Risk Mitigation for Rig Compensator Lockup

Locked-to-Bottom / Pinned-to-Seabed Operations from Floating Drilling Rigs

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The following report was written to provide oil and gas operators and drilling contractors some guidance and clarity with regards to mitigating the risks associated with 'locked-to-bottom' or 'pinned-to-seabed' drilling and well operations.

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1 EXECUTIVE SUMMARY

Floating rigs utilise a drill string compensation system to provide rig heave compensation. Subsea well work that includes locked-to-bottom (also known as pinned-to-seabed) operations requires re-assessment of several risks, since the landing string / workover riser is connected to the subsea wellhead / tree. An important risk to re-assess is that of motion compensator failure, where the consequence of failure (or lock-up) may have increased, particularly during hydrocarbon flow-back operations.

Operators are concluding that motion compensator lock-up / failure is a credible risk and a potential major accident event that must be mitigated.

Operators are concluding that motion compensator lock-up / failure is a credible risk and a potential major accident event that must be mitigated. This is despite a lack of detailed records around its probability of occurrence, which is primarily due to the fact that motion compensator lock up is not a major accident hazard when it occurs during normal drilling operations, and therefore has not been widely reported. After risk assessment, many Operators have determined that a backup motion compensator is required to reduce this risk to 'as low as reasonably practicable'.

Each campaign should be risk assessed with consideration given to at least the eight situational factors outlined in Section 3 of this report, each of which may affect the likelihood and consequence of motion compensator failure. Options to mitigate this risk have developed and improved in recent years. An assessment of current options against key safety and performance criteria is presented in Section 6.3. Within a legislative regime with an expectation of continuous improvement, newly developed yet field-proven equipment should be considered in risk assessments.

In many cases, Operators have opted to install independent backup compensators designed to provide full system redundancy as this mitigates the risk 'as low as reasonably practicable'.

In many cases, Operators have opted to install independent backup compensators designed to provide full system redundancy as this mitigates the risk 'as low as reasonably practicable', compared to other solutions. For a safe and effective back-up compensator, the following features have been deemed advantageous:

- Automatic and rapid activation from back-up mode to primary mode.
- Over-tension protection, to ensure integrity of the string on an up heave.
- Under-tension protection, to protect the string from compression / buckling failure on down heave.
- Smooth back-up heave compensation after activation, to ensure even loading of the string.
- Maintain fixed work window after activation / when compensating, to ensure personnel safety.
- Anti-recoil system, to protect against sudden loss of load.

- Conditioning monitoring and alarms, to ensure system is operating within specification.
- Code compliant. Note: Although no design code specifically addresses backup compensators, primary compensators and structural load path components in drilling hoisting systems are designed to DNVGL-OS-E101 and API 8C respectively, and these codes provide best practice guidance for the design of backup compensation systems.

ICON offers a range of ARTPs (Advanced Riser Tension Protectors) to mitigate compensator lockup consequences.

Backup compensation systems have been installed and activated on live wells, and represent the solution that is most versatile to a range of situational, well configuration and loading requirements.

ICON has built a range of compensators to suit different lock-up scenarios and equipment configurations.

2 INTRODUCTION

This report describes the risks associated with, and history of, lock-up or failure of a drilling rig's primary drill string motion compensation system while conducting "locked-to-bottom" operations. It also summarises implemented or available risk mitigation solutions, and industry and design requirements.

An ARTP B-Series Compensated Tension Lift Frame deployed on an Australian LNG project.

The rig compensator presents a single point failure risk when a backup is not installed, and is a major accident hazard during flowback operations.

The rig compensator presents a single point failure risk when a backup is not installed, and is a major accident hazard during flowback operations. "Locked-to-bottom" operations refer to those on subsea wells from a floating rig where there is a landing string or workover riser connecting the rig to the subsea well head. Such operations include well testing, well completions / clean-ups and well interventions, where it is essential to support the landing string / workover riser in constant tension while allowing the rig to heave.

This report has been compiled via public domain information, surveys of Operators and Drilling Contractors, and ICON's experience from working in this niche area since 1998.

<u>Assessment of Locked-To-Bottom Risks (Section 3)</u>

When assessing the risk of rig compensator lock-up, every project is different and it is important to conduct a thorough risk assessment on a case-by-case basis to achieve an ALARP solution. Factors to consider throughout the risk assessment process include:

Every project is different and risk assessment needs to be conducted on a case-by-case basis.

a) the type of planned operations and exposure to hydrocarbons;

b) the type of rig compensator and its potential failure modes;

c) the well access system;

d) water depth and riser stiffness;

e) metocean conditions and rig heave; and

f) results from global riser analysis incorporating accidental load cases.

History of Incidents (Section 4 / Appendix A)

There is no industry database or statistics due to a general lack of reporting and disclosure, however industry papers and first-hand accounts provide a list of 26 incidents (see Appendix A). Further, there is substantial anecdotal evidence of compensator unreliability, and while rig compensator lock-up is not an everyday occurrence, it does occur relatively frequently and cannot be considered remote or rare.

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Industry Requirements (Section 5)

Currently there are no unified industry regulations, standards or requirements for managing the risk of rig compensator lock-up. Industry standards do however raise the need to assess it, and under a Safety Case regime, Operators have a legal obligation to minimise environmental, health and safety liabilities to ALARP.

Operator Past Approaches to Mitigate Risk (Section 5.2)

In some historical cases the risk of rig compensator lock-up has not been fully understood or mitigated, with low reporting leading to a perception of low probability of occurrence, and a belief that procedural controls could manage the risk. However, Operators are becoming more aware of the risks and advances in proven technology options are leading to a trend of use of back-up compensation system to achieve ALARP.

Industry Solutions (Section 6)

Include: procedural controls, rig system upgrades, weak link bails, compensating bails, compensated coiled tubing lift frames, and back-up compensation systems, each providing different levels of protection. Some (other company) marketed systems are only conceptual, and have not been designed or manufactured. In many cases a back-up compensation system for full system redundancy is required to mitigate to ALARP.

In some historical cases the risk of rig compensator lock-up has not been fully understood or mitigated, with low reporting leading to a perception of low probability of occurrence, and a belief that procedural controls could manage the risk.

