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IN SERVICE EXPERIENCES WITH SHIP-SHAPED FLOATING PRODUCTION UNITS

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ABSTRACT

FPSOs and FSOs have been used on the Norwegian continental shelf for petroleum production, storage and offloading since the 1980's and have been increasingly common since the end of the 1990's. During these years a significant amount of experience has been gathered.

On the Norwegian Continental Shelf (NCS) shipowners and operators are obliged to report damages and incidents to the Petroleum Safety Authority Norway (PSA).

This article gives an overview of reported incidents related to the structural and maritime systems on offshore ship shaped units in the petroleum activity (FPSOs and FSOs) on the Norwegian Continental Shelf. Reported incidents are summarised with a focus on the period 2000 to 2019. The incidents include cracks, dents, corrosion, turret incidents, green water, position keeping systems, stability and ballasting, collisions and incidents related to the offloading systems as reported by operators and shipowners to the PSA.

A summary of the reported damages and incidents are discussed with respect to common causes based on available data. The importance and the possible consequences of such incidents are further discussed.

Keywords: FPSO, FSO, spar buoy, cracks, dents, turret, green water, mooring, heading control, stability, ballasting, collisions and offloading.

INTRODUCTION

Two articles describing the floating production unit experiences were published by Ersdal and Kvitrud (2000) and Leonhardsen et al (2001) with the aim of providing the industry and researchers data from incidents and accidents on the Norwegian continental shelf. The intention of this paper is to provide an update to these papers with more recent experiences.

All data used in this paper is based on the incidents reported by operators to the Petroleum Safety Authority Norway (PSA). The data is mainly based on the PSA's CODAM and RNNP databases. In addition, some data is taken from other types of communication with operators.

17 floating production and storage units (FPSOs and FSOs) have been in operation on the Norwegian Continental Shelf in the period of 2000-2019, see Figure 1, representing approximately 210 platform years in this period. A short description of each of these units are provided in Appendix B.

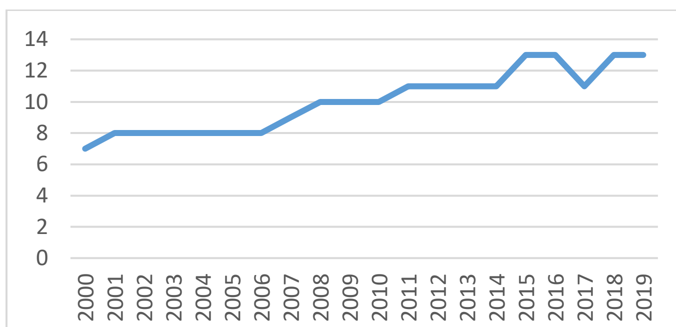

FIGURE 1: THE ANNUAL NUMBER OF FPSOS AND FSOS ON THE NCS IN THE PERIOD 2000-2019.

REQUIREMENTS IN REGULATIONS

The oil and gas activities on the Norwegian continental shelf is regulated by PSA (framework, management, facilities and activity regulations). The safety of structures and maritime systems is regulated by the PSA facilities regulations and for mobile facilities the Norwegian Maritime Authority's (NMA) regulations are optional. PSA facilities regulation allows the use

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of NORSOK standards for structures and NMA regulations for maritime systems.

The relevant technical requirements in the NMA regulations for mobile facilities with supplementary accepted classification rules (DNV GL, ABS and Lloyds Register) can be used for facilities registered in a national ship register.

In addition to flag state certification Norway requires all mobile units to have an acknowledgement of compliance (AoC) from the PSA where the owners shall document the present status of the unit in accordance with the present requirements. FSOs are exempted from the requirement of an AoC.

The competence requirements to personnel handling maritime systems such as DP, anchoring, ballasting and stability shall be in accordance to the NMA requirements for the corresponding personnel on mobile offshore units. The competence recommendations for maritime operations were introduced in the PSA operational regulation in 2002. These includes:

- central control room (CCR) operators,
- the person responsible for the stability,
- the person responsible for DP operations on FPSOs.

CRACKS

All ship shaped FPSOs and FSOs on the NCS are fabricated and built based on the same methodology, and with the same type of structural details as conventional tankers.

Ship structures are very exposed to fatigue caused by cyclic loading and in some cases enhanced by fabrication defects and residual stresses. This is due to the thousands of local details in the hull girder, like scallops, slots, lugs, air-holes, cut-outs, doubling plates, penetrations and bracket-toes.

In addition, traditional double hull tankers will have a significantly more complex load situation compared to, for example fixed offshore structures (jackets). These include local loads on the side shell and bottom structure such as:

- Large external and internal static differential pressures.
- External dynamic pressures and slamming loads due to wave actions.
- Variable internal dynamic pressures due to the motion characteristics of the unit.

Similarly, local loads on the longitudinal bulkheads, transverse bulkheads and inner bottom will include:

- Static differential pressures.
- Internal dynamic pressures caused by the motion characteristics of the unit.
- Sloshing loads caused by wave actions.

Further, the global hull girder static and dynamic response will cause alternate hogging and sagging condition in the hull girder due to the respective loading conditions and wave action, especially in the bottom and main deck structure. In addition, effects from springing and whipping are known to cause fatigue damage and cracks on for example bulk carriers. However, cracks caused by such vibration in the hull girder have not been reported so far for FPSOs and FSOs.

All these global and local loads will result in high dynamic stresses in the hotspots of the structural details mentioned above.

The common structural details of the main loadbearing structure in the ballast- and cargo tanks that are vulnerable to high stresses will normally be transverse girder bracket toes, upper- and lower hopper knuckle areas, cross-tie end connections, stringer bracket toes and corresponding heel connections. In hostile weather conditions even the bilge keel, deck longitudinal and side longitudinal connections to transverse frames, bulkheads and adjacent plates can be vulnerable to fatigue cracks.

The largest differences between offshore units (FPSOs and FSOs) and conventional tankers are normally that offshore units:

- are continuously loading and discharging in a variety of sea states,
- have more global load cycles,
- are weather vaning, meaning that the bow is constantly pointing towards the dominant weather,
- have no possibilities to avoid severe sea states,
- have a discontinuity on the bottom and/or main deck due to a moonpool,
- have large loads that are transferred from the topside, the mooring system, cranes and the flare to the hull girder,
- need repair work in tanks normally to be done in situ in unfavourable conditions, such as humid conditions and poor access,
- are normally designed based on site specific wave statistics with a 100-year return period, while tankers are normally designed for the North Atlantic wave statistics based on a 25-year return period.

These differences may cause cracks at different locations for offshore units compared to conventional tankers. However, since the hull structural details are similar, apart from discontinuities by means of moonpools, cracks are normally expected to develop for the same structural details with some deviations caused by the differences stated above.

