PETROLEUMSTILSYNET

Investigation report

Report	
Report title Investigation of overpressurisation in sludge cell 11 on Statfjord A on 26 November 2019	Activity number 001037047

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

Involved	
Team T-1	Approved by/date Kjell Marius Auflem/8 May 2020
Members of the investigation team Ove Hundseid, Terje L Andersen	Investigation team Roger L Leonhardsen

Contents

1 Summary

Sludge cell 11 on Statfjord A was subject to an overpressure of 2.6 bar on 26 November 2019. The cell is designed to be operated with an internal pressure five bar below the ambient seawater pressure. The overpressure occurred because oily produced water was added to the cell while ballast-water valve HV3124 to the outlet had been left closed following maintenance of its actuator. This overfilling caused in the lines down to the cell to fill with water, and the consequent liquid column resulted in an overpressure of 2.6 bar. That in turn caused cracking in the cell dome and subsequent leakage of about 150 m^3 of oil and sludge to the sea. The Petroleum Safety Authority Norway (PSA) decided on 29 November to launch an investigation of the incident.

Modifications of and changes to operating methods between storage and sludge cells have introduced system vulnerabilities and allowed a single action to shut off barriers. The direct cause of the overpressure was filling cell 11 with the ballast-water valve closed. Underlying causes related to the absence of barriers owing to modifications from storage to sludge cells, lack of risk assessments of the modifications, inadequate risk and system understanding when planning maintenance work on the ballast-water valve, and the failure of applicable system and operating documentation to reflect the technical or operational changes.

The investigation has identified nonconformities related to inadequacies in the process safety system against overpressurising sludge cells, inadequate risk and system understanding when planning maintenance work on the ballast-water valve, lack of safeguards on safety-critical valves, and inadequate governing documentation. An improvement point related to deficiencies in Equinor’s own follow-up has been identified.

2 Background information

The dome in sludge cell 11 on Statfjord A was subject to an overpressure of 2.6 bar on 26 November. This occurred because ballast-water valve HV3124 to the outlet had been left closed following maintenance of its actuator and oily produced water was added to the cell. The overpressure resulted in local areas of cracking in the cell dome where the concrete’s tensile strength had been exceeded. That led to a leakage of oil and sludge to the sea (DSHA 01 B) from the cell, which lasted about four hours. The leak could be observed as an oil slick on the sea surface. Estimated to total 150 m^3, the discharge consisted primarily of oil.

2.1 Description of facility and organisation

Statfjord A is an integrated production and drilling facility with three concrete shafts. It came on stream in 1979. Equinor is the operator, with Statfjord organisationally incorporated in the operations south (EPN OS) unit.

The platform is provided with 16 storage cells for stabilised crude oil. These were originally divided into three groups. Crude oil is added to one cell group at a time, with a minimum of five cells per group. Storage cells 11-13 are designated for sludge and have, since 2012, received oily produced water from degassing tanks CD2119 and CD2219 as well as from open and closed drains. Filling occurs to one cell at a time, and is transferred about every 14 days to give the sludge time to separate into oil and water, limit corrosion in the pipes to the sludge cells and avoid high temperature in the concrete.

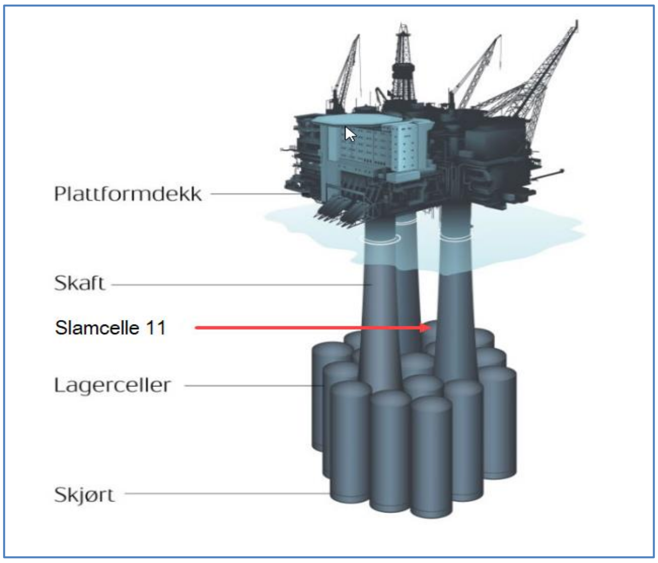

Figure 1: Statfjord A (source: Equinor).
Key: Platform topside; Shaft; Sludge cell 11; Storage cells; Skirt

The storage and sludge cells on Statfjord A are designed to be operated with an internal pressure about five bar below the ambient seawater pressure.

2.2 Design

The water depth at the location is roughly 150 metres. Levels and fluid pressures will be discussed in more detail below. Platform levels are measured from the underside of the steel skirt driven into the seabed.

Statfjord A is supported by a concrete gravity based structure (GBS) kept in place on the seabed by its own weight. This installation has an underlying skirt driven into the seabed. The GBS itself comprises 19 cells, each about 70 metres high. Three are extended to form shafts which carry the topside (quarters, utility, process and drilling areas). The two drilling shafts are water-filled. The utility shaft is water-free right down to the seabed (and has an annulus almost 50 metres high at the bottom). The other 16 cells are closed with domes at top and bottom. Each cell has a liquid volume of about 18 000 m^3. Figure 2 presents a cross-section of the utility shaft, while figure 3 shows the position of the primary cells.

The cells are numbered from 1 to 19, where

- number 1 is the utility shaft, free of water
- number 3 is the northern drilling shaft, filled with water
- number 5 is the southern drilling shaft, filled with water
- cell 11 is the storage/sludge cell which sprang a leak.

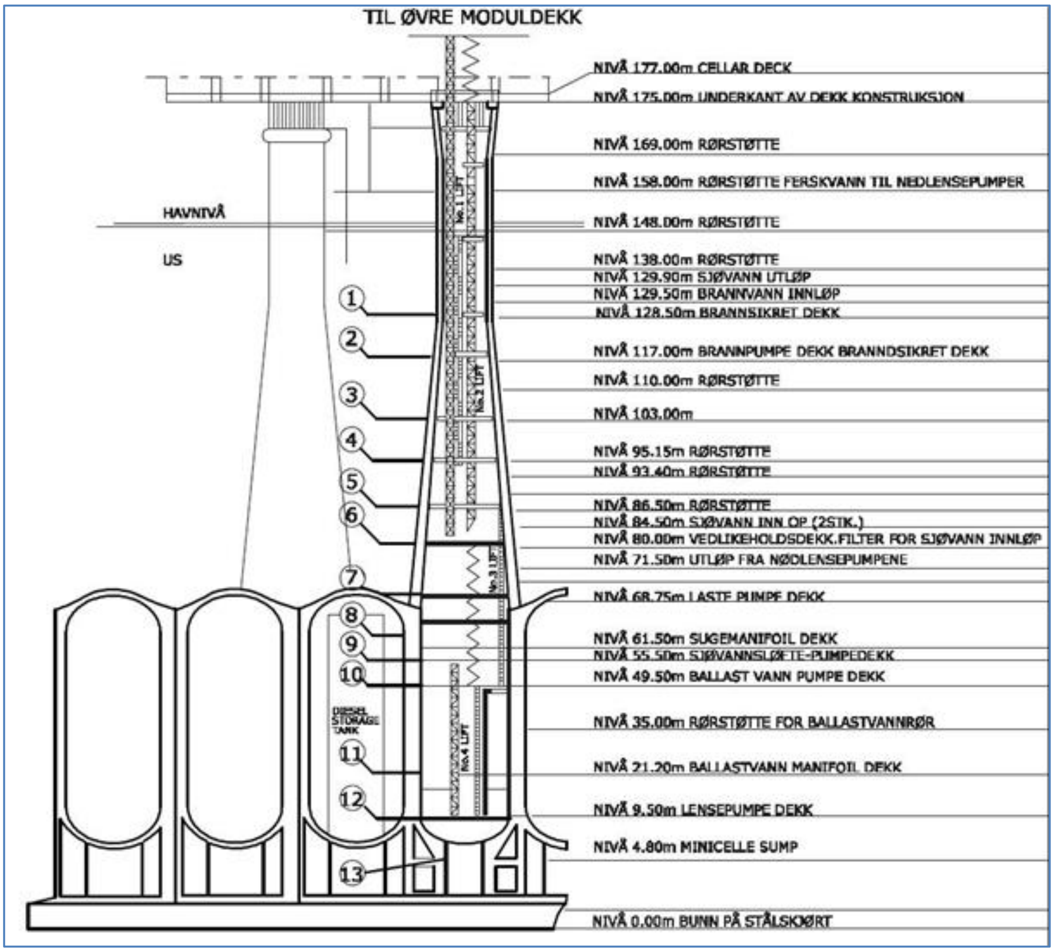

Figure 2: Overview diagram of the various levels in the utility shaft (shaft number 1) on Statfjord A. The diesel tank placed in cell 6, cited as cell 51 in the P&ID, can be seen in the centre of the diagram (source: Equinor).
Key: To upper module deck; *Nivå* = level; *Havnivå* = sea level; *US* = sub-surface.