Design Requirements for Back Up Compensation System (Section 7)

No codes or standards specifically address the design and manufacture of back-up compensation systems; however back-up systems should meet the same safety and functional requirements as primary systems. Governing codes include: DNVGL-OS-E101 for the overall compensation system and safety and functional requirements; API 8C for the primary structural load path; and ISO 13628-7 for global riser analysis.

3 ASSESSMENT OF RISK

Well testing, completions and interventions require a landing string or workover riser extending from the subsea wellhead to the floating rig. This report refers to these operations as 'locked-to-bottom' operations, as compared to normal drilling operations where the drill bit is free to move vertically within the well.

The risks associated with locked-to-bottom operations differ to normal drilling operations, and need to be assessed separately as a major accident hazard.

The risks associated with locked-to-bottom operations differ to normal drilling operations, and need to be assessed separately as a major accident hazard. For locked-to-bottom operations, heave compensation is essential to isolate the vertical heaving motion of the rig from the subsea wellhead. It is also essential to keep the landing string / workover riser in relatively constant tension to minimise fatigue stresses.

Without heave compensation, forces from the rig as it heaves up and down would be imposed directly on the landing string / workover riser and subsequently to the wellhead, potentially leading to catastrophic failure in either tension failure on an up-heave, or a buckling / compression failure on a down-heave.

Due to the potential consequences of locked-to-bottom risks (i.e. catastrophic or "major accident event" risk characterisation), they require the highest level of corporate scrutiny.

ALARP:
As Low As Reasonably Practicable
"A level of residual risk that is as low as reasonably tolerable and cannot be reduced further without the expenditure of costs that are grossly disproportionate to the benefit gained, or where the solution is impractical to implement."

Modern floating rigs are equipped with heave compensators, primarily designed for efficient drilling operations. During locked-to-bottom operations, the heave compensator is also used to support and provide heave compensation to the landing string / workover riser. Failure and/or lock-up of the rig's heave compensator during locked-to-bottom operations is a potential single point failure in the system.

Due to the potential consequences of locked-to-bottom risks (i.e. catastrophic or "major accident event" risk characterisation), they require the highest level of corporate scrutiny. The greater the initial level of risk, the greater the degree of systematic rigour required to show reduction to ALARP and provide transparency to the regulator, rig owner, service companies, public and other stakeholders.

ALARP (As Low As Reasonably Practicable) Definition: *A level of residual risk that is as low as reasonably tolerable and cannot be reduced further without the expenditure of costs that are grossly disproportionate to the benefit gained, or where the solution is impractical to implement.*

Risks can have safety, financial, environmental, or reputational consequences. A key factor in determining if a risk has been reduced to ALARP is the test of 'gross disproportion'. Solutions reducing risk should only be ruled out if the sacrifice involved in implementation is grossly disproportionate to the benefits. In measuring this, if there are several options they should each be considered against the present situation to determine whether further risk reduction measures are reasonably practicable. Common practice or precedent may not be considered 'ALARP' if better practicable options exist.

Features such as:

- ***automatic and rapid activation;***
- ***over and under tension* protection;**
- ***smooth back-up compensation;***
- ***recoil protection;***
- ***fixed work window;***
- ***code compliance;***

are generally accepted as required to achieve a solution that is ALARP.

Reasonableness of solutions to mitigate locked-to-bottom risks are improving in definition, with purpose built back-up equipment deployed by leading operators around the world. Features such as automatic and rapid activation, over and under tension protection, smooth back-up compensation, recoil protection, fixed work window, and code compliance are generally accepted as required to achieve a solution that is ALARP.

Factors to consider in a rig compensator lock-up risk assessment include:

3.1 TYPE OF PLANNED OPERATIONS

Different types of locked-to-bottom operations each pose different risks. In each case, in the event of rig compensator failure or hydraulic lock-up it must be determined whether the landing string / workover riser will part, and if so, what barriers are still in place and what is the potential for loss of well containment.

3.2 TYPE OF RIG COMPENSATOR

Rig compensators can be categorised as 1) active or 2) passive, although there are active-passive systems. The most common active system is the Active Heave Drawworks (AHD), and most common passive system is the Crown Mounted Compensators (CMC) / Drill String Motion Compensators (mounted above top drive).

Failure modes vary with compensator type.

Failure modes vary between systems, for example when an AHD fails the drawworks functionality is also lost, and when a CMC locks the drawworks can still be operated. Active systems can experience programming faults, computer errors, power outage, input errors, and passive systems can experience fluid contamination, seal failures, fluid/gas leaks, accidental valve closure, incorrect positioning of the cylinder stroke, impact; many of which can cause the compensator to suddenly lock. 'Ton mile' limits with AHD should also be specifically considered.

Historically, compensator lock-up has focused on those rigs with AHD due to the newer technology, electrics and complex computer programming creating a perception of higher failure probability, and due to the system failure default position to set the brakes. However, upon review of incidents that have occurred, there are an equal or greater number of issues with passive systems when compared to active systems.

3.3 WELL ACCESS SYSTEM

The two main types of well access systems are:

1. Landing string with subsea test tree inside a marine drilling riser and BOP
2. Open water completion workover riser with EDP/LRP

Each system will respond differently during a rig compensator lock up event, particularly during a down heave where the completion workover riser will more likely buckle without top tension.

Upon review of incidents that have occurred, there are an equal or greater number of issues with passive systems when compared to active systems.

3.4 WATER DEPTH

In shallow water (<500m) the landing string / workover riser can accommodate little elastic elongation before allowable stress limits are exceeded after compensator lock-up and up heave leads to excessive top tension. In deeper water (>1000m) several feet of elastic elongation can be developed without catastrophic failure. Conversely, deeper water increases susceptibility to compression failure due to increased weight.

3.5 METOCEAN CONDITIONS AND RIG MOTIONS

Rig heading and motion characteristics, in response to metocean conditions; affect the forces imposed on the landing string / workover riser, with larger heave imparting larger forces. In shallow water, a small rig heave may lead to over stress of the landing string / workover riser due to its relative stiffness.