For the purpose of this paper some additional cracks are included as reported by operators outside the CODAM database. These cracks are marked with an *) in the figures in this paper. Incidents and inspection findings in CODAM are to be classified into one of three severity levels; insignificant, minor or major. The severity levels are based on the operator's subjective evaluation and may differ between operators.

The severity levels are defined for ship shaped units as:

- major severity: cracks that may threaten the integrity of the main loadbearing structure or the hull girder within 0.4 L (ship length) amidships or in the moonpool area,
- minor severity: penetrating cracks in the side shell, bulkheads, tanks or in primary loadbearing structures, or cracks that are not defined as major severity,
- insignificant severity: minor cracks in secondary structures, at corners of cut outs, slots and similar details, or cracks that are not defined as minor severity.

As can be seen from Figure 2, a total of 494 cracks are reported for the 17 units between 2000 and 2019. 466 are classified by the operator as cracks of minor severity while 26 are classified as cracks of insignificant severity. Only two cracks are reported to be of major severity, in 2000 and 2013 respectively. These classifications are based on the operator's subjective evaluation and have not been quality controlled by the authors.

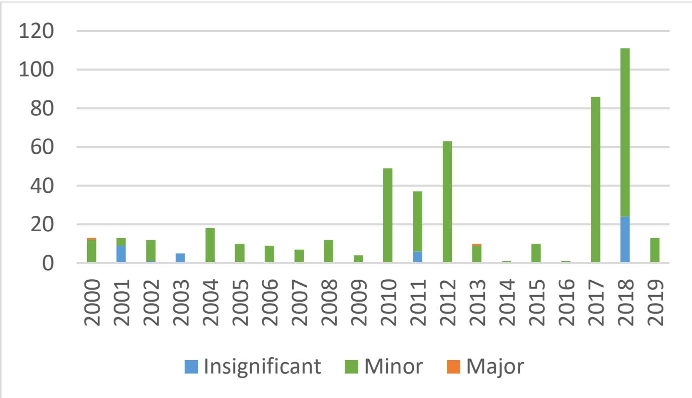

FIGURE 2: THE CRACK AS CLASSIFIED INTO CLASSES OF SEVERITY PER ANNUM ON ALL 17 PRODUCTION UNITS ON THE NCS IN THE PERIOD 2000-2019. NOT NORMALIZED.

Figure 3 identifies reported cracks on FPSOs / FSOs in the period 2000 to 2019 which are normalized by yearly numbers of units in active operation indicating an average of approximately four cracks yearly per unit. Some peaks can be identified and this may be caused by inspection campaigns or winter seasons with harsh weather. Several of these FPSOs have been life extended causing enhanced inspection campaigns and some correlation with these life extension projects has been identified.

Figure 4 identifies cracks on all units given by location in the hull. Most of the cracks are in

- ballast tanks located in the stiffeners in the longitudinal side shell connection to transverse frames,
- bulkheads (bracket toes, lugs and slots) in the weld between the side shell and the longitudinals.

The same also applies to cracks reported in the bow area. Many cracks are also reported in void spaces in the fore and aft ship, such as cofferdams, engine rooms and pump rooms. Many of these cracks are located in the corner of door openings and are normally caused by a small radius in the corners of the cut-outs and often in combination with a reduced effective shear area in the bulkheads of the hull girder.

Few cracks are reported in the main deck, in the cargo area and the bulkheads between cargo and ballast tanks. However, cracks have been reported in the knuckle lines of the inner side longitudinal bulkhead causing extensive repair work for an FPSO in 2004.

A closer study was done on crack lengths and crack appearances as a function of the year for the six FPSOs and FSOs with most reported cracks. The crack lengths are identified in Figure 5, while the crack appearance as a function of the year are reported in Appendix A.

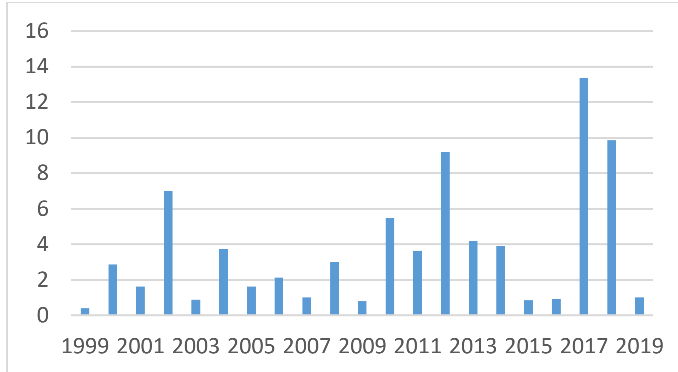

FIGURE 3: THE ANNUAL NUMBERS OF CRACKS*) ON ALL 17 PRODUCTION UNITS NORMALIZED BY NUMBERS OF UNITS IN ACTIVE OPERATION THE ACTUAL YEAR.

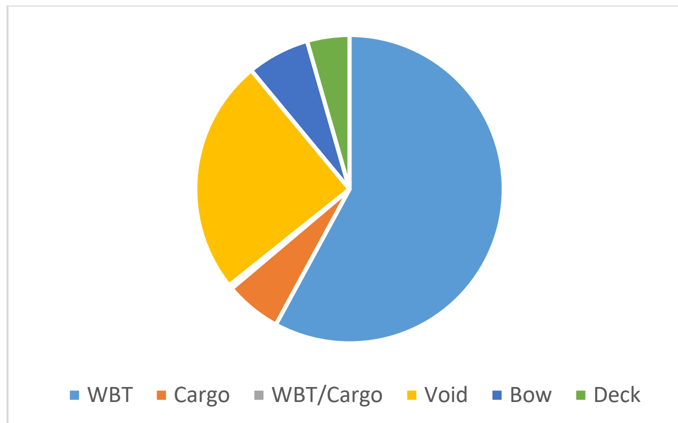

FIGURE 4: CRACKS ON ALL 17 PRODUCTION UNITS GIVEN BY LOCATIONS OF THE CRACKS. NOT NORMALIZED.

As can be seen on Figure 5 many of the operators have failed to report the crack length or other vital information. However, most of the reported cracks have a length between 25 and 500 mm, while a few are reported to have a length less than 25 mm. In 2004, 2007 and 2018 several cracks have been reported to have a length more than 500 mm. These cracks have been reported to be in the main deck (2 cracks), water ballast tanks (WBT) (10 cracks), between the WBT and cargo tanks (2 cracks), bow (1 crack) and the void spaces (10 cracks).

Most of the cracks are reported to be caused by fatigue, but in recent years the operators have also specified design or a combination of design and fabrication as the primary causes of the cracks.