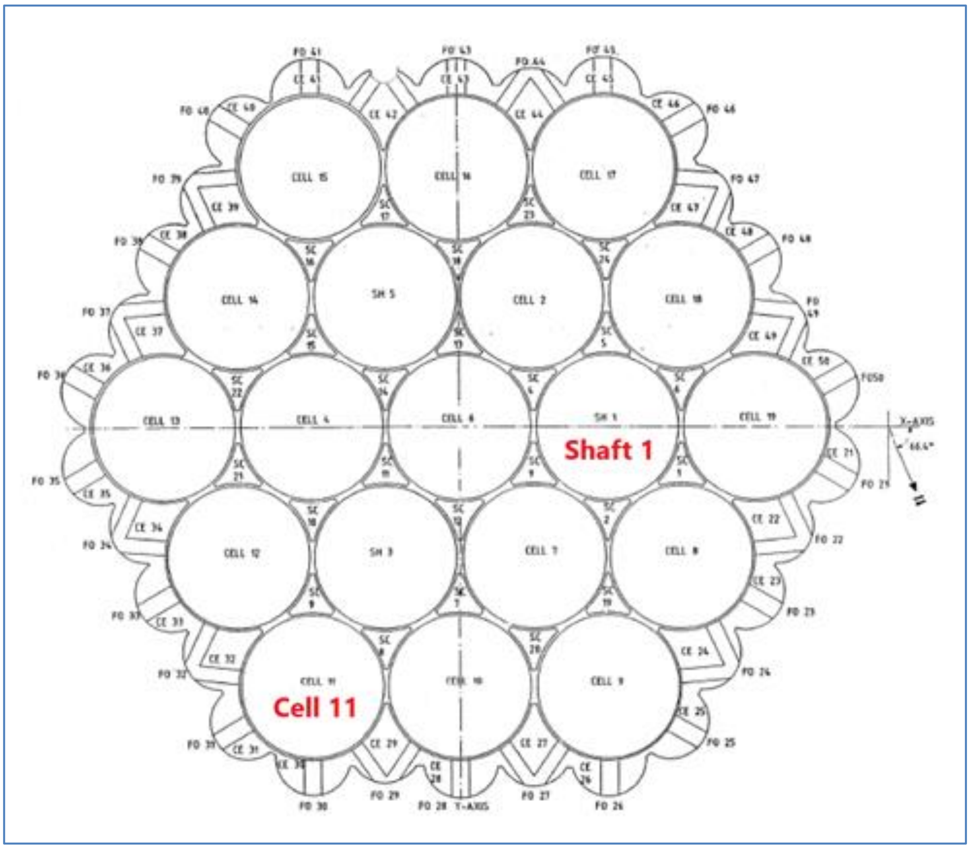

Figure 3: Horizontal cross-section through the primary cells on Statfjord A. Cell 11, which suffered the leak, is shown at bottom left, while the utility shaft (number 1) is at centre right (source: Equinor),

The external diameter of the primary cells is 20 metres. Their tops are closed with a dome measuring 14 metres in radius. In addition to 16 cells and three shafts (19 primary cells) come 30 “mini-cells” in the base immediately above the seabed and 24 “star cells” between the primaries. The latter are open to the sea at their top on a level with the domes.

The 16 cells have three main functions:

- load-bearing structures which distribute loads from the three shafts to the foundation (mini-cells and skirt) and thereafter to the seabed
- filled with water as ballast for the platform
- storage for produced oil until the latter is loaded into shuttle tankers.

A design condition is that the cells are operated below the ambient water pressure [design, fabrication and installation (DFI) document]. This underpressure must be about five bar, corresponding to a 50-metre water column.

This underpressure ensures that:

- the concrete in the cell walls and domes is under constant pressure to ensure that variations in loading do not impose tension on the concrete, which could cause cracking because concrete has a low tensile strength
- possible leaks in the cells involves seawater intruding rather than oil escaping.

To ensure that the cells have the correct and equal pressure, valves on piping from the ballast tank in the utility shaft to each cell must always be open. Only in the event of unforeseen incidents might a need arise to close the ballast-water valve to a cell. If damage to a cell causes water intrusion, for example, the cell must be isolated to avoid overfilling the ballast tank, exceeding pump capacity and causing water to intrude into the utility shaft.

Where the ballast system is concerned, normal operation of the GBS can be summarised as:

- all the ballast valves at the bottom of the utility shaft must remain open
- the ballast valve to each cell is designed to isolate the connected cell in the event of damage which causes water intrusion in the cell, when the valve can be closed to prevent water flooding the utility shaft.

The design assumptions for the GBS are described in the DFI document. Normal operation assumes that the 16 cells are below the ambient pressure to ensure that the structure has sufficient capacity to withstand the other loads, particularly from waves and wind. The normal condition is illustrated in figure 4.

Some scenarios with abnormal water-filling for maintenance and physical access through the manholes into the storage cells are described in the DFI document. These deviations from the two above-mentioned circumstances must be planned in detail and take place in calm weather when natural loads on the structure are small. A common denominator for all the scenarios is that no conditions are defined with internal overpressure in shaft or cells.

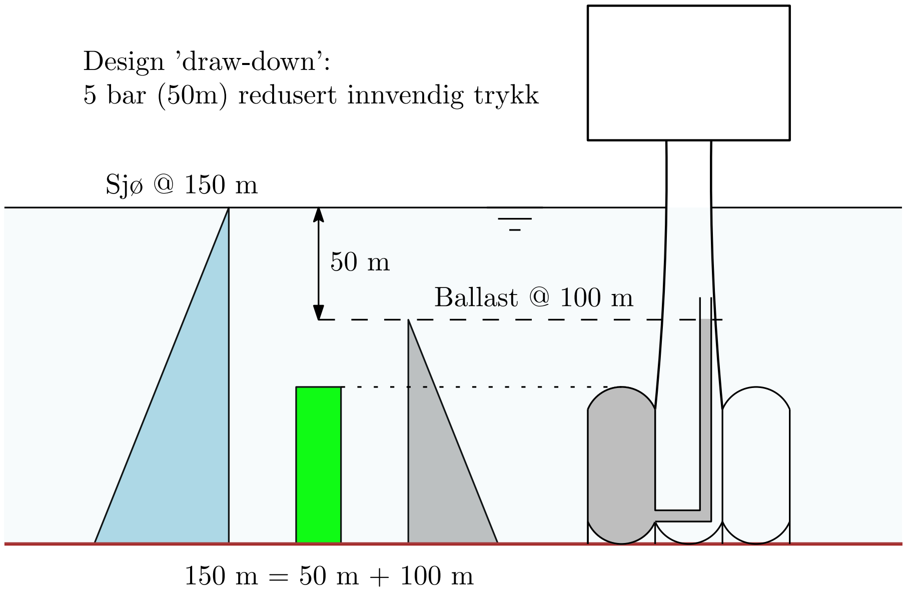

Figure 4: Illustration of the principles for normal operation with ambient water pressure and internal ballast pressure. The 50 metre (equal to five bar) different compresses the concrete in the cells. Ambient overpressure equals internal underpressure, also called "draw-down".
Key: 5 bar (50m) reduced internal pressure; Sea level @ 150m

