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RISK SESSION

Risk Analysis of DP Operations
for CAT-D Drilling Unit in the Troll Field

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ABSTRACT

The CAT-D drilling units are dynamically positioned semisubmersible drilling rigs designed for operations on the Norwegian Continental Shelf. The rig is designed to meet DYNPOS-AUTRO and DYNPOS-ER notations. There are three DP redundancy groups designed on the rig, and single failures including fire or flooding in one compartment will in maximum result in loss of one DP redundancy group, i.e. two diesel generators, or two connected 11kV switchboard sections, and/or two thrusters. Within each DP redundancy group the rig is designed with extra fault tolerance capability against single failures. Except for fire/flooding events and failures related to 11kV bus coupler, single failures can only result in loss of one DG, or one 11 kV switchboard section, and/or one thruster. This represents a significant step forward to reduce the vulnerability of DP class 3 system towards single failures.

The enhanced reliability in the overall DP system and in particular, the most likely expected single failure effect, i.e. loss of one thruster in station keeping, is the background for this risk analysis. After significant extra investment on the design and construction of the rig, should rig operator still plan the DP operation in a similar way as other contemporary DP class 3 rigs, i.e. based on single failure effect of losing two thrusters? Or can this rig be operated with single failure effect of losing one thruster? If so, what if a fire happens and consequently results in loss of two thrusters? It may result in a drift-off situation. What is the risk of losing the well integrity? Moreover, how frequent had a fire event happened on DP drilling rigs? And how frequent may such event occur on the CAT-D rig that can result in drift-off in the Troll field? A risk analysis is performed to provide answers to above questions. It should be noted that failures related to 11kV bus coupler are also analyzed in the risk analysis project, but contents in this paper are focused on fire and flooding.

The objective of the risk analysis is to evaluate the risk of loss of well integrity in the Troll field due to DP position loss. The focus is to analyze and compare risks given two different DP operational bases for the CAT-D rig, i.e. WSF2 (which means DP operations are based on the worst case single failure of losing two thrusters), vs. WSF1 (which means DP operations are based on the worst case single failure of losing one thruster). The historical fire and flooding frequency is derived in this study for mobile offshore drilling units. Fire/flooding as well as 11kV bus coupler failures can cause loss of two thrusters, and rig will slowly drift off given DP operation based on WSF1. Such scenarios are simulated by time-domain simulations using rig specific model and environmental conditions in the Troll field. Event tree analyses of rig position loss and barriers, i.e. automatic EDS, human operator, and independent ADS system, are performed. The results demonstrate that DP operations based on WSF1 have equivalent safety level of well integrity as DP operation based on WSF2 in the Troll field. Recommendations to relevant DP operational procedures, DP software consequence analysis function and relevant operator trainings are further proposed.

GLOSSARY/ABBREVIATIONS

ADS	Automatic Disconnect System
DP	Dynamic Positioning
DPO	DP operator
Drift-off	There is insufficient thruster force so that vessel is drifted away from the target position by the environmental loads, and has an excursion beyond the red limit
Drive-off	There is abnormal thruster force so that vessel is driven away from the target position, and has an excursion beyond the red limit.
DSWB	Drilling switchboard
EDS	Emergency Disconnect Sequence. On some rigs this may also be called as EQD (emergency quick disconnect)
ESD	Emergency Shut Down

IMCA	International Marine Contractors Association
HIL	Hardware In the Loop
HPR	Hydroacoustic Position Reference
HS1 to HS6	11kV switchboards No.1 to No.6
HV	High Voltage
HSE	Health and Safety Executive
Position loss	The vessel loses, either temporarily or for an extended time, the capability to maintain its position by means of thruster force, and consequently has a position excursion which is beyond the normal range.
LMRP	Lower Marine Riser Package
LS1 to LS6	230V switchboard No.1 to No.6
LV	Low Voltage
MODU	Mobile Offshore Drilling Unit
MS1 to MS6	690V switchboard No.1 to No.6
MTS	Marine Technology Society
NCS	Norwegian Continental Shelf
OGP	The International Association of Oil & Gas Producers
Power Group	Within each fire/flooding segregated redundancy group, there are two power groups. Each of the power group consists of one DG, one thruster and associated DG and thruster auxiliaries, one 11kV SWBD section, one 690V SWBD and one 230V SWBD and one switchboard control UPS. There are in total six power groups designed on the rig. The control & monitoring system is also split according to the six power groups.
Redundancy Group	This refers to the three redundancy groups (so called power splits) designed in the DP system. They are fire and flooding segregated, and designed against all kinds of single failures, including active failures, static failures, hidden failures, single inadvertent action, fire and flooding of one compartment, other common cause such as gas exposure.
PRS	Position Reference System
T1 to T6	Thruster No.1 to No.6
WSF1	This abbreviation refers to the DP operational basis, i.e. DP operations are based on W orst case S ingle F ailure of losing one (1) thruster.
WSF2	This abbreviation refers to the DP operational basis, i.e. DP operations are based on W orst case S ingle F ailure of losing two (2) thrusters.
WOAD	Worldwide Offshore Accident Databank

INTRODUCTION

The CAT-D unit is a dynamically positioned semisubmersible drilling rig designed for operations on the Norwegian Continental Shelf. The DP system for the CAT-D rig has been designed to meet equipment class 3 requirement in the IMO/MSC Circular 645 (Ref. [1]), and DNV DYNPOS-AUTRO (Ref. [2]). There are three DP redundancy groups designed on the rig, and single failures including fire or flooding in one compartment will in maximum result in loss of one DP redundancy group, i.e. two diesel generators, or two connected 11kV switchboard sections, and/or two thrusters. An illustration of the three DP redundancy groups is given in Figure 1. These are equivalent to other contemporary DP class 3 drilling rigs. However, significant efforts have been made on the Cat-D rig to further reduce the DP system's vulnerability towards single failures. This is reflected by the following two aspects.