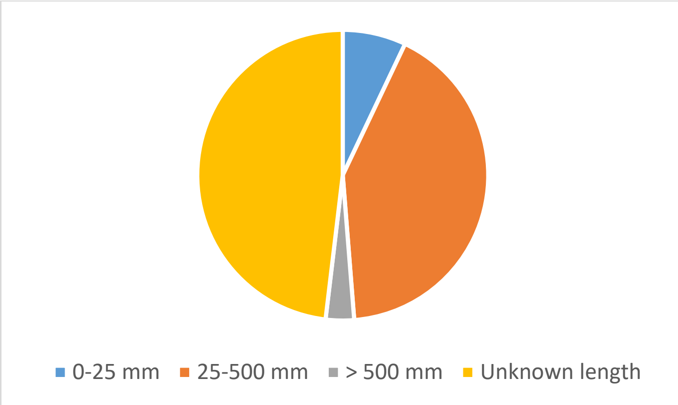

FIGURE 5: MEASURED CRACK LENGTH*) ON SIX UNITS.

Detailed figures for cracks in the six selected units as described below are provided in Appendix A.

FPSO 1 was in service from 2001 to 2013. She was refurbished in 2000-2001 and many outer hull plates and details were changed. The vessel was 27 years old when it left NCS. A total of 173 cracks were reported, most of which in the last three years of operation. They are probably caused by an old and unsatisfactory design, unfavourable details and fabrication errors, combined with the age of the unit.

FPSO 2 has been in service on the NCS since 2001. A total of 229 cracks have been reported for this unit. Most of the cracks were reported in the last seven years of operation. There is a weak trend towards increase with age, but the number of cracks detected can also be caused by inspection campaigns or harsh weather in the winter season 2013/14 and 2014/15.

FPSO 3 has been in service on the NCS since 2000. A total of 184 cracks have been reported for this unit. Most of the cracks were reported in 2003 and in the last two years. There is a weak trend towards a “bath tube” curve, but the number of cracks detected can also be caused by inspection campaigns and the tail of the “bath tube” curve can be caused by harsh weather in the winter 2013/14 and 2014/15 as shown in Figure 6.

FPSO 4 has been in service on the NCS in the entire period since 2000. A total of 150 cracks have been reported for this unit. Most of the cracks were reported in 2017 and 2018. There is a weak trend towards an increase with age, but the number of cracks detected can also be a result of inspection campaigns or harsh weather in the winter 2013/14 and partly 2014/15 as shown in Figure 6.

FPSO 5 has been in service on the NCS in the period from 2000 to 2016. A total of 18 cracks are reported for this unit. Most of the cracks were reported in 2015. No trend is observed indicating that ageing effects are present.

FPSO 6 has been in service on the NCS since 2011. A total of 26 cracks have been reported for this unit. Most of the cracks were reported in 2017. These cracks are related mostly to sharp corners of door openings and cut-outs and often in combination with a reduced effective shear area in the longitudinal bulkheads of the hull girder. This peak in the number of cracks in 2017 can be caused by a combination of a possible inspection campaign, unfavourable structural details and the harsh weather in the winter seasons 2013/14 and 2014/15 as shown in Figure 6.

Fatigue damage will vary in different years depending on the severity of the annual wave conditions. This can be calculated in a simplified form by summing the damage from each sea-state. The damage is set as a function of the significant wave height and associated period (the method is further described in Ersdal (2005)). Figure 6 gives the relative generic accumulated fatigue damage for a structural detail in an FPSO based on the NORA 10 hindcast data (Reistad et al., 2011). As can be seen from Figure 6 the fatigue damage in the worst years is a factor of 2 greater than the mildest years which may have a significant effect on the number of cracks found.

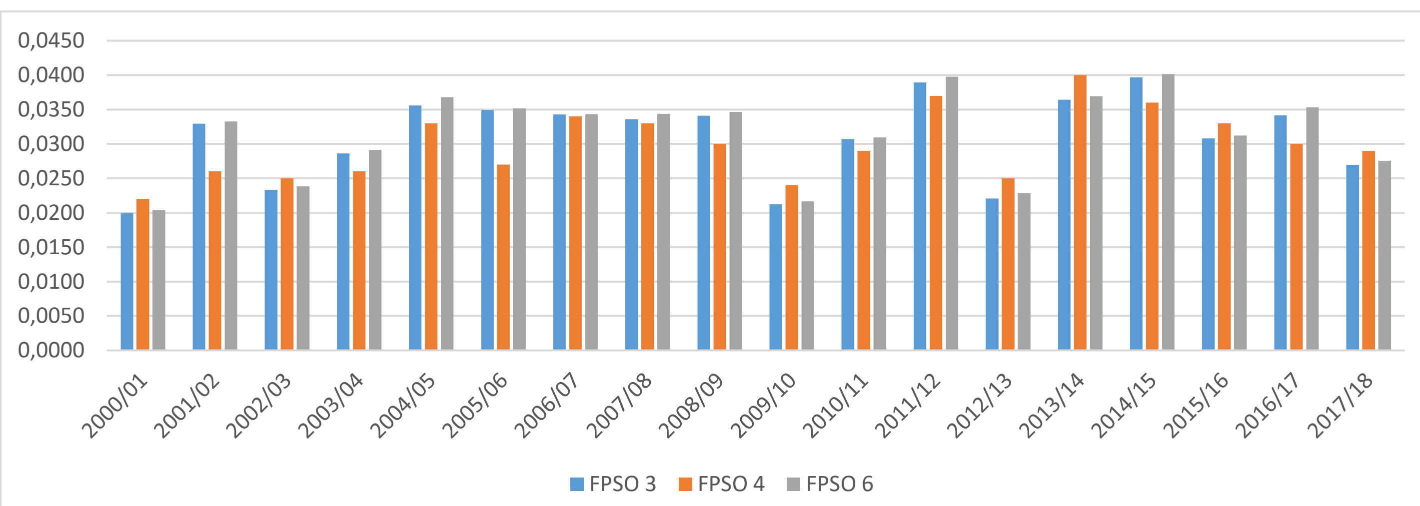

FIGURE 6: RELATIVE ACCUMULATED FATIGUE DAMAGE OF THREE FPSOS BASED ON SEASONAL HINDCAST DATA (JULY TO JUNE) FROM 2000-2001 TO 2017-2018.