2.3 System description for oily water in sludge cells

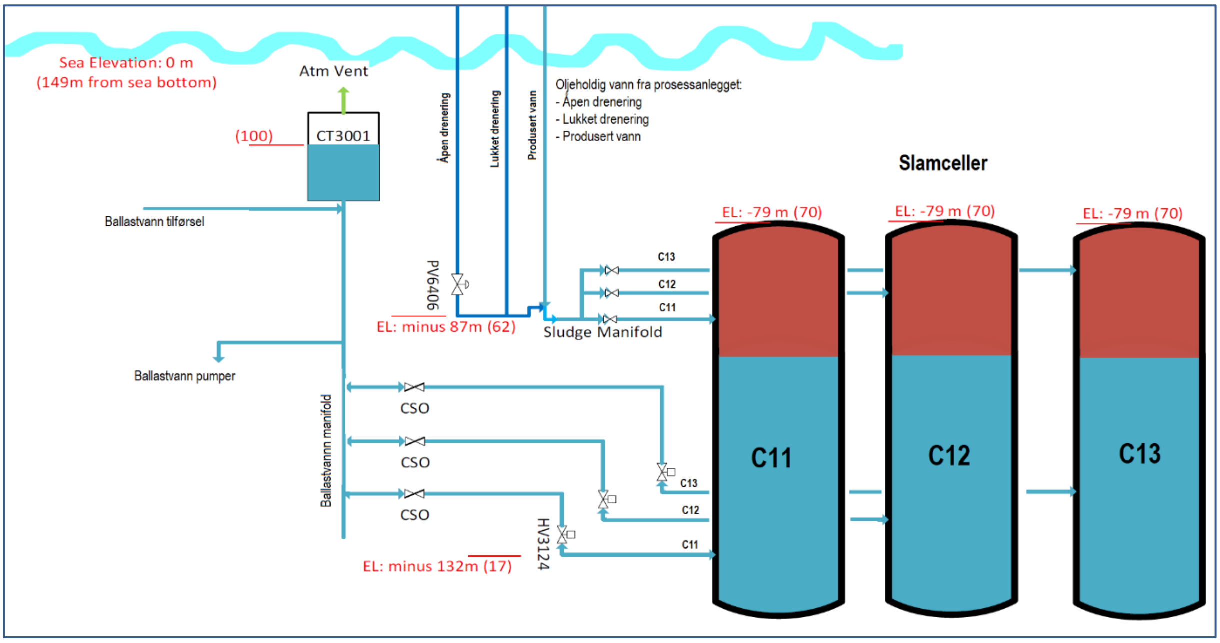

Figure 5: Sludge cells 11, 12, and 13 (source: Equinor).
Key: Oily water from process plant – open drains, closed drains, produced water; Ballast water supply; Sludge cells; Ballast-water pumps; Ballast-water manifold

On Statfjord A, oily water from the process plant (open/closed drains and produced water) is sent for oil/water separation to a one of the three sludge cells, which are basically the same as the crude oil storage cells. All three are connected to a manifold used to route water to one cell at a time. The two sludge cells not in use are isolated from the manifold by manual valves. Since the water is corrosive, the recipient sludge cell is regularly changed in order to limit corrosion in the piping. This is done by first opening the valves connecting the new sludge cell to the manifold. The manifold valves to the cell which has been in use is then closed. That allows oily water to flow continuously to the sludge cells during a transfer. Once a cell has been taken out of use, a little oil is produced into it to prevent corrosive water remaining in the pipe from manifold to cell.

All the cells, for both sludge and oil storage, are connected to the ballast-water system, which has three important functions:

- ensuring an underpressure in the cells
- ensuring that the cells are always filled with liquid
- preventing overpressurisation of the cells.

Ensuring an underpressure
The storage cells are designed so that they are always kept below ambient pressure. This is ensured through their connection to the ballast-water system, which is maintained below ambient pressure with the aid of an atmospheric tank (CT 3001) located about 50 metres beneath the sea surface. That keeps all the cells at about five bar of underpressure and also ensures that seawater intrudes in the event of a storage-cell leak rather than oil escaping.

Ensuring that the cells are always filled with liquid
When a sufficient number of storage cells have been filled with oil, this is pumped across to a shuttle tanker. The ballast-water system then ensures that oil taken from the top of the cells is

replaced with seawater at the cell base. Similarly, when oil is produced to the cells, the ballast-water system allows the oil to displace seawater in the cells by pumping out the latter from the base. The cells must always be filled with liquid to maintain platform stability and to withstand structural loads on the GBS.

Preventing overpressurisation

Since the cells are not designed for internal pressure, it is important that they are not exposed to this. As long as the cells are connected to the atmospheric tank in the ballast-water system, which keeps them five bar below the ambient seawater pressure, they cannot be overpressurised. The ballast-water system is therefore a very important safety system for the cells and must never be disconnected in normal operation. To ensure that the storage cells are not isolated from the ballast-water system, oil is produced to one group of several storage cells at a time. The cells are thereby connected to the ballast-water system by several cells. Should a storage cell be isolated from the ballast-water system through the erroneous closure of its ballast-water valve, it will still be connected to the system via the other cells in the same group. In order to overpressurise the storage cells, the ballast-water valves to each of the cells in the group must therefore be closed. However, this does not apply to the sludge cells. Since oily water is sent to one of these at a time, it could be overpressurised if it is isolated from the ballast-water system. A single error – in other words, closing one valve in the ballast-water system – is enough to overpressurise a sludge cell.

2.4 System for oily water

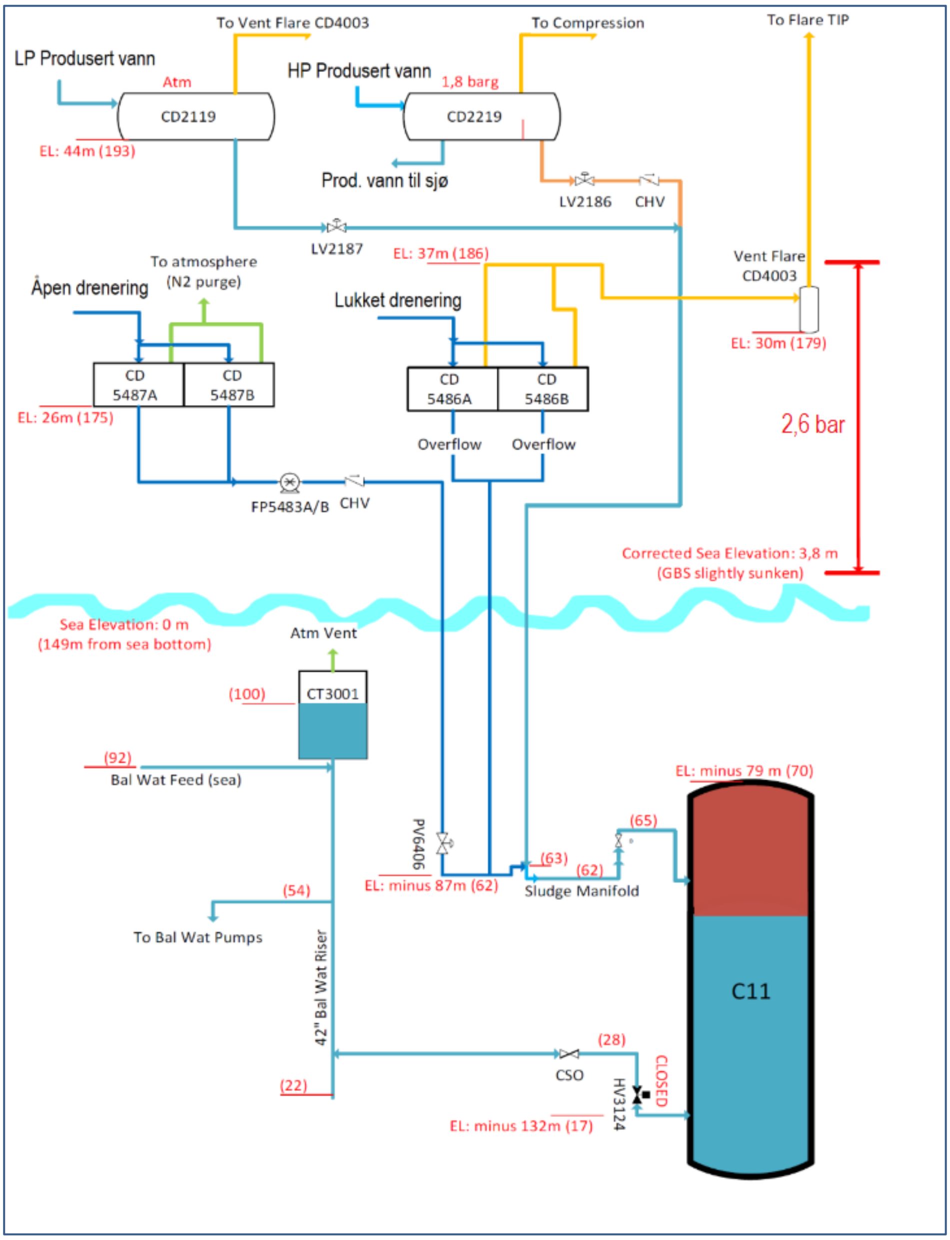

Figure 6: Process diagram for the oily water system (source: Equinor).