First, the DP system on the CAT-D rig is designed to comply with the DYNPOS-ER requirements (Ref. [3]). The DYNPOS-ER is a relatively new class requirement to ensure Enhanced Reliability of DP system. It requires additional failure tolerance by use of e.g. advanced protection systems for failure

detection and discrimination of failed components. Two barriers shall be in place in case of a hidden failure to the primary barrier in relation to the power system protections. The alternative DP-ER control system provides increased availability to the automatic position keeping ability of the rig, both at the main bridge and overall for the rig. It has its own network which is independent to Net A and Net B which are used by main and backup DP control system. The DYNPOS-ER also requires more autonomous thrusters and diesel generators. This can limit the effect from single failures largely within single thruster or single diesel generator.

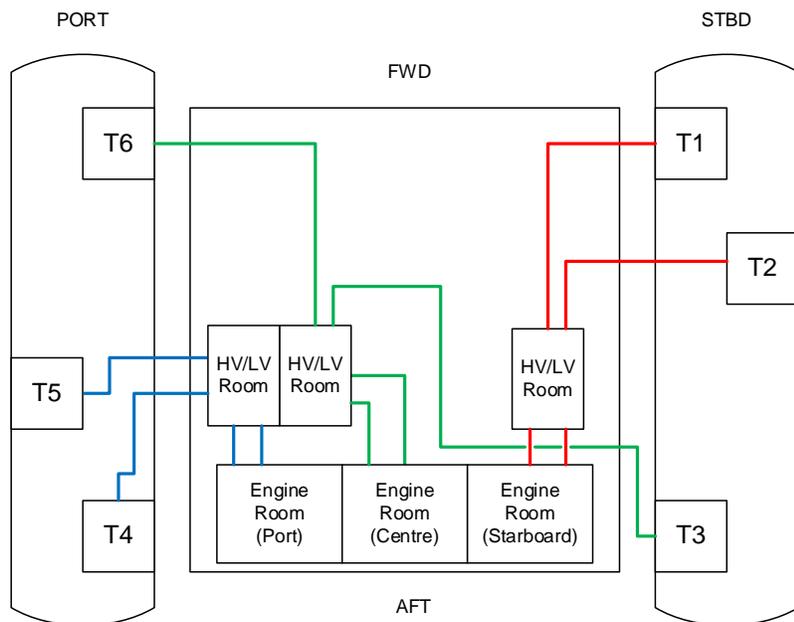


Figure 1: Power plant and thruster configuration on CAT-D rig

Second, the rig is designed with extra fault tolerance capability against single failures within each DP redundancy group. This is reflected by a concept of six power groups designed in the DP system. Within each redundancy group which is fire/flooding segregated, there are two power groups. Each of the power group consists of one DG, one thruster and associated DG and thruster auxiliaries, one 11kV SWBD section, one 690V SWBD and one 230V SWBD and one switchboard control UPS. The control & monitoring system is also split according to the six power groups. An illustration of the six power groups is given in Figure 2. According to the DP FMEA verifications for the rig (Ref. [4]), except for fire/flooding and failures related to the 11kV bus coupler, i.e. the single breaker connecting the two 11kV SWBD sections within each redundancy group, single failures can only result in loss of one power group, i.e. loss of one DG, or one 11 kV switchboard section, and/or one thruster.

The high fault tolerance capability on the CAT-D rig may be exemplified by the following example. On a contemporary DP class 3 rig, failure of one 690V ship service switchboard (e.g. short circuit) will typically cause loss of auxiliaries for two diesel generators in one engine room. Such single failure will typically lead to partial blackout of one engine room and loss of two thrusters. On the CAT-D rig, such single failure of the equivalent 690V switchboard will only trip one running diesel generator, or affect one standby diesel generator from being able to start. There will be no impact on the 2nd diesel generator in the same engine room, nor loss of thruster. This example demonstrates the improvement in the fault tolerant design of the electrical power system, as well as the enhanced redundancy in the design of auxiliary systems for diesel generators and thrusters on the CAT-D rig.

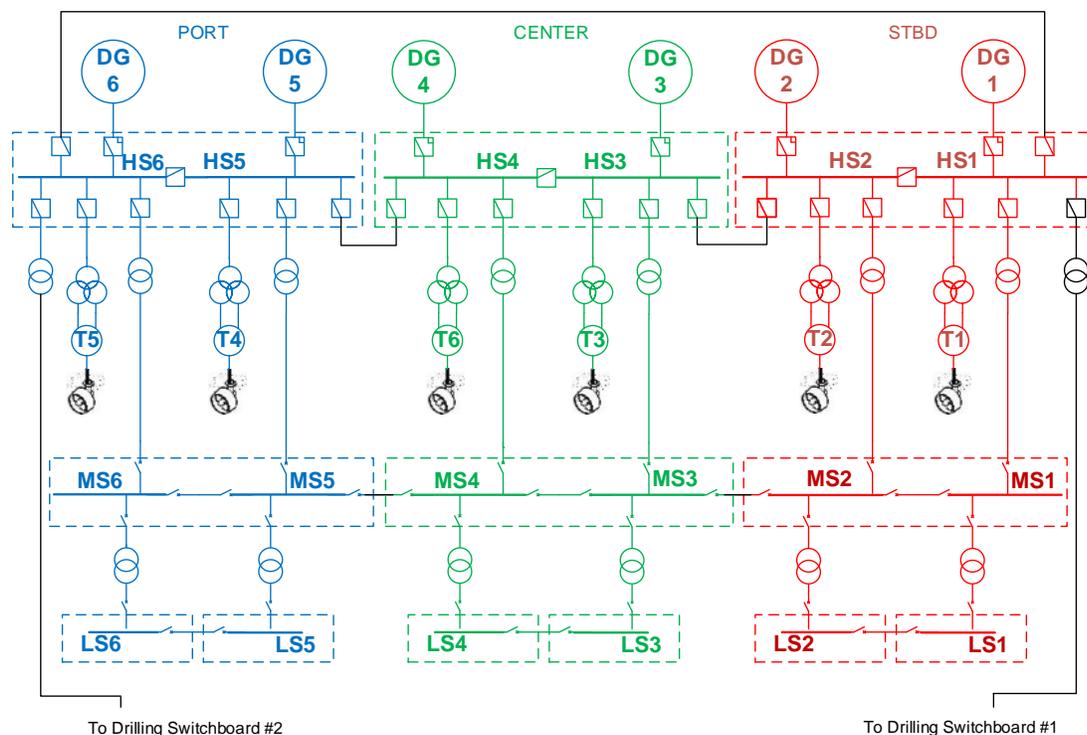


Figure 2: Power plant and distribution: Concept of six power groups (Note: the six 440V switchboards are not shown on the illustration. DP related consumers are mainly HVAC systems, taut wire and HiPAP hoist control units.)