3.6 GLOBAL RISER ANALYSIS

Required to assess normal and accidental load cases due to rig compensator lock-up, modelling the well access system including the cross section and strength of each component, the water depth, the rig motions for various metocean conditions, vessel offset, internal reservoir pressures, etc. This analysis will inform the risk assessment of rig compensator lock-up and to determine what the potential failure mode is.

3.7 EQUIPMENT MAINTENANCE AND RELIABILITY

Effective maintenance will reduce the likelihood of a compensator failure, but not eliminate the issue.

Equipment upgrades can increase the risk due to teething problems / faults with new equipment, as experienced on one rig where the AHD failed and locked three times after commissioning system upgrades where new motion reference units were installed.

3.8 HUMAN FACTORS

In addition to equipment failure / malfunction, root causes of rig compensator lock-ups have also been traced to operator error, inadequate training or inadequate procedures. Improvements on these aspects will reduce but not eliminate the likelihood of this risk.

In addition to equipment failure / malfunction, root causes of rig compensator lock-ups have also been traced to operator error, inadequate training or inadequate procedures.

A full onshore testing and training programme reduces human error, mitigates risk and helps eliminate offshore downtime.

4 HISTORY OF INCIDENTS

What is the probability or occurrence frequency of rig compensator lock-up or failure?

Several operators and independent researchers have conducted surveys and attempted to collate a database of incidents. Unfortunately, it is difficult to accurately analyse the frequency of failures quantitatively as many incidents are not reported or not disclosed publicly. There are several reasons:

There is substantial anecdotal evidence to suggest that rig compensator lock-up incidents occur relatively frequently.

a) Incidents that occur during normal drilling operations often have minor consequences (i.e. small NPT), and are noted in daily rig reports but not investigated nor reported as a formal incident.

b) Incidents which occur within an organisation are often confidential and not disclosed publically.

While there is no comprehensive industry database or statistics on rig compensator lock-up incidents, ICON has compiled a list of 26 incidents since 1984 either from first-hand accounts or from other papers. See Appendix A.

In addition to these 26 incidents, there is substantial anecdotal evidence to suggest that rig compensator lock-up incidents occur relatively frequently. A study conducted by Nardone et.al. (1) lists responses from 40 survey contributors citing issues with rig compensators. A surveyed BP UK employee stated that for the North Sea rig fleet alone, there are 1 to 2 compensator lock-ups per year. Extrapolating globally, rig compensator lock-up is not a rare or remote occurrence.

5 INDUSTRY REQUIREMENTS

5.1 INDUSTRY REGULATORS

5.1.1 Australian Waters

In the Australian jurisdiction, the Regulator NOPSEMA administers the OPGGS act. (2) There are two primary safety management mechanisms which NOPSEMA uses to monitor compliance with the Act;

1. The Well Operation and Management Plan (WOMP), (3) and
2. The Facility Safety Case (FSC), (4)

A WOMP must be presented by the Operator and approved by NOPSEMA, addressing all activities associated with the full life of a well from planning, through drilling, completion, testing, production to final suspension and abandonment.

The Facility Safety Case mechanism helps ensure that the Drilling Contractor considers and manages foreseeable risks associated with the drilling of a well to ALARP.

The full range of ICON ARTP Compensated Tension Lift Frames has been field tested in Australian and more recently, Africa.

The WOMP mechanism helps ensure the Operator considers and manages foreseeable risks associated with the drilling of a well to ALARP.

NOPSEMA views the WOMP as focussed on description and definition of the well design, construction, operating plans, and identification of necessary physical "barriers" to prevent loss of containment of hydrocarbons throughout the life of the well.

A FSC is required for all vessels or facilities directly involved in the exploration, development, production or abandonment of hydrocarbon resources. The FSC for any Facility is "owned" by the owner of the Facility.

The Well Operation and Management Plan mechanism helps ensure the Operator considers and manages foreseeable risks associated with the drilling of a well to ALARP.

In the case of the drilling, completion, clean-up/testing of a development well, the MODU FSC is the responsibility of the MODU Contractor, and is prepared in close consultation with the Operator.

The FSC mechanism helps ensure that the Drilling Contractor considers and manages foreseeable risks associated with the drilling of a well to ALARP.

NOPSEMA looks for matters such as the equipment and systems relating to safety of "locked-to-bottom, live well operations", to be addressed by the FSC, but acknowledge that these complex operations are often addressed by the MODU Contractor and Operator together.

5.1.2 Norwegian Waters

Analogous to the Australian regime, the Norwegian Regulations are non-prescriptive, other than requiring management of risks to ALARP via a 'Safety Case'. A recent audit conducted by the Norwegian PSA (Petroleum Safety Authority) on the Norwegian Continental Shelf on a project found that the risk of rig compensator lock-up had not been properly assessed nor mitigated to ALARP. Refer to: Petroleum Safety Authority Norway Framework Regulation 11 (5) and Facilities Regulation 50 (6).

A recent audit conducted by the Norwegian PSA found that the risk of rig compensator lock-up had not been properly assessed nor mitigated to ALARP.

5.1.3 United Kingdom Waters

Analogous to the Australian regime, the UK Regulations are non-prescriptive, other than requiring management of risks to ALARP via a 'Safety Case'. Refer: UK Government – Offshore Installations (Offshore Safety Directive) (Safety Case) (7).

5.2 OPERATORS

Operators have acted in response to the need for approved FSCs and WOMPs, and in the interests of their own Corporate Risk Mitigation policies and profiles. The authors of this report are not aware of any openly published Operator policies addressing the specific risks of 'locked-to-bottom live well' operations.

However, the following Operators have committed to, and have deployed, back-up or auxiliary heave compensation systems for these operations. It is deduced that risk assessments for FSCs for these operations concluded that the use of auxiliary compensation system was required to reduce 'locked-to-bottom live well operations' risks to ALARP.