DENTS FROM WAVE ACTIONS

Dents and deformations in ship structures are normally caused by wave impacts, wave slamming or impacts from supply vessels. Dents caused by ship impacts are covered in the section on collisions. A few dents and damages to structural elements in the hull have been reported due to wave action. The reported cases are:

- damage of bow stringers 25-27 m above the keel level of an FPSO due to wave impact during a storm in 2005. The maximum wave height at the time was reported to be approximately 23 m,
- dents was reported on another FPSO located in the same area and in the same storm. The dents were caused by wave impact at the bow. A crack in a horizontal stringer was also reported,
- buckling caused by wave impact on the bow was reported on a FPSO in a storm in 2007. The buckling was localized on the first web frame on the port and starboard side from the centre line,
- during a storm in March 2019 parts of the bulwark on the fore-castle deck was deformed and dented on an FPSO due to green water in the bow area of the unit (see also the section on green water).

The incidents indicate that the design requirements may be insufficient for bow flare slamming up to 2007. However, the incident reports are not sufficiently conclusive on this matter.

GREEN WATER

Green water events caused several local damages on Norwegian production vessels during 1998- 2001 as reported by Leonhardsen et al (2001) and Ersdal and Kvitrud (2000). Four FPSOs were exposed to green water in the bow area, amidships, in the aft ship area or a combination of these. Tailor-made mitigations were made for all these FPSOs by means of local protection of the exposed equipment, strengthening of local supports and areas, fitting wave-breaking walls between tank- and process decks, operational measurements such as adjustment of draft and trim and restrictions in personnel access to green water zones.

After the early green water incidents several model tests were conducted, enhancement in calculation procedures and computer programs were implemented and standards and guidelines were updated with new requirements related to exposure of green water and corresponding loads on ship-shaped production vessels. Such model tests are presently performed for all new FPSOs. However, experience has shown that practical knowledge should be used in addition to the model tests and the results should be properly included into the operational procedures.

From 2002 to 2015 there were no reported green water incidents resulting in structural damage or injured persons.

In 2016 a person was hit by green sea on the cargo deck of an FPSO. The incident occurred in a sea state with a Hs of 8.3 m. The person was located on the cargo tank deck above the side shell and was hit by green water penetrating through the green water barrier. The wave was reduced in intesity by the barrier and transformed to “white water”. The person lost his helmet and radio but managed to protect his head. He was not injured, and no material damage was observed. The original instruction was that the cargo deck was to be closed for people for sea states larger than 10 m. The mitigating action taken was a further restriction in personnel access to green water zones at Hs larger than 6 m. Both model testing during the design phase with Hs of 8m and a new analysis after the incident, demonstrated that green water can occur on the tank deck for the experienced conditions.

During February and March 2019 two serious incidents with water on the deck were reported for an FPSO. The first incident occurred in a ballast condition, where a wave “broke” over the fore-castle deck and resulted in the loss of two inflatable life rafts on the port side. The significant wave height was reported to be 8 m. The second incident occurred in a reduced full load condition with a significant wave height of 12 m and a wave period (Tp) of 16 s. There are some uncertainties related to the actual loading conditions and whether the operational restrictions were followed in trim and draft set by the operator as a consequence of the green water incident in 1998 (Ersdal and Kvitrud, 2000). This was due to some malfunctions in the loading computer. However, two life rafts were released from the starboard life raft station and damage occurred on external and internal ventilation piping, piping ducts and adjacent motors. A weathertight door to the inergen (inert gas) room was opened by the sea and the room was consequently filled with water. Parts of the bulwark on the fore-castle deck was deformed and dented, and pipe supports, cable trays and gratings below the helideck were crushed and a room with spare inergen bottles was loosened, crushed and compressed. Several short-term mitigating actions were taken such as updating of the load computer, change of weathertight doors on the fore-castle deck and the proper fastening of gratings. The long-term mitigating actions (some still ongoing) were reanalysis of green water incidents along the entire hull based on updated knowledge on hydrodynamics, updated metocean data and a corresponding evaluation whether a new model test should be conducted. In addition, an evaluation of loads on the LQ and other critical equipment such as helideck, ventilation pipes and ducts were acceptable was proposed to be conducted in both ULS and ALS conditions. So far, the results obtained are not conclusive and the work is still under investigation by the operator.

In 2019 another green water incident occurred on an FPSO. In this incident green water came over the production deck (above the cargo deck) on the starboard side and broke loose some scaffolding equipment, deformed some railings, damaged light fixtures, moved a container and deformed a wall on a chemical storage unit. The incident occurred in a sea state of 7 meters.

In total, since 2001 four incidents with green water causing damage are reported, all of them during the last three years. However, green water incidents may have occurred in this period but without causing damage and injuries. It is observed that the incidents coincide in time with the high number of observed cracks and with a high number of waves in deck incidents on semi-submersibles.

The incidents reported were all in relative moderate sea states (Hs = 8.3m; 8m; 12m and 7m respectively). However, the incidents may have occurred in relatively steep waves, even if this is not specifically reported in the incident logs.

These incidents indicate that green water as a phenomenon need to be revisited, even if the design standards and calculation methods have improved since the late 1990's.

COLLISIONS WITH VESSELS AND SHUTTLE TANKERS

In 2000 a shuttle tanker collided with an FPSO on the starboard side aft with a collision energy of 31 MJ. Further, in 2006 a shuttle tanker collided with an FSO with a collision energy of approximately 61 MJ. The FSO experienced damages in the stern. Despite the high collision energy, the damages on the production units in both occasions were moderate. Further description of these incidents can be found in Kvitrud et al. (2012). No collisions between production units and shuttle tankers have been reported since 2006.

Three incidents of collisions between floating production units and supply vessels are reported over the last 20 years. The first incident occurred in 2001 when a supply vessel of 2926 dwt collided with an FPSO. The second incident occurred in 2008 with a supply vessel of 3100 dwt. More recently, a supply vessel of 1637 dwt collided with an FSPO in 2015. None of the incidents caused significant structural damage to the production units.

A low number of collisions have been reported. This is most likely due to strict regulation for operation of shuttle tankers and supply vessels entering the safety zone.

TOPSIDE STRUCTURES

On topside structures cracks have been reported in catwalks, crane boom rests, green water bunting and wind walls. These cracks are regarded to be of no significance to the integrity of the FPSO's hull girder or the topside structure as such.

Large numbers of anomalies are reported on secondary structures on the topsides and on maritime equipment with corrosion as the most frequent cause.

An average of five incidents of falling objects (signs, light fixtures, bolts, etc.) have been reported yearly on ship-shaped production units in the period 2010-2018 (with a maximum of 10 and a minimum of 1 per year). The incidents include a large variety of causes and it is not easy to find common causes.

Incidents of loose bolts reported as falling objects are reported almost yearly with a slight reduction in the latest years.

Supports of topside modules to the main deck of FPSOs have been a concern with respect to fatigue. However, no cracks have been reported in way of topside support stools.