The enhanced reliability in the overall DP system and in particular, the most likely expected single failure effect, i.e. loss of one thruster in station keeping, is the background for this risk analysis. The rig operators and other relevant stakeholders including safety authorities may ask a few key questions, i.e.

- For rig owner/operator: after significant extra efforts and investment for the fault-tolerant DP system, should we still plan the DP operations in a similar way as other contemporary DP class 3 rigs, i.e. based on single failure effect of losing two thrusters? Or can this rig be operated safely with single failure effect of losing one thruster?
- For oil companies and safety authorities: if the rig is being operated based on single failure effect of losing one thruster, what if a fire happens in one HV switchboard room and consequent loss of two thrusters? What if a hidden failure of 11kV bus coupler results in loss of two thrusters? What will such drift-off look like? And how frequent can such events happen on the CAT-D rig resulting drift-off in the Troll field? What is the risk towards the well integrity?

The risk analysis is to provide answers to the questions as outlined above. The overall objective is to evaluate the risk of loss of well integrity in the Troll field due to DP position loss. The focus is to analyse and compare risks given two different DP operational bases for the CAT-D rig, i.e. WSF2 (which means DP operation is based on the worst case single failure of losing two thrusters), vs. WSF1 (which means DP operation is based on the worst case single failure of losing one thruster). The risks towards the well integrity in the Troll field from these two DP operational bases are to be concluded.

The above objective is achieved by the following three key tasks in this study:

- The historical data for DP related fire and flooding events on mobile offshore drilling units during 1998 to 2010 are collected, and historical frequency is derived. Facts regarding design advantages

on the CAT-D rig are provided, and such advantages against fire/flooding and position loss are evaluated.

- Fire/flooding as well as 11kV bus coupler failures will cause loss of two thrusters, and the rig may slowly drift off given DP operations based on WSF1. Such drift-offs scenarios are simulated by using rig specific model and site specific environmental conditions. The results are basis for assessing the well barrier integrity in such slow drift-off scenario.
- Event tree analyses of rig position loss are performed. Barriers to ensure well integrity in shallow water drilling in the Troll field, i.e. automatic EDS, human operator, and independent ADS system, are analyzed. The additional risk of loss of well integrity given DP operations based on WSF1 vs. WSF2 is concluded.

Failures related to 11kV bus coupler with potential to fail two thrusters are also analyzed in the risk analysis project, besides fire and flooding events. However, the contents in this paper are focused on the fire and flooding risk in order to limit the paper with a readable size.

The Activities Regulations from the Petroleum Safety Authority of Norway (Chapter XVI Maritime Operations, Section 90 Positioning, Ref. [5]), and its Guideline (Ref. [6]) state that DP equipment class 3 should be used for drilling and well activities. This study is not intended to argue for DP class 2 rigs to perform drilling and well activities on the Norwegian Continental Shelf. Rather, it is a specific study for the CAT-D rig which has been designed and constructed with higher degree of fault tolerance in the DP system against single failures. It is to provide a decision making basis to determine the optimum DP operational basis.

SYSTEMS AND OPERATIONS

CAT-D Drilling Rig

The main particulars of the CAT-D rigs are summarized as follows.

Dimensions:

Length overall	116.00 m
Beam overall	97.00 m
Normal Operation Draught	23.15 m
Transit Draught	9.45 m

Electric power plant:

Engines and Generators	6 x Wärtsilä diesel engines 6 x Siemens generators
Engine rooms	3 x A60 segregated engine rooms Two diesel generators in each engine room
HV Switchboards	6 x Siemens HV switchboard sections, 11 kV, 60 Hz
HV switchboard rooms	3 x A60 segregated HV switchboard rooms One 11 kV switchboard per HV switchboard room, and it consists of two 11 kV switchboard sections with a normally closed bus coupler.
LV / Drilling Switchboards	Siemens, 690V, 440 V, 230V, 720V, 60 Hz

Propulsion:

Thruster Drives	6 x Siemens VFDs
Thrusters	6 x Wärtsilä Thrusters. 3 pairs of thrusters, see illustration in Figure 1.

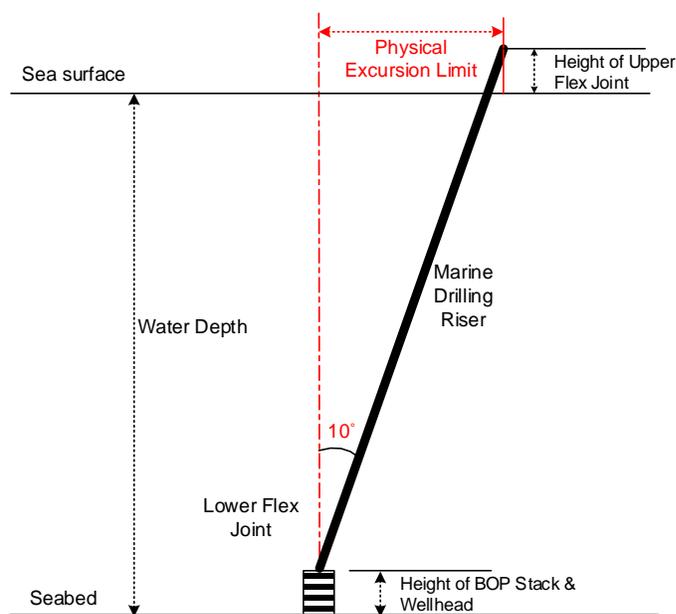
DP Control and monitoring:

Kongsberg K-Pos Dynamic Positioning system
Kongsberg K-Chief IAS and PMS systems

It is noted that there are in total four CAT-D rigs that have been built. The specifications and results in this paper are applicable to No.1 and No.2 CAT-D rigs.