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Implemented Mitigations				
Operator	**Development**	**Compensator**	**Type of Mitigation**	**Decision attributes**
Chevron Human Energy	Gorgon 200mWD	Active Heave Drawworks: *Atwood Osprey*	**ICON inline compensated TLF** with "SafeLink" functionality planned as back-up to rig primary system. Rig swapped to Ocean America	Landing string in drilling riser, concern over AHD lock up risk and long flowback durations with high ton miles.
Chevron Human Energy	Gorgon 200m WD	Passive CMC: *Ocean America*	Weak Link Bails	Landing string in drilling riser.
Chevron Human Energy	Wheatstone / Iago 150-400mWD 2016	Active Heave Drawworks: *Atwood Osprey*	**ICON ARTP E Series.** ICON ARTP used in back-up mode to land out, and as the ***primary*** compensator (with rig AHD in stand-by) once locked-to-bottom.	Completion riser + EDP/LRP. Long flow-back with high ton-miles.
ExxonMobil	Io / Jansz 2013	Active Heave Drawworks: *Deepwater Frontier*	**ICON ARTP E Series planned** Planned as primary compensator with rig AHD in stand-by during well completions and flowbacks. Development plan changed to exclude rig flowback.	Finally, the wells not cleaned up to the rig. Instead this was done to the onshore production facility.
INPEX	Ichthys 235-270mWD 2015 onwards	Passive CMC	**ICON ARTP B Series.** Secondary compensation as back-up to rig primary system.	Here, landing string could self-support in drilling riser.
Quadrant Energy	Julimar 2015	Passive CMC: *Ocean Monarch*	Weak Link Bails	Proven product in 2014 & lead time suitable.
eni	Offshore Ghana Cape 3 points 800-900mWD 2016	Active Heave Drawworks: *Maersk Voyager* drillship	**ICON ARTP C Series.** Secondary compensation as back-up to rig primary system.	Landing string in drilling riser.

eni	Norwegian Continental Shelf	Passive compensator	Considered competitor back-up compensator, but to our knowledge the system was not used due to issues encountered during onshore testing.	GRA required over and under tension protection.
eni	Nigeria 600mWD	AHD	CCTLF	Drilling contractor policies
ExxonMobil	Gulf of Mexico	Active Heave Drawworks	Compensated coiled tubing lift frame as primary compensator, with rig's AHD in stand-by.	
Chevron Human Energy	Gulf of Mexico Tahiti Ph2 1200mWD	Active Heave Drawworks: *Clear Leader*	Compensated coiled tubing lift frame as primary compensator, with rig's AHD in stand-by.	
Chevron Human Energy	North Sea Alder Field2016	Passive CMC	Weak Link Bails	Adopted same as Chevron Gorgon
Statoil	Norwegian North Sea 2004 to 2010	Various rigs	Weak Link Bails	
Statoil	Offshore East Canada	Passive compensator	Back-up compensator with over tension protection only. To our knowledge, the unit was deployed but not used due to operational changes.	
Statoil	Norwegian Cont. Shelf	Passive compensator	Back-up compensator with over tension protection only.	
Lundin Petroleum	Norwegian Cont. Shelf	Passive compensator	Back-up compensator with over tension protection only.	
wintershall	Norwegian Cont. Shelf	Passive compensator	Back-up compensator with over tension protection only.	
bp	Med. Sea / West Nile Delta	Passive CMC: *Maersk* MODU	Procedural controls. ICON unaware if rig compensation system has single points of failure.	Perceived lower lockup risk with CMC (opposed to AHD). Maersk have no prior history of failures during locked-to-bottom operations.
Other	Global Since 2002	Active Heave Drawworks	Numerous operators have been using passive compensated coiled tubing lift frames as the primary compensator (with the rig's AHD in stand-by) for locked-to-bottom operations since 2002.	In the absence of back-up systems at the time, a passive CCTLF was considered a lower risk than an active AHD

5.3 DRILLING CONTRACTORS

Drilling Contractors are also re-evaluating the risks associated with 'locked-to-bottom live well operations', as they regularly review their Facility Safety Cases. Reviews account for changes to the features/capabilities of the MODU, any recommended updates that MODU sub-system Vendors have published, and for the Drilling Contractor risk management plans and well specific objectives of each Operator.

Nevertheless, few of the major Drilling Contractors have published specific policies on locked-to-bottom live well operations, with Transocean as an exception, which states that back-up or auxiliary heave compensation systems shall be used during 'locked-to-bottom live well operations'. Refer (8) Performance and Operations Policies and Procedures - Section 4.1.5 Procedure Requirements for Well Testing.

Maersk Drilling advise that they generally defer to the requirements and/or policies of the Operator. Both Stena and Noble Drilling advise that they have assessed the risk but generally defer to the requirements and/or policies of the Operator.

5.4 DRILLING EQUIPMENT PROVIDERS

As discussed in Section 3.2, different MODU primary heave compensation systems exhibit different failure mode behaviours. Vendors of MODU sub-systems often publish recommendations or cautions in Operating and Maintenance documentation. NOV, as one of the main suppliers of Active Heave Compensated Drawworks, recommend that their systems not be used for 'locked-to-bottom live well operations' without some form of back-up or auxiliary heave compensation system. Refer (9).

5.5 CODES / STANDARDS

Published Codes vary in approach to risk management and the degree of "prescription" which they present. To some degree, they may reflect the policies of the Regulator of the jurisdictions from which they emanate, but not always. The codes most relevant to 'locked-to-bottom live well operations' are:

One of the main suppliers of Active Heave Compensated Drawworks recommend that their systems not be used for 'locked-to-bottom live well operations' without some form of back-up or auxiliary heave compensation system.

5.5.1 Det Norse Veritas [DNV] / [DNVGL]

DNVGL-OS-E101 (10)

Covers a broad range of drilling plant and references both API 8C and ISO 13628-7.

It is prescriptive in relation to 'locked-to-bottom live well' scenarios.

Clause 4.2.4 states that MODUs with AHC Draw works require some other protection than the primary heave compensation system.

5.5.2 American Petroleum Institute [API]

API does not address back-up heave compensation systems, although DNVGL-OS-E101 references the following, indicating their relevance:

API 8C – Drilling and Production Hoisting Equipment (11)

Structural design, manufacture and testing of drilling and production hoisting equipment for any item in the primary load path, be it part of a primary or back-up system.