The sludge cells receive oily water from three sources: open drains, closed drains and produced water – high pressure (HP) and low pressure (LP) – as presented in figure 6.

Open drains
Removes water and oil collected from drains in deck areas as well as from collection tanks under process equipment. If no rain, jetting, fire water activation or the like occurs, water does not enter this system. It was not in use during the incident.

Closed drains
This system is connected to process tanks and used to drain off liquid, typically in connection with inspection of or modifications to the plant. In normal operation, therefore, no liquid flows through this system to the sludge cells – and that was also the case during the incident.

Produced water
This comes from two sources – LP and HP. The main source of liquid for the sludge cells is LP produced water from the CD2119 degassing tank, where the pressure is reduced to atmospheric level and the gas gets vented to the air through the flare stack. The water is led down to the sludge cell by gravity.

HP produced water derives from the CD2219 degassing tank, where the final oil residues are separated out and led down to the sludge cell. The water is discharged to the sea. Rates here are very small compared with the flow from CD2119, which was the primary source for overfilling and overpressurising sludge cell 11 during the incident.

2.5 Equinor's governing documentation

Equinor's *TR3001 Prosess sikkerhet* technical requirement document reflects the regulatory specification that tanks and separators must be provided with two functionally independent barriers against overpressure and fracturing. Converting storage cells 11-13 to sludge cells in 2012 means that produced water is led to one sludge cell at a time. The ballast-water system is the only barrier against overpressurising and cracking in the sludge cells. Closing the ballast-water valve removes the overpressure protection.

A description of and operational requirements for the ballast-water system are provided in the *System PB, UJ – Lagring av råolje og ballastvann* SO document. Piping and the valve manifold connecting storage cells 11-13 to the CD2119 degassing tank were taken into use in 2012. Since 2015, both water and oil phases from CD2119 have been piped to the sludge cells, followed by the oil phase in CD2219 from 2019. The current SO description of September 2016 describes neither the modifications nor the change of use.

Filling is transferred between sludge cells roughly every 14 days. This routine was introduced in 2012. The sludge cells are used to separate oil residues from produced water, which is corrosive. Which of the three sludge cell receives the water changes in order to limit corrosion in the piping. Produced water has a temperature of up to about 70°C, and the transfer is also intended to help prevent the concrete in the sludge cells getting too hot. Manual valves in the utility shaft are used to transfer from one cell to another. The practice is that the area authority/shaft operator calls up the central control room (CCR) by walkie-talkie, with two-way communication maintained during the operation. The transfer time is logged on a separate form. No procedure has been established for the transfer.

Section 2.7 of Equinor's *TR2315 Valve Locking, Interlocking and Other Position Securing Systems* technical requirement specifies that the facility must establish a system for logging the traceability and status for all secured valves. That also follows from *Aris – R-101833 Securing important valves in the correct position*.

2.6 Similar incidents with overpressure

During 1989, the E1 storage cell on Statfjord C was subject to overpressure from 21.00 on 9 August to 11.40 on 10 August. The cell was isolated in this period from safety systems (ballast water, control tanks) intended to prevent overpressure in storage cells while oily water was pumped from the reclaimed oil sump to the cell.

Overpressure in cell E1 caused leakage through the concrete in the cell dome and the leak valve in the ballast-water system.

2.7 Position before the incident

Sludge cell 11 was connected to open and closed drains as well as the CD2119 and CD2219 degassing tanks. Liquid flowing into cell 11 during the incident came primarily via CD2119, which is connected to atmospheric ventilation. No liquid is thought to have flowed from open or closed drains during the incident. Ballast-water valve HV3124 was in the closed position because of ongoing maintenance work.

2.8 Abbreviations and terms

Aris: Management system in Equinor
CCR: Central control room
DFI: Design, fabrication and installation
DSHA: Defined situation of hazard and accident
GBS: Gravity based structure
Hazop: Hazard and operability study
HP: High pressure
LAT: Lowest astronomical tide
LP: Low pressure
NCA: Norwegian Coastal Administration
Nofo: Norwegian Clean Seas Association for Operating Companies
PCDA: Process control and data acquisition
PI&D: Piping and instrument drawing
ROV: Remotely operated vehicle
SAP: Computer system for such functions as maintenance management
Sludge or slop: term for oily water flows which must be cleaned of oil before discharge.
SO: System description and operation documentation
EPN: Exploration and production Norway
TR: Technical requirement
TTS: Condition monitoring of technical safety
WO: Work order

3 The PSA's investigation

3.1 About the investigation

The PSA was notified by Equinor Marine at 10.27 on 26 November 2019 that oil had been observed on the sea around Statfjord A. It was reported that this came from a sludge cell and that the leak had ceased when oily water was transferred to another cell. Video meetings were held with Equinor on 27 and 29 November. The PSA decided on 29 November to investigate the incident.

A meeting was held with Equinor on 9 December. Two members of the investigation team visited Statfjord A on 16-17 December for inspections and conversations. Interviews with personnel who had been on Statfjord A during the incident and with members of the Statfjord operations organisation took place in Equinor's premises at Forus East on 13 and 30 January and on 10 February.

Documentation has been obtained from Equinor.

The investigation team has prepared its report on the basis of conversations and inspections, meetings, interviews and documents received. It has not done its own technical investigations. Design weaknesses have been identified when modifying storage cells to sludge cells. The team has not investigated why these were not picked up by quality assurance during the modification project.

3.2 Mandate

The mandate for investigating the incident was established in consultation between the team and the client.

a. Clarify the incident's scope and course of events (with the aid of a systematic review which typically describes the timeline and events)
b. Assess the actual and potential consequences
1. Harm caused to people, material assets and the environment
2. Potential of the incident to harm people, material assets and the environment
c. Assess direct and underlying causes (barriers which have not functioned)
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

Composition of the investigation team:

Roger L Leonhardsen, structural integrity discipline (investigation leader)
Ove Hundseid, process integrity discipline
Terje L Andersen, structural integrity discipline

4 Course of events

Timeline
6 November
Notification established concerning the repair of a hydrocarbon leak in the actuator block for ballast-water valve HV3124.

13 November
WO 24993459 established in SAP for repair of the hydraulic leak in HV3124. Duration of the work stipulated as 17-20 November. The WO was set at level 2, with risks assessed to include "exposure to hydraulic oil, slippery deck, danger of slipping".

14 November
The actuator (hydraulic system) could have been maintained with the valve either open or closed. Because the valve could not be operated during maintenance, the risk assessment determined that the best course was to close the valve before work began.

16.40: The CCR registered the closure of HV3124 to cell 11 because of “hydraulic leak actuator”. The registration in the CCR shift log read: “Closed gate valve to cell 11 on US15 because of hydraulic leak actuator”.

The CCR placed this information on the PCDA screen, described as “Envelope”, with details of the closure of ballast-water valve to cells 4, 11 and 17.

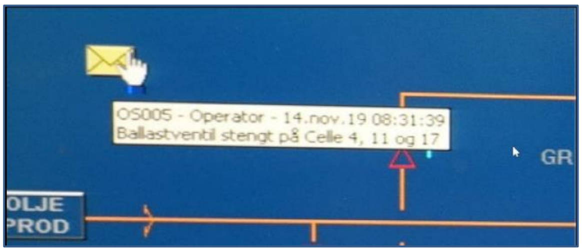

Image 1: “Envelope” on the PCDA screen (source: Equinor).