Shallow Water Drilling in the Troll Field

Drilling and well operations in the Troll field are considered in this study. The water depth in the field is about 330 m in average. A simplified sketch of marine riser, BOP, and excursion limit for the rig is given in Figure 3.



Note: The figure is illustrative and not to scale.

Figure 3: Simplified sketch for riser, BOP and maximum excursion limit in the Troll field

The rig excursion limit in the field may be indicated by the maximum tolerable lower flexible joint angle. For standard marine drilling riser, it is normally 10 degrees, and it corresponds to maximum rig excursion of 58 m in the Troll field. Rig excursion beyond this limit while the riser still being connected with the BOP stack in the seabed will have potential to rupture the riser, or topple the BOP stack, or break the wellhead. Such situation could in worst case escalate into a subsea blowout. If EDS is successful, as long as the riser is disconnected before the rig passing the maximum excursion limit of 58 m, and the well is shut in, the consequence will be largely limited to financial losses only.

The EDS is to be completed in 30 seconds upon activation. It can be activated by driller at drill floor, or by DP operator at the bridge. The CAT-D rig is also equipped with two automatic activation functions for disconnection, i.e. Auto EDS and ADS systems. The Auto EDS is activated based on the position deviation in the DP controller exceeds the pre-defined red excursion limit. The DP controller is to activate the EDS signal and this signal is transferred from the DP control system to the vessel emergency shutdown (ESD) system, and then to the BOP control system which activates the emergency disconnect sequence.

The Automatic Disconnect System (ADS) is designed as a last resort to disconnect the LMRP/riser and prevent fatal damage to BOP and wellhead, if the EDS fails in a position loss scenario. The ADS is placed on top of the BOP. It is a mechanical actuation device consisting of two rings with hydraulic actuators underneath the lower ring. The rings are placed on each side of the lower flex joint. The

activation of the hydraulic actuators is at a predefined angle (6 to 8 degrees) if EDS has not yet been completed. It will disconnect the Riser/LMRP from the BOP after 6 to 8 seconds. No actuating signal from the surface is required. The riser tensioners will then lift the Riser/LMRP off the lower BOP. When this takes place the auto shear function on the lower BOP will automatically function, in a same way as in the EDS sequence, to close the casing shear ram after LMRP "lift off". Tubular inside the Riser/BOP will be cut if this is within the shear capacity of the casing shear ram. The upper end will be dragged out of the BOP as the vessel continues to move away from above the wellhead.

Metocean Conditions & DP Operability

The metocean conditions in the Troll field are documented in Ref. [7]. The CAT-D rig in the Troll field may be operated under the five environmental conditions in the Troll field as listed in Table 1. These five cases are referring to the operational condition, i.e. vessel is positioned at green zone with drilling riser connected. From the current speed distribution in Ref [7], it is observed that 95% of current in the field occurred yearly with speed below 0.5 m/s. Therefore, the current speed is set to 0.5 m/s for each environmental case. This represents a credible and slightly conservative operating condition for the rig in the Troll field.

The Case 5 is the maximum environment for DP operations based on WSF1 for the CAT-D rig. The Case 4 is the maximum environment for DP operations based on WSF2. These are derived by Kongsberg Maritime (Ref. [8]) based on DP capability calculations using the rig specific model/data.

Table 1: Operating environmental conditions in the Troll field

Metocean Case No.	Wind speed at 10 m, 1 hr avg. (m/s)	Significant wave height (m)	Mean Spectral Peak Period T_p (s)	Current Speed (m/s)
Case 1	4	1.4	8.6	0.5
Case 2	8	2.6	9.6	0.5
Case 3	12	3.9	10.4	0.5
Case 4 (WSF2)	16	5.6	11.5	0.5
Case 5 (WSF1)	23	8.1	13.1	0.5

The occurrence probabilities for wind in these five environmental cases i.e. 0-4 m/s, 4-8 m/s, 8-12 m/s, 12-16 m/s and 16-23 m/s, are found in the Troll metocean report (Ref. [7]). It is used as an approximation for the occurrence probabilities for the five environmental cases. The probabilities are summarized in Table 2. Accordingly, the following operability in the Troll field is predicted for the Cat-D rig:

- For DP operations based on WSF1, the CAT-D rig will have 99.3% uptime yearly on station-keeping, and 0.7% down time due to environment exceeds DP capability.
- For DP operations based on WSF2, the CAT-D rig will have 92.8% uptime yearly on station-keeping, and 7.2% down time due to environment exceeds DP capability.
- There is 6.5% increased DP operability if DP operation is based on WSF1 instead of WSF2. It should be noted that this figure is indicative and is based on the static DP capability only. In real operations the rig may be able to maintain position, but still have down time on drilling, due to, e.g. heave motion or other constraints from the riser system.

Table 2: Yearly occurrence probability for each metocean case in the Troll Field

Environment in the Troll Field	Case 1	Case 2	Case 3	Case 4	Case 5	> Case 5 (wind > 23 m/s)
Yearly Probability	16.3%	32.9%	28.3%	15.3%	6.5%	0.7%
Uptime for WSF1:	99.3%					0.7%
Uptime for WSF2:	92.8%				7.2%	

From the risk analysis perspective, the 6.5% in Table 2 is a representative probability to describe the likelihood of the rig slowly drifting off position in the Troll field after single failures (fire/flooding, or 11kV bus coupler) result in loss of two thrusters, while the DP operations are based on WSF1.