API RP16Q – Design of Marine Riser Equipment (12)

Non-prescriptive in regard to riser compensation systems. Acknowledges the various types in use.

API 16F – Specification for Marine Drilling Riser Equipment (13)

Clause 7.1: Riser tensioner systems shall be equipped with anti-recoil systems.

Clause 7.10: Riser tensioning systems are to incorporate provisions to limit damage to the riser or rig systems due to sudden loss of pressure in tensioner cylinders or tensioner rope failure or other forms of loss of tension in the primary load carrying system.

API RP 17G – Recommended Practice for Design and Operation of Completion-Workover Riser Systems (14)

Acknowledges use of riser tensioning systems, but does not address same.

API RP 5C7 – Coiled Tubing Operations in Oil and Gas Well Services

Acknowledges use of riser tensioning systems, but does not address same.

5.5.3 International Standards Organisation [ISO]

1. **ISO / DIS 16530-1.2** (15) - Currently in "Draft" form, promotes self-assessment and regulation to ALARP.
2. **ISO 13628-7** (16)
   i. Completion workover riser systems and rig compensator lock-up addressed.
   ii. Specifies rig compensator lock-up as an 'accidental load case' to be assessed and mitigated.
   iii. Covers global riser analysis and functional requirements for surface tension frames.

Clause 4.8: System design must ensure no single point failure

Clause 4.8: System design shall be fail-safe (a.k.a. fail-to-safety)

Clause 6.2.3.4: Motion compensator failure is cited as a specific "accidental load"

Clauses 3.1.1 / 4.9 & 6.2.3.4: Design for accidental loads such that the C/WO riser system is unable to transmit forces of such magnitude as to threaten barriers

Clause 6.4.11.2: Refers to "Stroke" which implies tensioner systems are in use

Appendix B.3.2.2: Tension is required to avoid global buckling

6 RISK MITIGATION OPTIONS

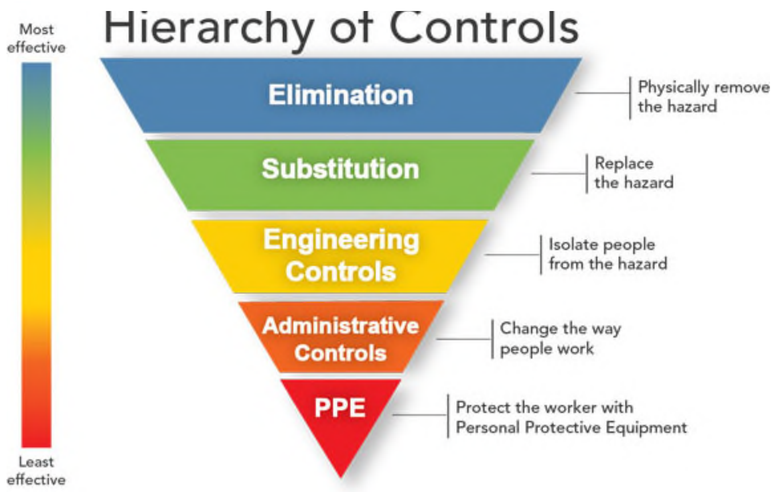
Each project must be assessed case-by-case, with mitigation strategies to ensure risks are ALARP.

6.1 HAZARD CONTROL HIERARCHY

Hazard Control Hierarchy can be applied to Rig Compensator Lock-Up, with hazard controls from most to least effective categorised as;

a. Elimination
b. Substitution
c. Engineering Controls
d. Administrative / Procedural Controls
e. PPE

Hazard Control Hierarchy.



6.1.1 Elimination

A heave compensator is essential when conducting locked-to-bottom operations from a floating rig. In shallow water, compensator failure risk can be eliminated through use of a jack-up rig.

6.1.2 Substitution

Although substituting a passive for an active compensator may reduce risk (a passive compensator has fewer 'locking' failure modes, and if it does, the driller can use the drawworks and manually compensate to an extent), this does not fully substitute / eliminate the risk, as passive compensators do fail / lock-up.

6.1.3 Engineering Controls

Appropriate, well designed engineering controls provide the best means of mitigating the hazard of rig compensator lock-up to ALARP.

Appropriate, well designed engineering controls provide the best means of mitigating the hazard of rig compensator lock-up to ALARP (Section 6.2). A back-up compensator configured to provide full system redundancy eliminates single point failures and protects from over and under tension.

6.1.4 Administrative / Procedural Controls

Human factors have contributed to known compensator lock-up incidents. These can be mitigated through well trained and competent operators, correct and thorough procedures, understanding of system capabilities and operating limits, equipment maintenance. These are 'weaker' than engineering controls, and are often insufficient to mitigate major accident hazard risks.

6.1.5 PPE

PPE is the 'weakest' hazard control measure, and although should be worn as standard practice, stronger controls are required to mitigate major accident risks such as compensator lock-up.

6.2 ENGINEERING CONTROLS

Where use of a floating rig cannot be eliminated, engineering controls may be required, and a full back-up compensator is the most comprehensive solution.

6.2.1 Equipment Upgrades and Reliability Reviews

It is important to understand the reliability and potential failure modes of the rig's primary compensator by looking at historical performance and via an FMEA of the rig's system. A common failure mode of crown mounted compensators is unintentional closure of the anti-recoil valve (a.k.a. Olmsted Valve). Replacing the Olmsted valve with a new valve with a hold open function prevents unintentional closure, yet still leaves other potential single point failures in the system left un-mitigated.

6.2.2 Riser Weak Links

To our knowledge, these are only feasible in completion workover risers (open water risers with EDP/LRP) and have not been implemented on any projects. Additional risks introduced via weak link in high pressure riser should be incorporated in any risk assessment.

6.2.3 Weak Link Bails

Long bails with telescopic tubulars and shear pins designed to shear and release at a pre-determined load. The bails can be rigged up with either standard elevators or an upper and lower spreader beam to form a Tension Lift Frame. Shear pin mechanism provides over-tension protection only, and once sheared, releases full top tension.