Registration in SAP action log: “Ready for execution”.

Actuator for ballast-water valve HV3124 and control panel tagged in red as “CLOSED”.

18 November
Registration in SAP action log: “Partially confirmed”.

19 November
06.29: The CCR establishes shift log: “Ballast-water valve closed to cells 2 (HV3116), 4 (HV3119), 11 (HV3124) and 17 (3130) as well as hydraulic supply and return owing to hydraulic leak on these HV valves”.

From the shift log: “Repaired actuator on sludge valve cell 2 Test operation ok Actuator for cells 4,11,17 still leaking after test operation”.

22 November
Registration in SAP action log: “Reset: No material components” and “Goods movement posted”.

It was reported in interviews that maintenance work on HV3124 had been postponed because of the need to obtain equipment parts.

26 November
04.45: Filling was transferred manually from cell 13 to cell 11, which was supplied with produced water from the CD2119 degassing tank at a rate of 44 m^3/h. With ballast-water valve HV3124 shut, pressure rose in the cell. This was because the lines from the cell to the process tanks in the plant filled with water. That can be seen from the fact that the level in drainage tanks CD5486 A and B began to rise. The pressure in the cell was a result of the hydrostatic pressure of the liquid column in the pipes up to the tank level.

05.15: Sensors showed that the level in drainage tanks CD5486 A and B was rising. At that point, cell 11 was receiving about 13.5 m^3/h.

07.00: High-level alarm in the CCR for the liquid level in CD5486 A and B.

07.15-09.00: Operators checked the plant because a smell of diesel oil/oil was noticed on the platform.

08.50: Oil on the sea observed from Statfjord A. Daylight had become sufficient for visual observation.

Around 09.10: Operator told to check the level measurements in CD5486 A and B. They observed a small pool of oil under the open connection point on top of the tank.

09.15: Registration in shift log: “Report of oil on the sea. We checked around as usual and saw that oil sheens were emerging on the eastern side. We then agreed to check cell 11 which was transferred to sludge during the night. The cause was then also found. The ballast-water valve for cell C was closed in connection with a hydraulic leak. This increased pressure in the cell, which began to leak to the sea. Have run down three wells in connection with the incident and stopped a machine in M4.”

09.30: Statfjord A established emergency response in accordance with DSHA 02 - Oil spill.

09.37: Equinor second line notified.

Around 09.40: Operator reported a sludge manifold pressure of 7.8 bar at level elevation 61 metres in utility shaft.

09.45: Supply of oily water returned to cell 13 and supply to cell 11 closed. Observation from Statfjord A that leakage to the sea stopped. Leak estimated at 50-150 m^3 of oily water.

10.05: Production reduced. Equinor second line established.

10.15: Nofo notified and mobilised own response organisation.

10.26: *Stril Merkur* arrived at Statfjord A. Observed thin oil film.

10.29: PSA notified of the incident.

10.38: Stavanger police district notified of the incident.

16.04: Equinor partly demobilised its second line.

16.15: Polwarn 001 from the Norwegian Coastal Administration (NCA) after overflight. No estimate of quantity.

20.10: Polinf 001 from the NCA. Estimated spill from overflight 40-80 m^3. Nofo/Equinor estimated maximum discharge at 100 m^3.

27 November
13.10 Polinf 002 from the NCA. Estimated spill after overflight 1.5-10 m^3.

28 November
First underwater ROV inspection of cell 11 implemented, covering the upper part of the cell wall. The top dome was also inspected, with special attention to the construction joint. No

visible traces of cracks were found. Access to the star cells is available via openings in the top of the tricell plate, but changed weather conditions prevented inspection of the star cells.

13.28: PSA updated on the incident and told that Equinor was demobilising its second line.

13.42: Equinor second line demobilised

14.00 Polinf 003 from the NCA. Overflight observed no oil on the sea.

5 December
23.00: Cell 11 reconnected to the ballast-water system, re-establishing five bar underpressure.

13 December
New underwater ROV inspection which included:

- new and more thorough inspection of wall and top dome for cell 11
- inspection of star cells 8 and 9, which border cell 11
- mapping traces of cracks or old damage along dome edge of cell 11.

Inspection of the cell wall and top dome did not find areas with fresh traces of cracks or definite signs of oil leakage.

Something which could be interpreted as oil residues, damage and cracking were found circumferentially about 75 centimetres from the outer edge of the dome and from the "embayment" to cell 10, and probably to the end of the towing attachment in the centre of the outer curve. The crack appeared to start from a foundation which spans from cell 11 to cell 10.

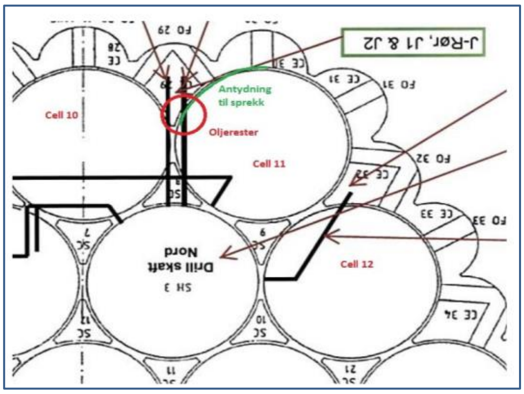

Figure 7: Inspection of cell 11 (source: I-Tech7).

Image 2: Crack indication on dome top (source: I-Tech7).

5 Potential of the incident

Actual consequences

Equinor has estimated that the incident spilt about 150 m^3 of oil and sludge to the sea. This volume is based of the amount of liquid led via CD2119 to cell 11 during the time the spill lasted. Density differences between oil and water mean separated oil will accumulate at the top of the cell, where the crack was identified by ROV, and the spill therefore probably comprised mostly oil. The slick on the sea surface was described as a thin film, and too thin for mechanical recovery to be effective. Mechanical dispersion was assessed as the best method of combating the spill.

Image 3: Oil on the sea, 26 November 2019 (source: NCA LN-KYV).

The closed ballast-water valve on cell 11 meant that produced water could not flow into the cell backed up in the piping system. That in turn increased internal pressure fairly quickly to sea level (where the cell's internal-external pressure difference is equalised). Continued filling raised the internal pressure above the ambient level. Material tension in the concrete therefore changed from compression to tensile. Concrete has very little tensile as opposed to compressive strength. Should cracking have occurred during the construction process or through erosion, shrinkage or loads, existing hairline cracks will open. If the concrete has no previous cracks or openings, it can withstand a small tensile load before cracking. The internal overpressure in cell 11 meant that either existing cracks opened or new ones were created. When reinforced concrete cracks, the prestressing steel will still be able to withstand the tensile load and the structure will not collapse as a direct consequence of concrete cracking. The cracks observed by ROV after the incident are located in the dome close to the transition to the vertical cell wall (see image 2). The image shows no sign of splintering or loss of any noteworthy material – the crack appears to have closed to a residual trace.

Appendix F to Equinor's investigation report states: "The hairline cracking caused to the structure will reduce the concrete's strength and elasticity module. However, this need not necessarily cause any structural weakening of significance for its function. The residual strength in the concrete should be adequate. Possible open hairline cracks can self-heal". Based on Equinor's experience from the earlier incident on Statfjord C mentioned above, the PSA team considers this to be correct with regard to the function of establishing an impermeable concrete shell between sea and oil for the cell. Equinor's report also states that water leaking into the cell (after the incident was halted and underpressure re-established) was declining, which indicates that the crack had closed. Where structural function is concerned, distributing the load from shafts to seabed is primarily done by the vertical walls of the cells. Since these have not displayed damage and are analysed to have greater capacity than the dome, the investigation team takes the view that Equinor's conclusion is also correct with regard to the structural function of the damaged cell.

Overpressure in the concrete cell

The difference between sea level and highest liquid level in the piping system directly indicates the highest overpressure experienced by the concrete cell on 26 November.

According to the original DFI documentation, the first year's water level in relation to the underside of the steel skirt was 151.3 metres (147 metres of water depth plus 4.3 metres of penetration and settlement in year one). The level is given by the platform's elevation, from the underside of the skirt to the lowest astronomical tide (LAT). Low tide would mean a more undesirable effect from overpressure in the concrete cell and is thereby regarded as a conservative reference point for overpressure in the incident.