FIRE/FLOODING ON DP MOBILE OFFSHORE DRILLING UNITS

Data Sources

The following incident data sources have been searched in this study:

- IMCA annual station keeping incident reports, from 1998 to 2010 (Ref. [9]).
- DP incidents on drilling and intervention units on the Norwegian Continental Shelf, from late 1990s to early 2004 (Ref. [10]).
- DNV, WOAD database (all available data since 1998)
- IHS Fairplay Accident database (all available data since 1998)
- Other possible data sources, e.g. UK HSE, OGP, MTS DP conference proceedings, IMCA DP seminar and workshops (via open publications)

The relevant fire/flooding incidents to this risk analysis are those that are related to station-keeping. Hence, the incident data are collected primarily from IMCA station-keeping incident reports.

The incidents on mobile offshore drilling units (MODU's), specifically drilling semisubmersibles and drillships, are manually picked out from IMCA annual station keeping incident reports. DP incidents happened on other types of vessels are not included. The same applies to other incident data sources.

Regarding fire events on DP MODUs, it is important to differentiate fire (including explosion) events that are drilling related vs. station-keeping related. Take an example, the Macondo blowout disaster happened on a DP semisubmersible drilling rig. Such fire/explosion accident had caused total loss of the rig, but such fire/explosion is considered as station-keeping related. It originated purely from drilling activity. In this study we exclude fire events which apparently would have no potential impact on station-keeping, e.g. typically fires happened and confined within drilling area/drilling facility. The incident data collected in this paper hence include only fire (including explosion) events that are station-keeping related.

Fire/Flooding Incidents on DP MODUs

Four fire incidents are identified on DP MODUs from the above data sources during 1998-2010. The four events are listed below. All had resulted in rig drift-off. Rig names are made anonymous in this paper.

1. 2006 IMCA #0635 + WOAD data: Fire event and CO2 extinguisher was used to extinguish the flame. The high current caused by the harmonic filter failure caused a short duration voltage dip on the main 11KV bus. That caused all the thrusters to come off line.

2. 2007 IMCA #0750: Engine room fire and all thrusters and propeller motors are tripped.
3. 2008 IHS Fairplay data: Fire in port engine room and the drillship lost 4 out of 6 engine generators.
4. 2009 IMCA #0906: Vessel on DP carrying out drilling operations and fire alarm sounded on fire in engine room. All three gyros lost from DP because cabling was through the engine room.

The results indicate that fire on DP MODUs were not frequent. The authors had expected that more findings could have been made in the WOAD database and IHS Fairplay database. This was however not the case.

In the WOAD database from 1998 to 2009, there were in total 29 fire/explosion incidents happened on mobile offshore drilling units, 27 fires and 2 explosions. Among them, only 3 fire events happened on DP drilling units. Among them, only 1 fire event caused position loss which was likely reported in IMCA #0635. In the WOAD database there were 28 out-of-position incidents on the drilling units. All appeared to be drift-off. Only 2 events were related to DP drilling units. Neither of these two events were related to fire or flooding. In the IHS Fairplay database during 1998-2012, there were 5 fire and explosion events on mobile offshore drilling units. However, only 1 fire event on DP MODU was found with relevance to station-keeping.

No flooding event had been reported in the above data sources that caused position loss. These may indicate that position loss incident had never happened on DP MODUs due to flooding. Or this may be because of under reporting. It is speculated that if a flooding happened in one compartment and caused a DP MODU to lose position during 1998 to 2010, such event would have been most likely captured by offshore media and/or by IMCA incident database. Given no evidences are found, flooding event is not further addressed in this study.

DP Time on MODUs Worldwide

Information of mobile offshore drilling units, i.e. including semisubmersibles and drillships, has been purchased from Rigzone which is a credible data provider in the industry (Ref. [11]). It shows that during 2000-2010, the number of drilling semisubmersibles and drillships actively in the worldwide market, including both DP and non DP units, are 162 units in 2000 and 221 units in 2010.

The number of DP MODUs in the above total figure is estimated in this study. The Rigzone data contain information of DP rigs based on the available information to Rigzone. The percentage of worldwide DP drilling semi-submersibles and drillships in 2010 was 38% of the total population, and in 2000 it was 20% of the total population. The actual number of DP MODU's could be somewhat higher given missing data and uncertainties as commented by Rigzone, especially in the early years. Assumptions are hence made as follows: the percentage of DP MODUs related to the total number of drilling semi-submersibles and drillships are 25% in the first five years, 35% in the middle five years and 45% in the last three years, during 1998 to 2010. It is also assumed that in 1998 and 1999 the total number of drilling semi-submersibles and drillships, including both DP and no DP units, are 150 units worldwide. This assumption is viewed in line with the Rigzone data of 154 units worldwide in June 2000.

The Rigzone data also contain utilization of competitive drilling semisubmersibles and drillships worldwide. The averaged utilization is 80% during 2000 to 2010. This rate covers both DP and non DP units. It is expected that DP units will in general have higher utilization than non DP units, and in late years rigs were more utilized than in early years during 1998 to 2010. Hence, averaged utilization factors for DP units are assumed in this study as follows: 80% in the first five years, 85% in the middle five years, and 90% in the last three years, during 1998 to 2010.

The estimated number of DP semi-submersibles and drillships worldwide during 1998 to 2010 are listed in Table 0.1. The DP time is also calculated based on the utilization factors. It is cumulatively 651 DP years.

Table 0.1: DP time from drilling semi-submersibles and drillships worldwide (1998-2010)

Year	Semisubs & Drillships	% for DP MODUs *	DP MODUs worldwide *	Utilization *	DP Time (years)	DP Time (hrs)
1998	150 *	25%	38	80%	30.0	262,800
1999	150 *	25%	38	80%	30.0	262,800
2000	162	25%	41	80%	32.4	283,824
2001	168	25%	42	80%	33.6	294,336
2002	168	25%	42	80%	33.6	294,336
2003	167	35%	58	85%	49.7	435,219
2004	166	35%	58	85%	49.4	432,613
2005	167	35%	58	85%	49.7	435,219
2006	169	35%	59	85%	50.3	440,431
2007	169	35%	59	85%	50.3	440,431
2008	178	45%	80	90%	72.1	631,508
2009	199	45%	90	90%	80.6	706,012
2010	221	45%	99	90%	89.5	784,064
SUM					651	5,703,592

* Data based on Assumptions.