CORROSION

Mobile offshore units are normally built without any corrosion additions (allowance) due to an assumption of a proper corrosion protection system. However, FPSOs and FSOs have in addition to a corrosion protection system included a corrosion allowance to the net scantlings, as specified by the classification rules (DNV GL 2019).

Protection against corrosion is done with anodes, coating and impressed currents. For structural elements the concern is thickness diminution due to general and pitting corrosion affecting strength, buckling, water ingress and fatigue resistance. In addition, for marine systems galvanic corrosion may lead to leaks.

General and pitting corrosion are reported at several locations on FPSOs/FSOs such as:

- plates between ballast and cargo tanks on an FPSO in 2014,
- the hull envelope (side shell and bilge radius) on an FPSO in 2016,
- areas with inactive anodes. The same FPSO as reported above for 2016,
- axposed equipment on topsides. The same FPSO as reported above for 2016,
- deck plates,
- pitting corrosion in the box keel area underneath the forward pump room was reported in 2010. The pitting had varied depth, the deepest of which was found to be approx. 15mm.

Galvanic corrosion may give serious consequences, but few structural incidents are reported. However, leakage is reported in an internal 10-inch pipe in the return flow of the cooling water system (see section on stability).

TURRET AREA

Few incidents have been reported for the turret area. Roller supports have been reported to be replaced on two FPSOs. Cracks in way of brackets supporting the gripper flange for turning the turret have been reported on one FPSO.

HEADING CONTROL

Heading control is of vital importance for FPSO's and FSO's in harsh waters as they are designed to be weather vaning (heading towards the dominant weather). For most units this is achieved by use of internal (in hull) or external (front of bow) turret systems. On the NCS only internal systems are used with a sufficiently forward location of the turret. However, some units are dependent on additional thrusters to maintain their heading.

Most units are free to rotate either through a conventional turret or an STL. A few units have limitations in the number of rotations.

Heading control depends on thrusters and a sufficient power supply. Experience demonstrates that the thrusters and their components have a limited service life. Two thruster failures have been reported and 8 thrusters have been replaced. In some cases thrusters have failed after just a few years in service and it is therefore important to have thruster redundancy. In addition, it is important to plan for maintenance and replacement of thrusters and components during operations. Since 2010 a total of 14 cases of loss of main power supply have been reported from ship shaped production units. Three of the cases included loss of "all" power supply including loss of the emergency generators. However, in these cases some power on UPS (uninterruptible power supply) was maintained. Heading control were maintained in these situation as they occurred in mild sea states.

The following incidents have been reported related to heading control:

- In 2000 an FPSO experienced that one of the two gyros failed resulting in signals to the starboard thruster to give maximum power. The FPSO changed heading, but due to swift reactions by the operator an uncontrolled turning of the FPSO was avoided, but in less favourable weather conditions the mooring lines could have been damaged.
- In 2011 an FPSO experienced a heading control problem during the inspection of the turret (in 12 m/s wind and Hs= 3.5m). During the inspection the turret was in a locked position. The FPSO was turned to an assumed optimal heading. However, a few seconds later the heading control was lost and the FPSO rotated approximately 40 degrees. During this incident the line-breaking alarms occurred for all ten mooring lines although non of the lines actually broke.
- In 2012, during loading of a supply vessel an FPSO turned slowly approximately 10 degrees without the CCR operator noticing it. A warning system should have alerted the CCR operator and thrusters should have been able to correct the situation. However, there were issues with both the warning system and the available truster capacity at the time.
- During off-loading in 2013 an FPSO lost the power to the thruster, and the heading control could not be maintained. Consequently, she turned 35-40 degrees, while the tanker stayed connected within the operational zone. The cargo pumps were stopped. A close dialog with the tanker was maintained until the thrusters were restarted to achieve heading control. After ten minutes offloading was restarted. The weather conditions were calm at the time of the incident.

In general, a low number of incidents on loss of heading control have been reported. The few reported incidents indicate that instrumentation, control systems and human factors are important.

MOORING SYSTEMS

In general, the mooring systems of FPSOs and FSOs on the NCS have shown an acceptable performance. However, since 2000 one double line failure, one case of two failures on the same line and four single line failures have been reported. No obvious common cause for these failures has been identified, see Kvitrud (2014) for more details and references.

In 2006 a line broke on an FPSO. The ruptured link was not found, and the cause of the incident was uncertain since the neighbouring links were found to be satisfactory. In 2008 and 2009 two cases occurred on the same FPSO, caused by failures during fabrication. In one case, the dimensions of the chains were too large, making it impossible to change the position of the links in the fairlead. The second was a failure caused by unauthorized repair of the link by the manufacturer.

In 2011 two of nine steel wire ropes failed on an FSO. The failures were located at the bottom end of the upper steel wire segment.. It is likely that the failures took place on two different occasions with harsh sea states several months prior to the inspection. There was no active monitoring of the mooring line tension during operation. The direct causes of the incidents were ductile overload of the steel wire rope strands at the rope termination at the seabed. This resulted from high local dynamic “snapping” loads after the line had experienced a temporary slack condition. The failures were reported to be ductile and to be of the type «cup and cone». The upper wire rope segments were touching the sea bed in some load conditions and weather situations. It was also evident that the system had experienced "slack" in many loading situations.

In 2012 two links in the same anchor chain of an FPSO failed probably simultaneously. One failure was caused by fatigue and was due to abnormal loads or bending of the chain. The other failure was caused by overload. The lines had operated with higher pretension (about 160 tons) than presupposed in the design (140 tons).

In 2012 one chain broke on an FPSO. The same line also failed in 2006. The failure was due to high-cycle, low stress fatigue that had initiated on the external surface of the link and propagated due to bending. This bending was most likely introduced due to a rotation or incorrect position of the chain link in the fairlead, or of out-of-plane bending.

One of the cases highlights the importance of measuring the tension in the lines. The last two cases demonstrate the importance of reducing bending and wear of chains in the fairlead areas. Only one incident related to equipment failures has been reported, where several bolts to a fairlead wheel failed.

The number of reported incidents related to mooring lines and equipment on floating units on the NCS reached a peak in 2014. Based on significant efforts in the industry the number of incidents was significantly reduced both on mobile units and on floating production units. Several line segments have been replaced and several chains have been observed to have pitting corrosion, probably caused by sulphate reducing bacteria (Gabrielsen et al, 2019).

STABILITY AND BALLASTING

Because of the accident with the column stabilized unit Alexander L. Kielland in 1980, the NMA made new regulations related to stability and ballasting applicable to units of ship design, self-elevating units and semi-submersible units. These regulations have since been slightly modified but are to a large extent still valid. The regulations give strict requirements specially to damaged conditions and to reserve buoyancy.