The DFI specifies an expected long-term settlement of 700 millimetres. In meetings with the Statfjord operations organisation in 2018, the PSA was told that the measured settlement was then 750 millimetres. The 2019 water level on the structure was thereby 152 metres LAT.

In the DFI and drawings, the base of the topside is shown to be at level 175 metres. The air gap in 2019 was thereby 175-152 ≈ 23 metres. The cellar deck is two metres above that at 177 metres – 25 metres above sea level. Overpressure in cell 11 was thereby 2.5 bar (25 metres) when the liquid had climber to the deck plates at the lowest point on Statfjord A.

The fill ratio in the enclosed CD5486 A and B drain tanks on the cellar deck began to increase around 06.00 on 26 November, when there was an overpressure of at least 2.5 bar in cell 11. After the incident, the level in the tanks declined and was back to normal by 10.00. In other words, the concrete was subject to at least 2.5 bar overpressure for four hours on the day of the incident.

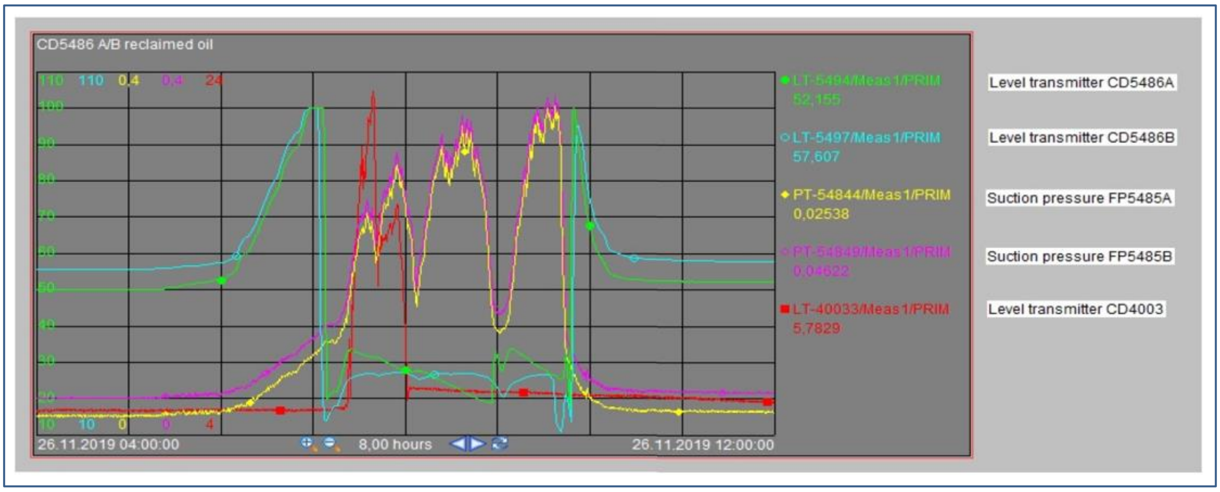

Figure 8 Level and pressure gauges in the relevant tanks. The graph extends over eight hours, from 04.00 at far left to 12.00 at far right. CD4003 fill is shown by the red curve, which reaches maximum value at 07.40. Levels in CD5486 A and B are the blue and green curves, which parallel each other to 07.00 and fall again a little before 10.00. The big jump from 07.00 to kl. 10.00 most probably reflects measurement error because the instruments were submerged in liquid and measured reflections within it rather than from the surface (source: Equinor).

Maximum overpressure is calculated to have occurred at 07.40, when the level gauge in the vent knockout drum (CD4003) showed 23 per cent full. According to the information in figure 6, the underside of CD4003 is at the 179-metre level and the highest point of the inlet pipe to CD4003 is at 186 metres. That indicates the highest pressure was 186-152 = 34 metres or 3.4 bar. Liquid was measured in the knockout drum from about 07.20 to 08.00 – in other words, with an overpressure of about three bar for roughly 40 minutes.

Figure 8 illustrates how internal liquid pressure caused overpressure in the whole of cell 11. The crack(s) in the concrete created contact between external seawater and internal oil. Overpressure was thereby (partially) bled off, in that oil leaked out through the crack(s). The curves for the tank levels fluctuated during the hours the leakage lasted, and these fluctuations probably correspond with variations in the oil leakage rate through the crack(s) on the concrete cell dome.

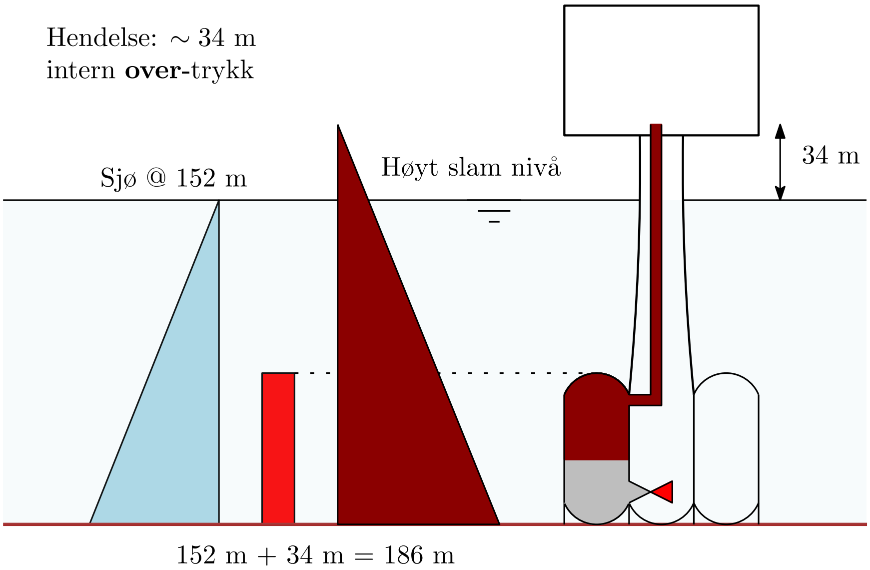

Figure 9 Illustration of the maximum overpressure in cell 11 on the incident day. Note that the upper level for pressure in the sludge system is based on the liquid column at the highest point in the piping run from CD5486 A and B to CD4003.
Key: Incident: about 34 m internal overpressure; Sea level about 152m; High sludge level.

Potential consequences

CCR personnel did not equate the liquid level alarms in CD5486 A and B with overfilling. If the transfer to sludge cell 11 had been carried out earlier that evening/night, oil and sludge would probably have leaked undetected until daylight. The spill would then have been larger, depending on the time from concrete cracking to observation of oil on the sea.

In the days following the incident, Equinor introduced weather-dependent manning reductions for Statfjord A because the condition and loadbearing capacity of the GBS were not known. The reason was specifically that uncertainty prevailed about whether concrete damage to cell 11 might be in areas where the prestressing steel for the shafts was anchored. The relevant anchorages are located both on the cell domes and between the cells. The prestressing steel is essential for maintaining compressive stress in the shafts. Later ROV observations showed no signs of cracking in the relevant areas, and Equinor dropped the temporary weather criterion for manning reductions. The potential consequences if the steel had been damaged would probably have been a permanent manning-reduction criterion for the rest of the facility's producing life. With extensive damage, this criterion could have meant substantial downtime, particularly during the winter.

Equinor's experience after the incident was normalised indicates that the crack(s) have largely closed and stayed sealed. Had the incident resulted in a crack which lost material and created a hole in the concrete, it might have been impossible to restore the underpressure which is a precondition for the structure's loadbearing capability throughout cell 11. A hole could have might a much larger oil discharge (the cell has a volume of about 18 000 m^3). If the underpressure could not be restored, cell 11 would have had to be isolated, structural integrity would have had to be reanalysed and possible weather restrictions could have been imposed for manning and operation.

6 Direct and underlying causes

The direct cause of the incident was opening the sludge valve to fill cell 11 with the ballast-water valve in the closed position. The sludge valve was opened in line with the routine of transferring between the sludge cells every 14 days. Ballast-water valve HV3124 was closed to deal with a hydraulic leak on the actuator. That led to overfilling and overpressurising in cell 11 and cracking in the cell dome.