Historical Frequency of Fire in Compartments

The fire incident frequency is estimated based on the worldwide DP MODUs DP time and the identified fire events. An under reporting factors of 50% is assumed for the fire event. This may be conservative. Once a fire event happened, e.g. in engine room, it would likely be captured by offshore media and news. The IHS Fairplay database and WOAD database were likely able to include such events too. Under reporting for fire events on DP MODUs that impact positioning is expected not likely during 1998 to 2010. For less visible events involving DP equipment breakdown or position excursion but only material damages, those events may be completely not caught by the media and went under reported.

The frequency of fire in compartments is calculated as: $4 \times (1 + 50\%) / 651 = 9.2E-03$ per DP year. The frequency is small, but not negligible. Among 4 fire events, 3 happened in engine rooms. The last one, which happened in a thruster room, was a small equipment fire which was extinguished by operator. A 75% vs. 25% distribution is made for fire in engine room vs. fire in other compartments. This gives the following historical frequencies for fire in compartments on DP MODUs:

- 6.9E-03 per DP year for fire in engine room.
- 2.3E-03 per DP year for fire in other compartments.

These historical frequencies are representative to generic DP MODUs which consist of a mix of DP class 2 and class 3 semi-submersibles and drillships worldwide. The four fire events happened on two DP class 2 rigs, and two rigs with unknown DP class. None of these rigs have been built according to the Norwegian regulations, i.e. the maritime regulations from the Norwegian Maritime Authority (NMA) for mobile offshore units, in Ref. [12]. The design specification and requirements for safety (including fire safety) from NMA are generally higher than the average level in the DP drilling industry. The CAT-D rig

is built according to the Norwegian regulations. The high specifications on safety will at least warrant the same, or more likely, a smaller fire frequency than the historical value.

Quantifying a reduction factor for the occurrence frequency of fire in compartments on the CAT-D rig is not further pursued. It is difficult to derive an “averaged” picture for fire detection and fire-fighting measures for the worldwide DP MODUs. Such information is largely not available without a wide and in-depth investigation. In order to be conservative in this study, the historical fire frequency is used for the CAT-D rig in the risk analyses. It is 9.2E-03 per DP year.

IMPAIRMENT OF WELL INTEGRITY: WSF1 VS. WSF2

Frequency Model

The frequency of impairment of well integrity is modelled by the following equation:

$$P(\text{accidents}) = P(\text{position loss}) \times P(\text{fail to disconnect})$$

The term $P(\text{accidents})$ is grossly denoted as the impairment frequency of well integrity. The term $P(\text{position loss})$ is the frequency of position loss of the rig. The term $P(\text{fail to disconnect})$ is the probability of emergency disconnect failure given position loss of the rig.

The accidents after two sequential events of “position loss” and “fail to disconnect” will likely be blowout or well release. In some fortunate situations, for example, if “position loss” and “fail to disconnect” only result in rupture of riser in overbalanced operation, while BOP blind shear ram is closed and sealed, and the mud column is in place and with riser margin, the well integrity may still be maintained. However, such accident will still imply huge financial losses to the stakeholders involved in the operation.

In this study the focus is on modeling of position loss frequency and the probability of failure of disconnection. The overall frequency of accidents is obtained and this enables risk comparison between DP operations based on WSF1 vs. WSF2. There is no further modelling of accidents outcomes. Detailed modelling of accidents outcomes requires the information from drilling programs, time duration for contact with reservoir, over vs. under balanced activities, non shearables passing BOP, breakage point along riser, BOP and wellhead given excessive excursions, and so on, and much of the information was not available at the time of writing this paper.

WSF1: Slow Drift-off Behavior

If the DP operations are based on WSF1, given fire or bus coupler failure events on the CAT-D rig, and such failure event causes loss of two thrusters, this may escalate into a slow drift-off under the Metocean Case 5 condition in the Troll field. However, if the DP operations are based on WSF2, there will be no position loss.

The behavior of such slow drift-off is demonstrated by loss of Thruster No.1 and No.2 under metocean Case 5 condition. The DP capability plot in Figure 4 (Ref. [8]) indicates that the rig will not be able to maintain position. One of the worst situations is collinear wind, wave and current come from 145 degree (clockwise to the North). In this study we choose this as a representative slow drift-off situation and performed time-domain simulations. The representative slow drift-off behavior is plotted in Figure 5 for the rig excursion in the first 180 seconds (Ref. [8]). It can be seen that that approximately after 128 seconds the rig will reach the excursion limit of 58 m.

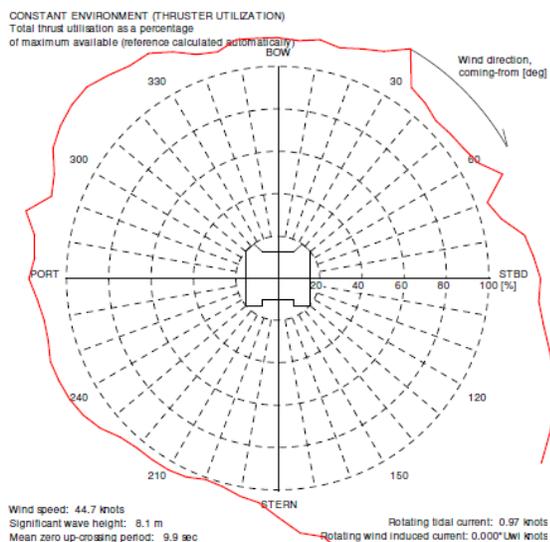


Figure 4: DP capability in Case 5 Metocean condition, upon loss of Thruster No.1 & No.2

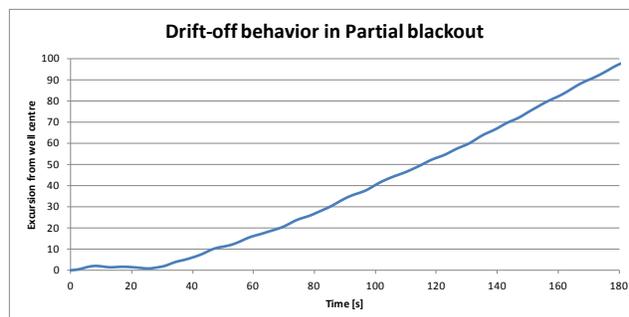


Figure 5: Representative slow drift-off behavior (Loss of Thruster No.1 and No.2 in Metocean Case 5, wind, wave and current from 145 degree clockwise from the North)

Frequency of Slow Drift-off

The frequency of slow drift-off, P(position loss), is modelled as follows.