Incidents related to stability and ballasting are more frequent on semisubmersibles compared to ship-shaped units due to the complexity in their ballast and tank configurations. A few cases of incidents related to stability, ballasting and seawater systems of ship-shaped units have been reported.

In October 2011 an FPSO suffered from a corrosion damage on an internal 10-inch pipe in the return flow of the cooling water system (two metres below the water line) caused seawater to flood a pump room at the stern of an FPSO. The volume of the room was 3.800 cubic metres and two gauges indicated approximately 30% water fill. Water was also detected in the stairways outside the pump room. The bilge pumps were started, but had insufficient capacity. A ballast pump was activated but experienced start-up problems. Starting the ballast pumps had no effect on the water level in the ballast pump room. Three gas-powered fire pumps and repair clamps were flown in. After trouble shooting, the leak was identified. The tube was immediately sealed with a plug and secured with cargo straps. The water intrusion was limited to the pump room and the adjacent stairway. The leak was stopped after about two hours.

In 2014 an FSO experienced ingress of water into the submerged loading (STL) room. A gas tight door had been installed instead of a watertight door and this was not detected before the vessel was in operation.

In 2016 negative stability was experienced on an FPSO causing the vessel to incline 4-5 degrees fourth and back to each side. The vessel was in a ballast condition and had just transferred 4000 cubic meters of oil to two cargo tanks. Simultaneously, the unit was in the process of preparing two ballast tanks for discharging and preparation for tank maintenance when the discharge operation accidentally stopped, and the inclining started. The cause of the negative stability was a large amount of partly filled tanks (slack tanks). The condition was brought back to normal by filling several of the ballast tanks full to reduce the free surface effect. However, it took about three hours to get the situation under control. A procedure was later prepared stating that all tanks shall either be full or totally empty to avoid any free surfaces. Further, only one ballast tank shall be discharged at any given time. One of the reasons why the vessel became more sensitive towards free surface effects is an increase in the VCG through the years, in combination with a large negative contribution to the GM value from free surface effects specially from U-shaped ballast tanks.

A relatively low number of malfunctions are reported to the PSA from testing of water tightness and proper function of watertight doors and valves in ballast systems. On average errors are reported in less than 0.1% of the tests performed.

OFFLOADING SYSTEMS

Offloading is an integrated and important part of floating production units. Several systems are used to discharge oil from the production and storage units to conventional shuttle tankers by means of tandem loading, submerged turret loading or loading buoys. The offloading activity has a large potential for causing harm to personnel and the environment. There are significant differences in the severity of the incidents from 2000 to 2009, compared with the last ten years. More details and references are found in Kvitrud et al (2012).

From the first ten years, two collisions have been reported. A shuttle tanker lost position after loading crude oil and hithe FPSO on the starboard side aft. The accident occurred when the shuttle tanker was disconnecting from an FPSO. The weather conditions were good with significant wave height of 2.9m. The collision energy was 31 MJ. The second incident was when a shuttle tanker got black-out when connecting to an FSO. As a result, most propellers stopped. System errors led to escalation. The shuttle tanker tried to avoid a collision, but hit the FSO at a speed of 1.2 m/s. The shuttle tanker was damaged in the bow, while the FSO was damaged in the stern. The collision energy was about 61 MJ.

Three near collisions have occurred. In 2000, a shuttle tanker came 45m from the FPSO. The second near incident was when the dynamic positioning system failed on a shuttle tanker in 2004. During the offloading the shuttle tanker came 72m from an FSO. The shuttle tanker changed heading and increased the speed ahead. ESD 1 was immediately activated. The DP system was activating high force in forward direction and the DP-operator therefore decided to change to manual DP-mode. The minimum distance reached was 26 meters when it stopped. In the third case in 2009 a combination of technical and human errors caused the shuttle tanker to move forward against the FPSO. The distance was 34 meters between the units before the shuttle tanker began to go astern. In addition, three reported incidents were related to minor position deviations.

Since 2010 ten incidents are reported related to FPSOs and FSOs:

- Three cases of loss of position of the shuttle tankers, fortunately with merely small position deviations. As an example, a shuttle tanker came inside the disconnect zone and the green line was broken in 2016. ESD 2 was activated and the loading hose was disconnected.
- Three cases of leakages to sea causing a total of approximately 700 litre of oil pollution to sea.
- Three cases of gas detections.
- One case of water filling of the offloading hose.

However, the activity the last ten years can to a large extent be regarded as a success history compared with the previous ten years.

SUMMARY

A total of 494 cracks are reported for the 17 FPSOs and FSOs between 2000 and 2019. No cracks are reported for six of these units which were mostly installed after 2015. The number of cracks per unit is approximately 45. Most of the cracks are reported as minor cracks, with only two classified as major. It has been attempted to identify if the crack appearance can be traced back to factors such as ageing, harsh winter seasons, inspection campaigns or due to poor fabrication or design. At least for two of the units, cracks appeared early after installation and can be traced back to poor design and fabrication effects. For four units, traces of ageing effects can be identified. As some of these units also have been subjected to a life extension process, the increase in observed cracks may be a combination of ageing effects and the results of enhanced inspections. Trends towards an increased number of cracks detected some years after harsh weather can also be identified. Obviously, all of these effects need to be closely monitored in the future, and the root cause of failure and crack details, (see Figure 5), should be more clearly stated and reported to PSA. A closer following up of the workmanship at the yards could have reduced the number of cracks considerably.

Three incidents of dents and deformation were reported before 2010 and one in 2019. The first three incidents were due to wave impact on the hull structure, while the last one was due to a green water incident. Some classification societies have enhanced their scantling requirements due to bow flare impacts in early 2000 and later, but it remains to be confirmed if this is followed up for the identified units.

Since 2002 four incidents with green water have occurred, all of which occurred during the last three years. They indicate that green water still should be given high attention and that the calculation methods recommended in the late 1990's and, early 2000's should be revisited to identify new knowledge.

No collisions between production units and shuttle tankers have been reported since 2006. It seems that better operational procedures for shuttle tankers approaching the production units have been a great contributor to the improvement.

Many anomalies in the topside structures are reported on secondary structures and on marine equipment due to corrosion. Similarly, cracks are reported in catwalks, crane boom rests, green water bunting and at wind walls. No cracks are reported in the main loadbearing structure of the topside modules or support stools between the modules and the hull girder. Corrosion in the hull girder (tanks and hull envelope) are reported for several locations, but without severe consequences. However, one incident with galvanic corrosion in a seawater piping, is reported with a serious leakage in a pump room.