Underlying causes can be related to the following.

Absence of barriers and system vulnerability
When making technical modifications for changing storage cells to sludge cells and operational changes by filling only one sludge cell at a time, the lack of barriers and the risk of a single error eliminating the barriers were not identified.

No pressure alarm or other information was available which could have informed operators in the CCR or the shaft that the cell was being overpressurised so that this could be corrected.

Inadequate risk and system understanding when planning maintenance
Maintenance planning for ballast-water valve HV3124 failed to take adequate account of the risk elements which closing the valve could involve. The valve and blind list was not used, for example, and the inlet valve to cell 11 on the sludge manifold was not marked. The operators therefore had to remember that the ballast-water valve to cell 11 was shut and that cell 11 must not be used until it was reopened. This became particularly challenging when the valve remained closed over a long period because maintenance work on HV3124 was postponed owing to missing spare parts. The incident occurred 12 days after the valve was shut. Marking valves included in an isolation in the field is crucial for safe operation of a process plant.

The WO for the maintenance activity was categorised as level 2, and risk elements related primarily to personnel exposed to hydraulic oil and the danger of slipping on an oily deck.

Although its functions include preventing overpressure in the cells, the ballast-water system is not defined as a safety system. Equinor has strict routines for disconnecting safety systems. In this case, the ballast-water system has a similar function to the flare system in the process plant. If the same established routine for isolating the flare system had been followed with the ballast-water system, necessary barriers – including the valve and blind list – would have ensured that no overpressure occurred in the sludge cell.

The “envelope” placed on the screen to remind CCR operators that the ballast-water valve for sludge 11 was closed had been moved away at some point. It was therefore no longer clear that this “reminder” related to sludge cell 11.

The CCR does not react to high-level alarms, since these are not unusual and do not normally require action by the CCR operator. This is because a parallel overflow in the tank allows the water to run out and down to the tank if the level gets too high.

Personnel in the Statfjord A organisation both on land and offshore had an inaccurate perception of overpressure protection in the storage cells. There was an understanding that the cells were fitted with a plug which would bleed off cell pressure to the sea if it became too high. This is not the case. Overpressurising the cell has more serious consequences than the organisation realised. Its understanding of the consequences of overpressurisation could have influenced risk assessment and planning of the job.

The organisation both on land and offshore was insufficiently aware that there had been a similar incident on Statfjord C, where a storage cell was overpressurised and consequently suffered cracking.

Inadequate system and operating documentation
Neither the system description of the sludge cells and the ballast-water installation nor the operation documentation has been updated to reflect the technical and operational changes. That includes a lack of process flow diagrams giving a good overview of the sludge cells and their connection to the process plant and ballast-water system. This could have made it hard to obtain an overview of the system and affected planning of repairs to the ballast-water valve.

7 Emergency response

The Statfjord A response organisation tackled the incident on the basis of DSHA 02 – Oil spill. Copies of the oil spill response action plan (Polwarn) and oil spread information (Polinfo) were obtained by the PSA from the NCA, which was responsible for following up and coordinating the oil spill response.

The investigation has not assessed Equinor's emergency response to the oil spill.

8 Regulations

The 2007 application to extend Statfjord A's producing life stated that operations were based on the technical requirements in the HSE regulations adopted in 2002.

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.

9.1 Nonconformities

9.1.1 Inadequate process safety system against overpressure in sludge cells

The process safety system on Statfjord A is inadequate for preventing overpressurisation of the sludge cells.

Grounds
If an error causes pressure to rise in the sludge cells, the process safety system will be unable to detect this increase or to prevent overpressurisation. The regulations require two independent safety levels against overpressurisation. No provision is made for pressure detection in the sludge cells, alarms in the CCR or automatic shutdown if pressure exceeds the permitted level.

Requirements
Section 34 of the facilities regulations on the process safety system
Section 8 of the facilities regulations on safety functions

Section 5 of the management regulations on barriers

9.1.2 Inadequate risk and system understanding when planning maintenance work on the ballast-water valve

Maintenance planning for ballast-water valve HV3124 failed to take sufficient account of the risk elements which could be involved in closing it.

Grounds
The WO was set to level 2, and risks identified related primarily to personal doing the work.

Despite not being necessary, the ballast-water valve was closed. Maintenance of the actuator (hydraulic system) could have been carried out with the valve either open or closed. Because the valve could not be operated during maintenance, the best course was assessed to be closing it before work started.

The valve and blind list was not used, and the inlet valve to cell 11 on the sludge manifold was unmarked. Despite being intended in part to prevent cell overpressurisation, the ballast-water system is not defined as a safety system. If the same established routine for isolating the flare system had been followed with the ballast-water system, necessary barriers – including the valve and blind list – would have ensured that no overpressure occurred in the sludge cell.

Personnel in the Statfjord A organisation both on land and offshore had an inaccurate perception of overpressure protection in the storage cells. There was an understanding that the cells were fitted with a plug which would bleed off cell pressure to the sea if it became too high.

The organisation both on land and offshore was insufficiently aware that there had been a similar incident on Statfjord C, where a storage cell was overpressurised and consequently suffered cracking.

Requirement
Section 29, paragraph 1 of the activity regulations on planning

9.1.3 Lack of safeguards on safety-critical valves

Safety-critical valves are not adequately secured to prevent erroneous operations which could result in overpressurisation.

Grounds
When preparing to isolate sludge cell 11, no isolation plan was produced to ensure that the valves isolating sludge cell 11 from the sludge manifold were marked in the field to prevent erroneous operation.

Valves connecting the sludge cells to the ballast-water system were not secured in accordance with Equinor’s requirements in TR2315. The guidelines require that isolating valves in pressure blowdown lines are locked in the open position. Where the sludge cells are concerned, this applies to the valves which can isolate the sludge cells. Documentation received by the investigation shows two valves which can isolate these cells – one manual and the other hydraulic, which is operated from a control panel in the utility shaft. The manual valve is not locked in the open position. A “car seal” is used. For its part, the hydraulic ballast-water valve has no protection against faulty operation. All hydraulic ballast-water valves, to both sludge cells and cells for oil storage, are operated from the same panel. No safeguard is provided against erroneous operation of the sludge cell valves, and no indication is given that these – unlike the other ballast-water valves – are particularly critical with regard to overpressurisation.

Feedback from conversations is that the ballast-water system is not defined as a safety system, even though one of its functions is to prevent overpressurisation.

Requirements
Section 4 of the management regulations on risk reduction
Section 10, litera a of the facilities regulations on installations, systems and equipment

9.1.4 Inadequate system description and operation documentation

The SO documentation has not been updated with technical and operational changes following modification of the oil storage cells to sludge cells. No process flow diagrams are available, for example, which provide a good overview of the sludge cells and their connection to the process plant and the ballast-water system.

Grounds
The regulations require that governing documentation, including technical operation documents, during operation must be updated and familiar to operating personnel. As part of the investigation, the team has received an overview of Statfjord's specific SO documents which are to be updated. These include the systems for oil storage, ballast water and sludge (systems PB and UJ).

Requirement
Section 20, litera b of the activities regulations on start-up and operation of facilities

9.2 Improvement point

9.2.1 Deficiencies in own follow-up

Equinor's own follow-up has failed to identify that process safety for the sludge cells is inadequate.

Grounds
Through conversations and documentation received, it has emerged that the condition monitoring of technical safety (TTS) conducted on Statfjord A has failed to identify inadequacies in process safety for the sludge cells. Since several TTS have been conducted on Statfjord A, this suggests that weaknesses exist in the systematics for implementing such verifications which meant that this did not get picked up.

Requirement
Section 21 of the management regulations on follow-up

10 Barriers which have functioned

Discharges of oil and sludge ceased when the flow to sludge cell 11 ceased and produced water was transferred to sludge cell 13. The transfer back to sludge cell 13 was done manually from the control panel in the utility shaft.

11 Discussion of uncertainties

According to Equinor's investigation report, the discharge lasted about four hours. It ceased when the flow of produced water was transferred back to sludge cell 13 at about 09.45. This indicates that cracking in the cell dome occurred around 06.00. In its description of the course of events, however, the Equinor report states that discharge from sludge cell 11 to the sea began at 07.03.

The discharge may have started around 05.15 when high level was reached in drainage tanks CD5486 A and B.