- Frequency of fire in compartments on CAT-D rig: 9.2E-03 per DP year.
- 75% of fire may happen in engine room. The frequency of fire in engine room on the CAT-D rig is: $9.2E-03 \times 75\% = 6.9E-03$ per DP year.
- The CAT-D rig will in most of operational time be operated in a closed ring bus configuration. The operational time split between 3-split and closed ring bus is assumed as 1/3 vs. 2/3. This gives the frequency that one engine room fire can trip two thrusters: $6.9E-03 \times 1/3 = 2.3E-03$ per DP year. Note that in 3-split configuration an engine room fire will cause loss of two thrusters, but in closed ring bus configuration there will be no loss of thruster given an engine room fire. Other DGs online or in standby will be able to provide the needed power (Ref. [4]).
- For other compartments, if fire happens in one HV switchboard room there will be loss of two thrusters. However, HV switchboard rooms are not vulnerable to fire. Based on the information from the switchboard vendor Siemens, there were only two reported failures on switchboards from a total of over 75000 switchgear panels. The two failures were caused by human error during installation, and there was no reported fire incident of switchboard fire. If fire happens on other compartments except engine room and HV switchboard room, the failure effect will be in worst case loss of one thruster.
- For fire in other compartments which accounts for 25% of all fire events, it is conservatively assumed that half may happen in the HV switchboard room on the CAT-D rig. This is conservative since there is no known HV switchboard room fire event found in this study. This gives a frequency of $9.2E-03 \times 25\% \times 50\% = 1.2E-03$ per DP year.
- Frequency of bus coupler failures that can result in loss of two thrusters for the CAT-D rig is analyzed in the study. As said detailed contents are not included in this paper. Two critical bus coupler failure modes that can result in loss of two 11kV SWBD sections and two thrusters are identified, i.e. i) Short circuit or earth fault within bus coupler, and ii) Mechanical failure of

circuit breaker resulting in bus coupler failure to open on demand. The result from a detailed reliability study (Ref. [13]) is: 5.2E-04 per DP year.

- 6.5% yearly operational time to encounter the Metocean Case 5 conditions.
- All weather in Metocean Case 5 will trigger the slow drift-off.
- Frequency of slow drift-off situation: $(2.3E-03 + 1.2E-03 + 5.2E-04) \times 6.5\% \times 1.0 = 2.6E-04$ per DP year.

Probability of Failure to Disconnect

The probability of failure to disconnect, P(fail to disconnect), is modelled as follows.

- Time available to disconnect based on drift-off simulation: 128 seconds to reach excursion limit of 58 m in worst case. This minus the 30 seconds needed for the EDS, gives 98 seconds to activate EDS after loss of two thrusters and slow drift-off.
- The Auto EDS will function after the rig passes the red limit, e.g. 15 m. This is around 58 seconds since slow drift-off (Ref. Figure 5). Additional 30 seconds are needed to complete the EDS. The rig excursion is about 32 m which is well within the 58 m limit. As a safety instrumented system, the Auto EDS may fail on demand. The SIL level of such safety system is assumed to meet equivalently to SIL1 level. This is viewed conservative. For SIL1 level it implies probability of failure on demand is between 0.1 to 0.01. In this study we consider failure on demand for Auto EDS is 0.1. This is again conservative.
- The human operator should be able to activate EDS after confirmed fire in one compartment, or upon observing loss of two thrusters and the slow drift-off situation, irrespective to Auto EDS function or not. The total available time for human intervention is roughly about 1.5 minutes. Failure of human operator to activate EDS given this time window is estimated below. In this study we aim to obtain a generically conservative figure of human error instead of lengthy detailed human reliability study.
- The task nature to push EDS button is a knowledge based task, i.e. operator has to observe the situation, judge DP capability after loss of two thrusters, and activate EDS if needed. It might also be such that upon major fire in one engine room, the procedure requires EDS without any additional decision process. Such activity will then be a rule based task, i.e. action takes less time. There are 1.5 minutes available for human operator to push EDS button. Hence, time pressure is generally there. It is relevant if DP operator can activate EDS (which is normal for DP MODUs operating on the Norwegian Continental Shelf and on the CAT-D rig), or if DP operator should talk to driller and driller to activate EDS. The latter will involve communication among operators and hence longer time. Last but not the least, commercial pressure behind EDS should not be neglected, and it may delay the operator's action on EDS.
- A human error probability of 0.5 is assumed in this study as the base case. Two sensitivity cases, i.e. 0.1 and 0.9 are also investigated. These may represent lower and upper band of this human error probability.
- The ADS system will be activated if the lower flex angle reaches the pre-defined angle while EDS is not completed. The probability of failure on demand for the ADS system complies with SIL2. The failure probability on demand is between 0.01 to 0.001. In this study we consider failure on demand for ADS is 0.01. This is conservative.
- The ADS system will be disabled if non-shearables passing through the BOP. Use of non-shearables is part of well planning, and is expected to be performed with mild or moderate weather conditions. Slowly drift-off at Case 5 metocean condition plus non-shearables passing

BOP so that the ADS is “not fully functioning” is eliminated by choosing proper weather window for non-shearables.