As with any weak link / shear pin mechanism, there is stored energy in the system which will be released instantaneously. The authors are not aware of any situations where Weak Link bails have activated and sheared, hence the full extent and consequence of this sudden release of stored energy has not been observed.

Consideration also needs to be given to the effect of telescoping bails on equipment / personnel in the work window, and procedures to recover the landing string after shearing.

6.2.4 Compensating Bails

Compensating bails are rigged with upper and lower spreader beams to form a TLF.

While compensating bails appear to be a simple solution on paper, they have several limitations. These limitations include the inability to maintain a fixed working window for pressure control equipment (PCE) operations. With compensating bails, the work window expands and contracts when activated, creating avoidable hazards for the operators working inside the work window and those below on the drill floor. With a fixed work window, the upper lift point is static with respect to the PCE, using compensating bails the upper lift point will move relative to the PCE causing additional hazards.

The tension variation associated with compensating bails are typically much larger than systems with remote air accumulation capacity, which can negatively impact fatigue performance of the well components.

6.2.5 Primary CCTLF

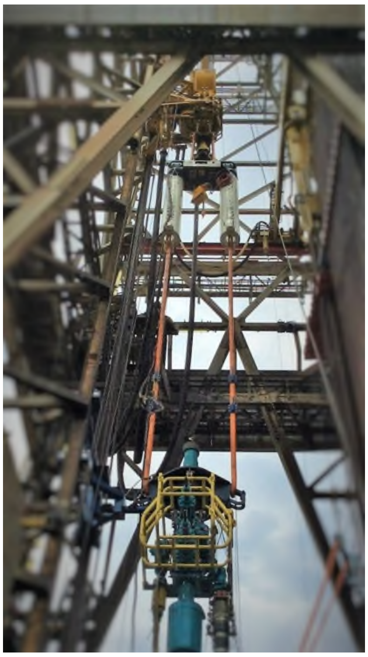
Compensated coiled tubing lift frames (CCTLFs) were first developed circa 2002, consisting of a CTLF with an integrated passive compensation system. They were often implemented as a risk reduction measure during locked-to-bottom operations with excessive ton miles on Active Heave Draw-work rigs.

While operating a CCTLF as primary, due to the time it takes to bring the AHD online, it cannot be considered as a backup system.

CCTLFs are intended to function as the primary compensator with the rig's AHD switched off (or in stand-by mode). Due to the time it takes to bring the AHD online, this cannot be considered as a back-up system. Given their inherent size and componentry, use of a CCTLF requires close consideration of rig interfacing, which can present challenges. CCTLF's also require a more detailed hazard identification and mitigation process.

6.2.6 Back-up Compensators

Back-up compensators provide the most comprehensive means of mitigating the risk of rig compensator lock-up, without introducing additional risks or operational inefficiencies. A well designed back-up compensation system will be fully independent of the rig's primary compensation system, providing full system redundancy. When the rig's compensator is functioning normally, the back-up compensator should form a rigid link, allowing the driller to operate as per normal with the rig's system.



A rigged up ARTP.

When there is an issue with the rig's system, then the back-up compensator must activate automatically and near instantly to prevent overloading the landing string / workover riser. Activation speeds of <100ms are typically required in shallow water.

Once activated, the back-up compensator must provide smooth heave compensation long enough for the situation to be made safe, and for appropriate action to be taken (i.e. activate primary compensator or shut in the well, vent the landing string and conduct a controlled disconnect).

ICON Engineering has designed and built systems that have been used and proven by INPEX, Chevron and Woodside.

6.3 SOLUTIONS COMPARISON TABLE

Evaluations of rig compensator lock up hazard mitigation solutions against key selection criteria.

Selection Criteria	**Procedural Controls (no back-up)**	**Weak Link Bails**	**Compensating Bails**	**Compensated Coiled Tubing Lift Frame (as primary)**	**Back-Up Compensator (i.e. ICON ARTP C Series)**
Back-up solution providing full system redundancy	✖ (a)	⚠ (b)	✔	✖ (c)	✔
Over tension protection (on up heave)	N/A (a)	✔	✔	N/A (d)	✔
Under tension / compression protection (on down heave)	N/A (a)	✖	✔	N/A (d)	✔
Smooth load vs stroke curve	N/A (a)	N/A	✖	N/A (d)	✔
Controlled activation	N/A (a)	✖ (e)	✔	N/A (d)	✔
Anti-recoil system (code requirement for heave comp. systems)	N/A (a)	N/A (g)	✔	⚠ (h)	✔
Condition monitoring and alarms (code requirement for heave comp. systems)	N/A (a)	N/A (g)	✔	⚠ (h)	✔
Fill and vent functionality to adjust for changing loads while unit is rigged up in the derrick	N/A (a)	N/A (g)	✖ (f)	✔	✔
Maintain fixed work window after activation / when compensating	N/A (a)	✖ (i)	✖ (i)	✔	✔
Level of rig interfaces	N/A (a)	✔	✔	✖	⚠
Ease of rig up	N/A (a)	✔	✔	✖	⚠

✔ = Good. Provides the required function / feature

⚠ = Partially provides the function / feature, but not optimal

✖ = Does not provide the required function / feature

N/A = Not applicable. Function / feature not applicable to the solution in its intended operation.

(a) Procedural controls help reduce the probability of a rig compensator lock up, but it does not reduce consequence. It does not provide system redundancy. The rig's compensator is still a potential single point failure in the overall assembly.
(b) Does not provide full system redundancy with over and under tension protection and back-up heave compensation.
(c) Intended to be operated as the primary compensator with the rig's compensator deactivated (i.e. no back-up).
(d) Over/under tension protection and back-up functionaility not applicable for a CCTLF intended to be operated as a primary compensator.
(e) When weak link activates in over tension, there will be a sudden release of stored energy when the pins shear with undesirable effects as top drive recoils upwards and SFT recoils downwards.
(f) For example load variation due to change in string bouyancy
(g) Functionality not applicable for the given equipment.
(h) Some models claim to have the stated functionality, but not all.
(i) These systems do not maintain a fixed work window when activating / compensating (i.e. side arms of frame extend / collapse changing the height of the work window. A risk for personel working in the frame and surface PCE rigged up in the frame)

7 EQUIPMENT DESIGN BEST PRACTICE

7.1 DESIGN CODES

There are three relevant drilling equipment design codes for heave compensation systems:

- **DNVGL-OS-E101, 'Drilling Plant'** (10)
  A prescriptive code, but does address back-up compensation systems, instead referring to:
- **API 8C, 'Drilling and Production Hoisting Equipment** (11)
  Most relevant to the "primary load path system" design of back-up compensation systems, and used for determining the strength of all system components.
- **ISO 13628-7, 'Design and Operation of Subsea Production Systems** – Part 7: **Completion / Workover Riser Systems**.' (16)
  Relevant to some of the operational features of back-up compensation system functions.