Few incidents are reported in the turret area. Cracks in brackets supporting the gripper flange for turning the turret have been reported

Four incidents in the heading control are reported related to loss of heading, none of them after 2013. None of these incidents occurred in severe weather. These incidents occurred due to technical deficiencies or due to negligence of alarms or routines. It seems that better operational procedures and more attention to alarms have contributed to a better performance.

In general, the mooring systems have had an acceptable performance. Since 2000 one double line failure, one case of two failures on the same line and four single line failures are reported. The number of reported incidents related to mooring lines on floating units on the NCS reached a peak in 2014 but based on significant efforts in the industry the number of incidents has been significantly reduced both on mobile drilling units and on production units.

Two incidents related to stability and ballasting have occurred involving water ingress and one incident of negative stability are reported. The negative stability case is of great concern and confirms that an increased focus on weight control should be implemented as the vessels gets older. This in combination with good competence on stability and the related free surface effects of many similar slack tanks is vital and should be given more attention.

Two collisions with offloading shuttle tankers, three near collisions and three position deviations of the FPSOs were reported. In the last ten years only, minor deficiencies have been reported and can to a large extent be regarded as a success compared with the previous ten years.

CONCLUSIONS

The large number of cracks reported since 2000 needs to be further investigated and evaluated, especially the reasons behind the cracks reported in 2017 and 2018. These should further be investigated to check if the supervision at the yards was sufficiently qualified and had the necessary experience on ship-shaped units. The reporting routines and reporting details to PSA need to be better described and followed up, because of the lack of information evident in Figure 5. Several of the cracks classified as minor, should be verified by critical crack length and crack propagation investigations, to get a more reliable classification. Improvements could also be introduced to investigations related to the root cause of failure.

The increasing number of incidents with green water in the latest years should be investigated to identify if new knowledge in hydrodynamics and vessel performance need to be implemented in the calculation routines.

Some issues regaring the remaining thickness of metallic seawater pipes have been reported and due attention should be paid to inspection of these.

The competence within stability, slack tanks and the relation to weight increase on older units should be given a high priority.

ACKNOWLEDGEMENTS

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ABREVIATIONS

ALS	Accidental Limit State
AoC	Acknowledgement of Compliance
CCR	Central Control Room
CODAM	Corrosion and Damage Database
DP	Dynamic Positioning
dwt	dead weight tons
ESD	Emergency Shutdown System
FPSO	Floating Production, Storage and Offloading unit
FSO	Floating storage and offloading unit
Hs	Significant wave height
LQ	living quarter
NCS	Norwegian Continental Shelf
NMA	Norwegian Maritime Authority
PSA	Petroleum Safety Authority Norway
RNNP	Trends in risk level in Norwegian Petroleum activity
STL	Submerged Turret Loading
Tp	Peak Period
UKCS	United Kingdom Continental Shelf
ULS	Ultimate Limit State
VCG	Vertical centre of gravity
WBT	water ballast tanks.

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APPENDIX A

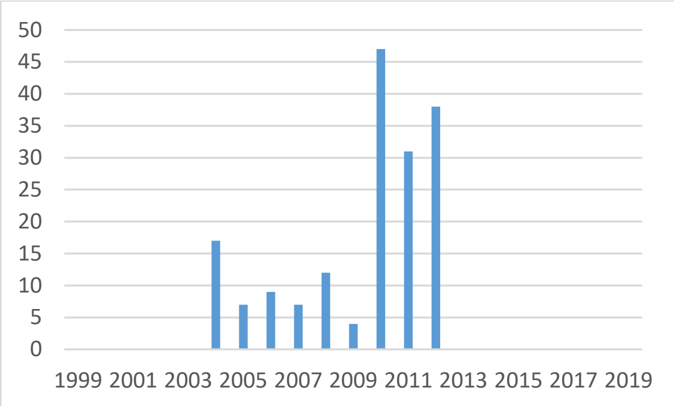

FIGURE 7: ANNUAL NUMBER OF CRACKS FOR FPSO 1. THIS FPSO WAS IN SERVICE FROM 2001 TO 2013.

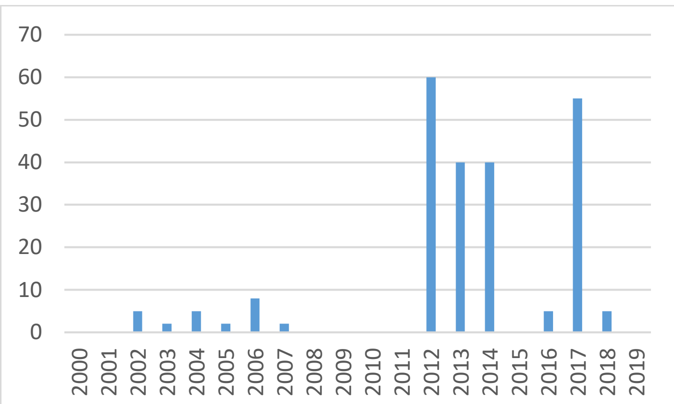

FIGURE 8: ANNUAL NUMBER OF CRACKS*) FOR FPSO 2. THIS FPSO HAS BEEN IN SERVICE SINCE 1999.

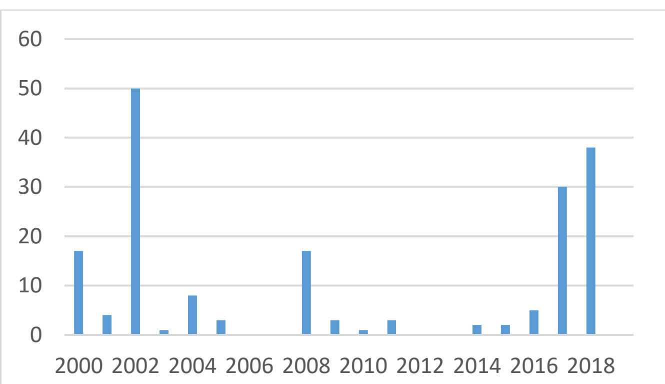

FIGURE 9: ANNUAL NUMBER OF CRACKS *) FOR FPSO 3. THIS FPSO HAS BEEN IN SERVICE SINCE 1997.

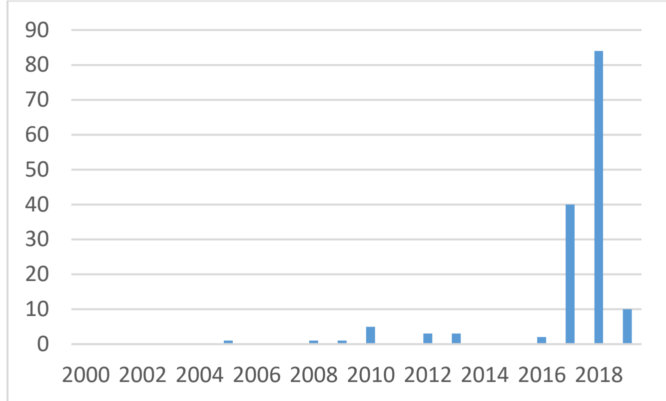

FIGURE 10: ANNUAL NUMBER OF CRACKS*) FOR FPSO 4. THIS FPSO HAS BEEN IN SERVICE SINCE 1999.