- The probability of “fail to disconnect” is calculated from human failure to activate EDS, combined with Auto EDS failure on demand, and ADS system failure on demand. The base case, i.e. 50% of human failure to activate EDS, is calculated as: $0.5 \times 0.1 \times 0.01 = 0.0005$.
- Sensitivity case 1, 10% of human failure to activate EDS, is: $0.1 \times 0.1 \times 0.01 = 0.0001$.
- Sensitivity case 2, 90% of human failure to activate EDS, is: $0.9 \times 0.1 \times 0.01 = 0.0009$.

Frequency of Impairment for Well Integrity

The base case P(incident), i.e. frequency of impairment of well integrity, is then calculated as $2.6E-04 \times 0.0005 = 1.3E-07$ per year. This is the additional risk to impairment of well integrity for DP operation based on WSF1 (instead of on WSF2) in the Troll field. This additional risk is at a negligible frequency level.

The sensitivity of human failure probabilities gives the following P(incident):

- 10% human failure to activate EDS: $2.6E-04 \times 0.0001 = 2.6E-08$ per year.
- 90% human failure to activate EDS: $2.6E-04 \times 0.0009 = 2.3E-07$ per year.

It can be seen that by assuming operator will most likely fail to activate EDS, the frequency of impairment of well integrity is still at a negligible level which is $2.3E-07$ per year. A more detailed human reliability analysis may give a more refined human failure rate which will be smaller than 0.9. However, the message of negligible frequency of impairment of well integrity will remain unchanged.

CONCLUSIONS AND RECOMMENDATIONS

This risk analysis study is to evaluate the risk of loss of well integrity in the Troll field due to DP position loss. The focus is to analyze and compare risks between two different DP operational bases for the CAT-D rig, i.e. WSF2 (which means DP operations are based on the worst case single failure of losing two thrusters), vs. WSF1 (which means DP operations are based on the worst case single failure of losing one thruster). The conclusions are drawn as follows.

Historical Fire/Flooding Frequency on DP MODUs. Historical fire and flooding incidents (related to dynamic positioning) on mobile offshore drilling units (MODUs) during 1998 to 2010 are collected. Four fire incidents on DP MODUs are identified. They resulted in four drift-off incidents. No flooding incidents on DP MODUs are identified that had contributed to position loss. The DP operational time for DP MODUs worldwide in the period of 1998-2010 is estimated to be 651 DP years, based on rig data purchased from Rigzone and a few assumptions as listed in the end of this paper. The historical frequency of fire in compartments on DP MODUs (mixed DP class 2 and class 3 units) is estimated to be $9.2E-03$ per DP year. The frequency is small, but not negligible on a yearly basis. A 75% vs. 25% distribution is found for fire in engine room vs. fire in other compartments.

Risk of Impairment of Well Integrity: WSF1 vs. WSF2. The study concludes that DP operations based on WSF1 have equivalent safety level on well integrity as DP operations based on WSF2 in the Troll field. This is demonstrated by the following:

- Fire in HV switchboard room, and fire in engine room when the rig is operated in 3-split configuration, and bus coupler failures (short circuit, earth fault and failure on demand) can cause loss of two thrusters on the CAT-D rig.

- For DP operations based on WSF2, and yearly operation in the Troll field, there will be no position loss given fire in compartment and loss of two thrusters. Hence, no impairment of well integrity.
- For DP operations based on WSF1, and yearly operation in the Troll field, such fire situation may escalate into a slow drift-off. The frequency of such slow drift-off on the CAT-D rig is $2.6E-04$ per year for operations in the Troll field.
- The frequency of impairment of well integrity given such slow drift-off is calculated to be $1.3E-07$ per year. It is negligible. Given possible human failure of EDS activation, such frequency may increase up to $2.3E-07$ per year. This frequency for impairment of well integrity is still negligible. Therefore, the increase of risk for impairment of well integrity given DP operation based on WSF1 instead of WSF2 is negligible.

It is recommended that DP operation in the Troll field can be safely performed based on WSF1, i.e. worst case single failure of losing one thruster. Relevant DP operational procedures, DP software consequence analysis function and relevant operator trainings should be arranged prior to operation. It is also recommended that the technical and operational information and assumptions used in the risk analysis for the CAT-D rig are validated prior to the operations in the Troll field or upon changes related to emergency disconnect systems/operations. This is to ensure validity of the risk analysis.

ASSUMPTIONS

The following assumptions are used in this risk analysis.

- Number of DP MODU's worldwide. The percentage of DP MODU's related to the total number of drilling semi-submersibles and drillships are introduced. It is a range between 25% in the first five years, 35% in the middle five years and 45% in the last three years, during 1998 to 2010.
- The averaged utilization factors for DP MODU's are assumed to be 80% in the first five years, and 85% in the middle five years, and 90% in the last three years, during 1998 to 2010. DP operational time is derived accordingly.
- Once a fire event happened, e.g. in engine room, it would likely be captured by offshore media and news. This is an assumption in this study. The chance of under reporting is not big during 1998 to 2010. 50% underreporting factor for the fire incidents on DP MODUs is used in the risk analysis in order to be conservative.
- The operational time split between 3-split and closed ring bus for the CAT-D rig in the Troll field is 1/3 vs. 2/3.
- For frequency of fire in compartments rather than engine rooms, it is assumed that 50% of such fire may happen in the HV switchboard room on the CAT-D rig. This is very conservative since there is no known HV switchboard room fire event identified in this study.
- The reliability of Auto EDS system is assumed to be equivalent to SIL1 level. A probability of failure on demand is chose as 0.1.
- The reliability of ADS system is assumed to be equivalent to SIL2 level given the BOP system complies with SIL2. A probability of failure on demand is chose as 0.01.
- In a slow drift-off scenario due to DP operation based on WSF1 and loss of two thrusters, the human failure to activate EDS manually is assumed to be 0.5. This is based on the available time window to perform such action (1.5 minutes) which is not long, and commercial pressure of EDS decision. It should be noted that there are clear indications on the rig to recognize such slow drift-off scenario.

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