An ICON ARTP with optimal functionality and design features will mitigate risks ALARP.

7.2 KEY CODE REQUIREMENTS

Structural rated load and design factors should be as per API 8C with load testing to 1.5 times rated load.

The main functional requirements stated in DNVGL-OS-E101, Ch.2, Sec.5, Cl.4 are:

1. Necessary condition monitoring of the system shall be provided and available to the driller to detect abnormal conditions that may lead to failure. Alarms shall be initiated for abnormal conditions. Fluid level, leakage and stroke should be monitored as applicable.
2. DNV states single component failure shall not lead to overall system failure. Rather than act as full redundancy, a back-up should control and not exacerbated the situation.
3. Anti-recoil or similar systems should be provided.
4. Flow restriction to be arranged to safeguard against hose rupture if required.
5. Air systems shall be fitted with safety valves.
6. Compressed air shall only be used with non-combustible fluids.
7. Power failure shall not lead to critical failures.
8. Systems shall be designed for allow for a certain loss of fluid.

7.3 FUNCTIONAL REQUIREMENTS BASED ON EXPERIENCE

From experience working with and designing back up compensation systems, desirable functions include:

1. Over tension protection.
2. Under tension protection.
3. Smooth back-up heave compensation. That is, no load jumps when the system is compensating.
4. Fast response time to activate.
5. No sudden energy release / recoil when activating.
6. No or minimal load spike when activating.
7. Maintains fixed work window after activation, thus preventing damage to PCE equipment.
8. Ability to rig up wireline and coiled tubing equipment as required.
9. Minimal rig interfacing.
10. Simple and fast rig up.

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APPENDIX A HISTORY OF RIG COMPENSATOR LOCK-UP INCIDENTS

The following table presents 26 incidents which have occurred throughout the industry associated with lock-up or failure of the rig's drill string compensation system.