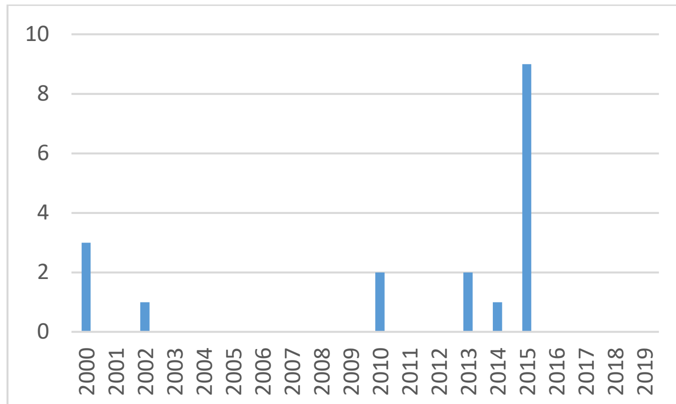

FIGURE 11: ANNUAL NUMBER OF CRACKS FOR FPSO 5. THIS FPSO HAS BEEN IN SERVICE FROM 1999 TO 2016.

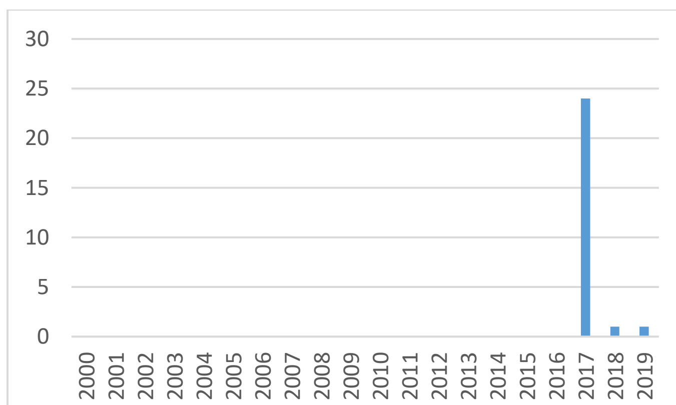

FIGURE 12: ANNUAL NUMBER OF CRACKS FOR FPSO 6. THIS FPSO HAS BEEN IN SERVICE SINCE 2011.

APPENDIX B

Alvheim FPSO is an FPSO built under the name MST Odin in 2001. She was installed at the Alvheim field in the North Sea in 2008. She has an oil storage capacity of 82.300 tons. The operator in 2019 was Aker BP. She is a flagged and classed unit.

Balder FPU is an FPSO at the Balder field in the North Sea. She was installed in 1999. She has an oil storage capacity of 55.600 tons. The operator in 2019 was Vår Energi.

Goliat FPSO is a circular FPSO of the Sevan type. She was installed at the Goliat field in the northern Norwegian Sea in 2015. She has an oil storage capacity of 151.000 tons. The operator in 2019 was Vår Energi.

Hanne Knutsen is an FSO on the Martin Linge-field in the North Sea. She was installed in 2018. She was originally built in 2000 as a shuttle tanker. She has a dead weight of 123.581 tons. The operator in 2019 was Equinor. She is a flagged and classed unit.

Heidrun B is an FSO at the Heidrun field in the Norwegian Sea. She came into operations in 2015. She has an oil storage capacity of 151.000 tons. The operator in 2019 was Equinor. She is a flagged and classed unit.

Jotun A is an FPSO at the Jotun field in the North Sea. She was installed in 1999. She has an oil storage capacity of 92.910 tons. The operator in 2019 was Vår Energi.

Navion Saga was an FSO on the Volve field from 2007 to 2016. She was built in 1991 as a conventional tanker. Her dead weight capacity was 149.000 tons. The operator at the field was Statoil. She was a flagged and classed unit.

Njord B is an FSO at the Njord field in the Norwegian Sea from 1997 to 2016 (going for refurbishment and thereafter planned into operation again in 2020) She has an oil storage capacity of 112.765 tons. The operator in 2019 was Equinor.

Norne is an FPSO. She came into operation at the Norne field in the Norwegian Sea in 1997. She has an oil storage capacity of 115.150 tons. The operator in 2019 was Equinor.

Petrojarl 1 was used in the period from 2001 to 2013 at the Glitne field in the North Sea. She has an oil storage capacity of 28.620 tons. She was originally built as an FPSO in 1986 and had earlier operated on several fields in the North Sea area. The operator was Statoil. She was a flagged and classed unit.

Petrojarl Knarr is an FPSO used at the Knarr field in the Norwegian Sea. She has operated on the field since 2014. She has an oil storage capacity of 127.500 tons. The operator in 2019 was Norske Shell. She is a flagged and classed unit.

Petrojarl Varg was an FPSO used at the Varg field in the Norwegian Sea. She was in operation in the period of 1998 to 2016. She had an oil storage capacity of 74.730 tons. The operator was Talisman Energy Norge. She was a flagged and classed unit.

Randgrid (Gina Krog FSO) is an FSO at the Gina Krog field in the North Sea. She was originally built as a tanker, refurbished and thereafter she was installed at the Gina Krog field in 2017. She has a dead weight of 124.502 tons. The operator in 2019 was Equinor. She is a flagged and classed unit.

Skarv A is an FPSO at the Skarv field in the Norwegian Sea. She has been in operation since 2011. She has an oil storage capacity of 132.500 tons. The operator in 2019 was Aker BP. She is a classed unit.

Åsgard A is an FPSO. She has been in operation on the Åsgard field in the Norwegian Sea since 2001. She has an oil storage capacity of 145.000 tons. The operator in 2019 was Equinor.

Jorunn Knutsen (Åsgard C) is an FSO. She has been in operation on the Åsgard field in the Norwegian Sea since 2001. She has an oil storage capacity of 136.196 tons. She is a classed and flagged unit. She was built in 2000. The operator in 2019 was Equinor.

Aasta Hansteen is a spar type platform, and for the purpose of this paper regarded as an FPSO. She is used at the Aasta Hansteen field in the Norwegian Sea. She was installed in 2018. She has a liquid storage capacity of 25.000 tons and a displacement of 137.000 tons. The operator in 2019 was Equinor.