The amount of overpressure caused in concrete cell 11 is not precisely known. Its size is directly related to the difference between

1. how high the liquid level rose in piping and tanks on the facility, and
2. how high the ambient seawater pressure was at the time of the incident.

In its investigation report, the operator writes that the seabed has subsided by 3.8 metres since Statfjord A was installed and uses this to adjust the amount of overpressure. Equinor believes it was 2.6 bar, as shown in figure 6. The PSA has earlier been informed that the facility had a measured subsidence of 750 millimetres in 2018 (which corresponds with expectations in the DFI documentation from the design period).

12 Assessment of the player's investigation report

The investigation team received Equinor's investigation report on 6 March. The latter was commissioned at level 2 in line with the company's applicable guidelines for investigating accidents. On the basis of Equinor's classification system, the incident is classified with the highest actual level of seriousness: *Actual Red – 2 Oil spill*, and highest possible level of seriousness under slightly different circumstances: *Actual Red – 2 Oil spill*.

Equinor's investigation finds that the incident did not have a major accident potential.

The investigation concludes that the direct cause of the oil spill to the sea was overfilling and overpressurisation of sludge cell 11. The three most important underlying causes are given as lack of a risk assessment and/or Hazop when changing the sludge system in 2012, failure to ensure system understanding and process safety of sludge cell 11, and the unsuitability of the SO documentation to serve as applicable governing documentation or for use in training new personnel.

Four action areas for learning are identified by the investigation.
Action area 1 – related to implementation of risk assessments.
Action area 2 – related to documentation and procedures.
Action area 3 – related to technical upgrading of Statfjord A.
Action area 4 – related to facility-specific expertise and compliance with requirements.

The investigation team finds that Equinor's report describes the direct and underlying causes of the incident, and that it recommends measures which address the causes. Its findings largely coincide with the team's observations.

13 Appendices

A: The following documents have been utilised in the investigation.

Equinor

1. Presentation from meeting, 9 December 2019
2. Minutes from meeting, 9 December 2019
3. Work order 24993459 – hydraulic leak HV 3124
4. Timp assessments for the PC system (sludge and reclaim), PB system (crude) and UJ system (permanent and temporary ballast water)
5. Principle for level measurements in storage cell 11
6. System PB, UJ – *Lagring av råolje og ballastvann – Systembeskrivelse,* SO00198, final version 5, valid from 9 September 2016
7. System PB, UJ – *Lagring av råolje og ballastvann – Operasjonsbeskrivelse*, SO00198-Opr, final version 1, valid from 9 September 2016
8. Images from Statfjord A in connection with discharge to the sea
9. Feedback concerning incident with oil spill Statfjord A, 26 November 2019, e-mail, 4 December 2019
10. Minutes, video meeting, 29 November 2019
11. Action points from video meeting, 27 November 2019, e-mail dated 28 November 2019
12. Graphs level measurement and pressure CD5486 and level measurement CD4003
13. Figure pressure measurement reclaimed oil
14. Principles for level measurement, storage cell 11
15. PI&D for CD2119, reclaimed oil, oily water, cargo pumps, ballast water in and out
16. DFI Statfjord A GBS Concrete structures, AP-BE-S-RE-011
17. GBS - Summary report
18. Utility shaft plant arrangement
19. Topside south view, north view and east view
20. Risers, J-tubes and shale chute layout
21. Piping plan top dome
22. GBS general view
23. Cellar deck plant arrangement
24. Cell heights and elevations
25. Foundation and Condeep structure
26. Images from the PSA's inspection, Statfjord A, 16 December 2019
27. R-101833 – Securing important valves in the correct position
28. *Valve locking, interlocking and other position securing systems*, TR2315, final version 5.02, published 9 May 2019
29. Timp PS 12 process safety, dated 16 October 2019
30. *Standard utviklingsplan for prosessteknikere SFA Utstyrsskaft*
31. E-mail dated 10 January 2020
32. TTS documentation for systems relevant for cell 11 (including PC, PB and UJ)
33. *Engineering flow diagram – Statfjord C crude storage and loading system storage cell group 1,* CP-U00-ZE-001.001, rev B11, 30 October 2019

34. *Statfjord C System PB, UJ – Normal drift – Operasjonsprosedyre*, SO-00183-Opr, final ver 1.01, valid from 15 September 2017
35. *Statfjord C System PB, UJ – Normal oppstart – Operasjonsprosedyre*, SO-00183-Opr, final ver 1.01, valid from 15 September 2017
36. *Statfjord C System PB, UJ – Normal nedstenging – Operasjonsprosedyre*, SO-00183-Opr, final ver 1.01, valid from 15 September 2017
37. *Statfjord C System PB, UJ – Bruk av miniballasttank CT3102 som reguleringstank for ballastvann – Operasjonsprosedyre*, SO-00183-Opr, final ver 1.01, valid from 15 September 2017
38. *Statfjord C System PB, UJ – Fylling av råoljelagercelle – Operasjonsprosedyre*, SO-00183-Opr, final ver 1.01, valid from 15 September 2017
39. *Statfjord C System PB, UJ – Oppfylling av permanent ballastvannsystem – Operasjonsprosedyre*, SO-00183-Opr, final ver 1.01, valid from 15 September 2017
40. *Statfjord C System PB, UJ – Tømming av permanent ballastvannsystem – Operasjonsprosedyre*, SO-00183-Opr, final ver 1.01, valid from 15 September 2017
41. *Statfjord C System PB, UJ – Tømming av råoljelagercelle – Operasjonsprosedyre*, SO-00183-Opr, final ver 1.01, valid from 15 September 2017
42. *Statfjord C System PB, UJ – Lagring av olje og ballastvann, Systembeskrivelse*, SO-00183, final ver 8, valid from 21 October 2015
43. Work order 24993459 Hydraulic leak from actuator C1
44. Images of hydraulic panel for operation of ballast valves (level 55m)
45. Shift log 19 November 2019 – CCR
46. Log for transfer and gas bleeding of sludge cells 2019 – table for transferring sludge cells
47. Work order 24618131 HV3124 hydraulic leak, established 18 November 2018
48. Registration for transfer and gas bleeding of sludge cells 2019, January-September
49. Image of hydraulic panel for ballast valves
50. E-mail dated 4 February 2020
51. Printout handover between shifts operations 25-26 November 2019
52. Printout action log for AO24993459
53. Printout from safety study Statfjord A conducted 1989
54. Exemption 159670: *Endring i krav til hvilke systemer som skal ha teknisk systembeskrivelse* (S document) and appendix to exemption application TR2381 for EPN
55. E-mail dated 18 February 2020
56. Statfjord systems which will be provided with updated system documentation
57. Image of log for transfer and gas bleeding of sludge cells 2019
58. Investigation report *Oljeutslipp fra sludgecelle på Statfjord A 26.11.2019*, A 2019-22 DPN L2, 11 February 2020
59. E-mail dated 14 April 2020
60. Operations follow-up of structures and marine systems, operations south, presentation from meeting 15 November 2018

Deepocean

1. IMR-19-622-Statfjord A-Leakage inspection, Cell 11, NO.E111111-ENG-REP-206, rev A, date 29 November 2019

I-Tech7

1. Statfjord A – Leak inspection cells, ESIS-IMR-19-637-EJR-01, rev 01, date 14 December 2019

Kværner

1. *Statfjord A Ulykkeslast: indre overtrykk i celle 11*, date 29 November 2019
2. Memo – Statfjord A *Overtrykk og lekkasje på celle 11 – strukturell vurdering*, AP-PB-S-RE-001, rev 1, date 19 December 2019

Mobile Exploration Norway Inc

1. *Simm: Structure Inspection Maintenance Manual, Statfjord A, Concrete Structure – Risers & Marine Pipeline*, volume 3, book 1 of 1. Revision no 1, April 1986.

Det norske Veritas, Industrial and Offshore Division

1. *DFI: Design, Fabrication and Installation Resumé, Statfjord A – Concrete Structures*. Veritas report no 54 28 05 A, 30 May 1979.

Statoil ASA

1. Consent application producing life extension SFA, SFLL-RA 00160, rev 0, 30 March 2007

B: Overview of personnel interviewed (separate document)

C: Schematic overview of the course of events (separate document)