COMPENSATOR LOCK UP - SUMMARY OF INCIDENTS

No	Date	Rig Name	Rig Type	Compensator	Field	Operator	Reference	Drilling / Completions Phase	Event	Consequence Short Term
1	1984	Unknown	Drillship	Passive Compensator	Coral Sea	Unknown	Nardone et.al. 2016	Unknown	3 incidents. 1. Olmsted valve closed in large swells. Stopped drilling. 2. Olmsted valve close due to hose failure. No consequence. 3. Lock up during drilling. No consequence.	Minor lost time.
2	1994	Polar Pioneer	Semi-sub	CMC	North Sea 34/8-11 - Visund Field Appraisal	Norsk Hydro	IDAC/SPE 59216, Storegjerde et.al., 2000	Drill Stem Testing. Flowing 11000 bpd. Water Depth: 332m. Heave: 2m	Compensator lock up	String parted just below surface test tree. Entire well flow release into derrick. Well shut in at subsea test tree and down hole valve. No injuries. Rig had a few days downtime and resumed operations.
3	1997	Unknown	Semi-sub	CMC	North Sea	Unknown	IDAC/SPE 59216, Storegjerde et.al., 2000	Drill string hung off in BOP in anticipation of adverse weather. 3 of 8 riser tensions were leaking. Connected riser pulling tool to relieve some load (118 tons) while transferring fluid from low to high pressure side of tensioners. Water depth: 4.2m.	Compensator lock up	Hook load reached approx. 363ton. Driller lowered blocks to reduce load. On next up heave drill pipe elevator parted. Inner barrel of riser, diverter handling tool dropped through rotary. Well secured. No injuries. Rig moved to shore for major overhaul of compensator system.
4	1998	DeepSea Trym	Semi-sub	CMC	North Sea 34/10-H-2 AH-Gullfaks Sor - Rimfaks sub-field	Statoil	IDAC/SPE 59216, Storegjerde et.al., 2000	General issues with a particular rigs compensator over a period of two years. Data taken form daily reports.	Lock Up (same as other DeepSea Trym case). Install manual valve on pilot valve. Close line bleed-off due to unintentional lockup (pressure build up in closing line). Failure of pilot valve diaphragm and replaced. Hydraulic leak through bleed-off to reservoir. Insufficient air pressure available. Top up with hydraulic fluid and investigate control panel anomalies. Troubleshoot PLC failure.	Unknown
5	1998	DeepSea Trym	Semi-sub	CMC	North Sea 34/10-H-2 AH-Gullfaks Sor - Rimfaks sub-field	Statoil	IDAC/SPE 59216, Storegjerde et.al., 2000 WTN MTM#16 powerpoint slides, Arild Fossa, Expro	In-riser production clean up. Water depth: 155m. Heave: 1-1.5m	CMC lock up	70ton operating hook load. Peak hook load grater than 500ton. String parted at Subsea Test Tree Latch and dual balls closed automatically. Riser ejected approx. 15m into derrick. SFT lodged in dolly guide and riser feel back into the marine riser later found in pieces. Hydrocarbons ejected and drillers cabin window shattered. No injuries. Rig inoperative for a month.
6	1998	Unknown	Unknown	Unknown	GOM	Unknown	COIN/WTN Q&A's, 1999	Unknown	Compensator bottomed out due to fluid leak.	Pulled the CTLF lifting sub trough the elevators.
7	pre 1999	Unknown	Unknown	Unknown	North Sea	Unknown	COIN/WTN Q&A's, 1999	Unknown	Compensator lock up.	Elevators broke, flowhead swivel parted and landing string stretched.
8	pre 1999	Unknown	Unknown	CMC	Unknown	Unknown	COIN/WTN Q&A's, 1999	Setting up for perforation	Compensator lock up due to insufficient number of accumulators on line and marginal weather .	Riser parted.
9	pre 1999	Discover Seven Seas	Unknown	Unknown	GOM	Unknown	COIN/WTN Q&A's, 1999	Unknown	Lock up due to anti-recoil valve closing.	Unknown
10	pre 1999	D-534	Unknown	Unknown	GOM	Unknown	COIN/WTN Q&A's, 1999	Unknown	Lock up due to anti-recoil valve closing.	Unknown
11	pre 1999	Unknown	Unknown	Unknown	Norway	Unknown	COIN/WTN Q&A's, 1999	Unknown	Compensator lock up	Tubing hanger running tool was ripped out of horizontal tree.
12	pre 1999	Unknown	Unknown	Unknown	Unknown	Conaco	COIN/WTN Q&A's, 1999	Setting up for well test	Rapid loss of load due to loss of fluid.	Put weight on flowhead and bent tubing over 90 degrees below the flowhead.
13	pre 1999	Unknown	Unknown	Unknown	Unknown	Unknown	COIN/WTN Q&A's, 1999	Unknown	Observed compensator locking up when operating for long period in small heaves and small tide. It took a small overpull 30/40kips to release. This was thought to be due to seal friction and recommended to stroke the compensator on a regular basis.	Minor overpull
14	pre 1999	Unknown	Semi-sub	CMC	Unknown	Unknown	IDAC/SPE 59216, Storegjerde et.al., 2000	General issues with a particular rigs compensator over a period of two years. Data taken form daily reports.	Compensator failure. Failure of pilot valve diaphragm, replace same. Unable to open compensator. RTTS packer unintentionally released as compensator bottomed out. Insufficient air pressure available. Compensator moving unintentionally from open to lock position.	Unknown
15	2006	Polar Pioneer	Semi-sub	CMC	North Sea 7121-7-N-4H-Snohvit Field, Albatross sub-field	Statoil	WTN MTM#16 powerpoint slides, Arild Fossa, Expro	Production clean up	Unknown	Workover riser parted at upper connection. 19 days non-productive time
16	2007	Unknown	Unknown	Unknown	North Sea	Unknown	Nardone et.al. 2016	Drill string hung off at wellhead due to poor weather but still connected to drill string and compensating. Water depth: 100m.	Compensator lock up due to Olmsted valve closed for the large heave.	Connection popped off hang off tool on next up heave.
17	2008	Unknown	Unknown	AHD	Unknown	Unknown	Nardone et.al. 2016	Unknown. Water depth: 700m	AHD lock up when installing completion due to PLC card issues.	No damage. Electrical technicians reset the PLC to re-enable the AHD.
18	2008	Transocean Searcher	Semi-sub	CMC	6517/11-V-1H-Yttergryta	Statoil	WTN MTM#16 powerpoint slides, Arild Fossa, Expro	End of wellbore	Compensator failure.	Damage to CMC. Cylinder on aft compensator bent, bent beam and damage to the crown block fastening.
19	2011	Unknown	Semi-sub	Unknown	North Sea	Unknown	Nardone et.al. 2016	Performing slick line with landing string locked. Water depth: 165m. Heave: 1-2m.	Temporary lock up.	Landing string experienced over tension but did not fail.
20	2011	Scarabeo 5	Semi-sub	Active-Passive	6507/2-N-2H-Marulk Field	ENI Norge	WTN MTM#16 powerpoint slides, Arild Fossa, Expro	Soon after spudding well	Uncontrolled release of the top drive when lowering it for running drill pipe. Heave compensator touch screen panel suspected to have been influenced by grease. Compensator system left un-intentionally in open system.	Uncontrolled release of top drive reported as a falling object.
21	2012	Unknown	Semi-sub	Unknown	Bass Strait	Unknown	Nardone et.al. 2016	Unknown	Lock up occurred during large swells and stuck in well for 8 days with parted drill string.	Unknown
22	2012	Unknown	Unknown	CMC	North Sea	Unknown	Nardone et.al. 2016	Well clean up	Driller operated wrong valve when attempting to increase pressure.	String parted and oil rained down on drill floor.
23	2012	Deepwater Champion	Drillship	AHD	Unknown	Unknown	Power point from Exxon	13 5/8" x 13 5/8" Casing Test	NOV said: "The low hook load combined with the short period wave when setting the packer was outside the operating limits of the AH drawworks in Active heave/ Landing Mode" Exxon reported that at the time of the incident 50% of the installed resistor banks (for dissipating the drawworks regenerative power) were offline due to repairs on the resistor cooling lines. Due to the restricted capacity of the AHD together with the short period vessel heave encounted, led to the AHD falling out of phase with vessel heave, resulting in the failed drill string.	Parted 5 7/8" pipe at rotary. Contents ejected onto drill floor. No injuries.
24	2012	Deepwater Frontier	Drillship	AHD	Australia	ExxonMobil	Personnal account from Exxon	Running casing	Rig had recently undergone a major upgrade, including an upgrade the the AHD system. There were a number of issues with the AHD after the upgrade, in one instance triggering a lock up and a ~350t overpull at the wellhead. Cause, amongst other factors, was tbeleived to be motion reference units installed incorrectly giving incorrect input data to the AHD.	350t overpull at wellhead due to lockup. No injuries.
25	Unknown	Unknown	Unknown	AHD	Norway	Unknown	Power point from INPEX	Unknown	Electric drawworks compensation failure on two occasions.	Riser parted.
26	Unknown	Stena Clyde	Semi-sub	CMC	Norway	Unknown	Power point from INPEX	Performing slick line with landing string locked.	DSC locked up.	Flowhead was moving as rig heave hitting the drill pipe etc. Driller got drawworks functioning and followed heave manually. DSC came good.

Note: This summary of compensator lock up incidents has been compiled based on public domain information, existing industry reports and first hand accounts from from Operators / Drilling contractors. It has been compiled based on the information available. It is a summary only and not comprehensive nor complete,. It may contain errors.