report - 2.pdf
DTI Report - 3.pdf
DTI Report - 4.pdf
DUO-TEC L.pdf
DW400 - Intervention concept risk analysis.pdf
DW400 - Intervention operational risk analysis.pdf
DW702.04 - Drilling and completion design.pdf
DW914 - Select and order materials and services.pdf
EQN Nokken Z1 - Main Job (Design vs Actual).xlsx
EQN Nokken Z1 Minifrac#1 Design vs Actual.xlsx
Extended Length CT String and iFC Power Price Proposal.pdf
Ferdig med utsirkulering av 25 m3 _MEG-mix_ i C-21.pdf
Flowback GFC21 events log sampling.pdf
G10U Utstyrskaft.pdf
G22U Utstyrskaft.pdf
GFC - DFU H2S (fra 2013 - dd).pdf
GFC - H2S fritekstsøk (fra 2013 - dd).pdf
Granskningsrapporter wireline and coil tubing operations Martin Linge 2017.pdf
Graph Flowback side.pdf
Gullfaks C - Dokumentasjon - Synergi H2S.msg
Gullfaks C - Dokumentoversikt gransking brønnkontroll hendelse - Sendt 08.02.2023.pdf
Gullfaks C - Oversikt over væskeprøver og analyser.msg
H2S måling i prosess.pdf
SLB shift handovers 23.12.22-31.1.23
I - 10.1 - Changelog GFC-21.pdf
I - 10.2 C-21 A Changelog - MoC 16 to 28.pdf
I - 12 - H2S contingency plan (example).pdf
I - 5.1 - Handover+WBS_Gullfaks_C-21_rev.20.pdf
I - 5.2 - WBS CT ops _Gullfaks_C-21_rev.20.pdf
I - 6.1 - CT Line Schematic Rev 27.pdf
I - 6.2 - Stack up As build 29.12.22 C-21, Rev 15.pdf
I - 8 - GF C-21 A Nøkken Intervention scope - concept selection and activity program (Signed Program_2022).pdf
I-9 - DOP readme.pdf
I-9 - DOP-02_ Drift Run 1_3.125 Venturi Junk Basket & 3.750 Drift Shoe. rev.pdf
I-9 - DOP-03 - Perforate bottom interval_Rev.8.pdf
I-9 - DOP-04 - mini frac, SRT and main frac - GFC-21 A Nøkken rev.6.pdf
I-9 - DOP-05 - Post Frac Cleanout_rev.7.pdf
I-9 - DOP-05.1 - Post Frac Cleanout_Screenout Contingency_05Aug20_v2.pdf
I-9 - DOP-05.1.1 - Post Frac Cleanout_Screenout Contingency_Reestablish barriers.pdf
I-9 - DOP-05.1.2 - Post Frac Cleanout to TD.pdf
I-9 - DOP-05.2 - Post Mini Frac Cleanout_Screenout Contingency-rev5.pdf
I-9 - DOP-05.3 - Bullhead TSW_ADD.pdf

Bilder
iptc-21826-ms.pdf
Jetta VA05, 480 m3.pdf
Latest Stack up C 21 GFC.pdf
Line sheematic Rev 27 GFC.pdf
M296.pdf
Material Certification-10346.pdf
MEG.pdf
måler til å ha på kjeledress.jpg
Nokken Startup Presentation_16092019.ppt
Nokken Zone 1 - Consolidaded Job Data.pdf
Optiseal.pdf
Org chart C-21 Well intervention planning and execution.pdf
Oversikt DW400.pdf
Oversikt over væskefordeling i brønn gjennom ulike faser.xlsx
RE_ Gullfaks C - Navn .msg
ReportExtended.xlsx
Request for equipment info from Slb Reel diameter vs coil diameter.msg
Risikovurdering for bruk av Sodium Persulphate.pdf
Run # no 3 – Cleanout mini frack.docx
Run #4 and #5 chemicals.docx
SAFE-SCAV NA.pdf
SCALEGUARD_4.1_EU.pdf
SDS CITRIC ACID.pdf
SDS Kryptosphere.pdf
Shacerrom D21M.pdf
SI-4130.pdf
SI-4154.pdf
Sikkerhetsdatablad for grotan ox.pdf
Sirkulasjonssystem.pptx
slamtankrom D11.pdf
Sodium Persulphate.pdf
Star-Lube.pdf
Stimwell chemical information.pdf
Sys 13 - C-21 Stopp i coil tubing operasjon. Brønnkontroll.pdf
Sys 13_20 - Tilbakestrømning C-21 pågår..pdf
Sys 44 - Åpnet vannutløp 2.trinn B da det ble stopp i CT operasjon og tilbakestrømning.pdf
T140a_Vandig_løsning-NO_nb_NO-25054.pdf
TR3504 Well Intervention operations.pdf
TR3532 - Selection and treatment of workover completion and stimulation fluids and scale treatment chemicals to avoid corrosion failure.pdf
TR3544 Well Intervention equipment and personnel markert EV.pdf
UK - 3% KCL-B - SDS20214.pdf
UK - BF-10L - SDS10049.pdf
UK - BF-H - SDS10021.pdf

UK - BR-ELT - SDS10024.pdf
UK - BR-HT-M - SDS10005.pdf
UK - BR-SPL - SDS10035.pdf
UK - Grotan OX - SDS20245.pdf
UK - GS-HTL - SDS10055.pdf
UK - LGC-H-M318 - SDS20227.pdf
UK - NE-G2W - SDS20167.pdf
UK - StimBor-HXXF (generic) - SDS20305.pdf
UK - StimGel-HXXF (Generic) - SDS20306.pdf
UK - XLB-D-GOX - SDS20243.pdf
WCI ONE PAGER (ext) - Parted CT string - Gullfaks C - C-21 A.pdf