Study on Mooring System Integrity Management for Floating Structures

FINAL REPORT

Submitted to

The Bureau of Safety and Environmental Enforcement (BSEE)

Submitted by

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EXECUTIVE SUMMARY

The U.S. Department of the Interior (DOI), Bureau of Safety and Environmental Enforcement (BSEE), Technology Assessment Program, has specific interest in Safety and Technology Verification in the U.S. Outer Continental Shelf (OCS). As the result of ABS Consulting's proposal entitled "Mooring System Integrity Management for Floating Structures," submitted in response to Broad Agency Announcement *E14PS00018, Safety and Technology Verification of Oil & Gas Operations in the U.S. OCS*, BSEE awarded contract E14PC00038 to ABS Consulting.

The scope of work was to assess in-service inspection and monitoring of permanent mooring systems, and was split into the following seven tasks:

Task	Description
1	Literature review of codes, standards, and other relevant documents
2	Conduct a gap analysis (U.S. vs. International codes and standards)
3	Recommendations to BSEE of filling the gaps
4	Review of existing inspection techniques
5	Gap analysis of inspection technology
6	Development of new techniques for inspection, monitoring, and life extension
7	Final report and documentation

The scope of this study encompassed only post installation monitoring and inspection, and does not address fabrication and installation quality control and quality assurance. Both are vital to integrity management of the mooring system. Fabrication and installation quality assurance (QA)/quality control (QC) methods are well established. By contrast, a high quality, comprehensive in-service monitoring and inspection program is more challenging and there is room for meaningful improvements.

The greatest value of in-service inspection is in finding unexpected degradation or damage, normally due to previously unexpected mechanisms (e.g., microbial action, excessive wear at the touchdown point [the thrash zone], interaction between different material types, out-of-plane bending of chain). In-service inspection is currently capable of finding larger scale, more obvious degradation such as pitting corrosion, excessive abrasion, etc. It is not good at finding smaller scale defects such as fatigue cracks in chain, wire breaks inside wire ropes, etc.

TASKS 1, 2 & 3 – CODES AND GAP ANALYSIS

The main standards addressing monitoring and inspection that are incorporated through reference by BSEE in U.S. regulations are the American Petroleum Institute Recommended Practice (API RP) 2I (inspection) and API RP 2SK (stationkeeping). API RP 2I gives very good detail on the inspection of mooring components, but was developed primarily for Mobile Offshore Drilling Unit (MODU) moorings. Therefore, it is largely based on in-air inspection. The latest revision includes information on inspection of permanent mooring systems, but these are almost exclusively done by either divers or remotely operated vehicles (ROV), and are based on visual inspection. There is some discussion on measurements, but it is limited. The inspection situation is further complicated by (1) the potential hazards to divers inspecting a potentially moving mooring system; (2) the potential damage to the mooring system caused by ROV contact; and (3) the need to clean components of marine growth in order to inspect/measure them (and the resulting increase in corrosion due to the cleaning).

Mooring Integrity Management: None of the standards assessed give significantly better information on the actual inspection process than API RP 2I, but they do provide much better information on the overall inspection philosophy. One of the main areas where other standards give added value is in planning the life cycle of the mooring system. Some standards recommend that an overall risk assessment be conducted on the mooring system, prior to installation. The assessment helps determine (1) where inspection should be focused; (2) what special measures should be taken; and (3) the course of action to be taken in the event of mooring system impairment. The results are then entered into the Mooring Integrity Management (MIM) plan. The lack of requirement for a MIM plan is a major gap in the U.S. regulations. In addition, the MIM should be updated on a regular basis, based on monitoring of the mooring system for possible changes over time, and any significant changes to the unit being moored that could affect the mooring system response.

Baseline (Post Installation) Survey: Another area that should be improved is the requirement for a baseline or as-built survey. The current requirements state that the installation be verified, but lack sufficient details and guidance. Much can be learned from completing a detailed baseline survey, including accurate determination of all the main points within the mooring system. This will give valuable information on the actual installed length of mooring components (including synthetic components after they are pre-stretched). Manufacturers do not necessarily supply these data to the level of accuracy needed to compare the facility response to the design and actual metocean conditions. These ongoing comparisons between responses (e.g., through GPS monitoring) and metocean conditions can provide excellent feedback on both the integrity of the mooring system, the validity of the original mooring analysis, and the remaining fatigue life (should future life extension become an issue).

Failed Line Detection: Current standards do contain some discussion on mooring system monitoring. However, we are aware of frequent reports that mooring tension monitoring systems (MTMS) have not proven to be reliable over any significant duration. There is general industry agreement that all permanent mooring systems should have an installed failed line detection system but not necessarily an MTMS. There have been a number of cases in recent years when inspections have revealed a failed line with no information as to when the line actually failed. Continuing operations without knowledge of the failed line is an unrecognized risk with potentially severe consequences. In addition to being able to detect a mooring line failure, there should be plans contained within the MIM that establish actions to be taken on mooring line failure. The criticality of a mooring line failure should help determine the method of monitoring for a failure, and how quickly the facility personnel are notified. Some systems can have real time feedback; others will only reveal a failure when they are deployed.

Tasks 4 & 5 – Monitoring/Inspection Technology & Gap Analysis

The intent of Tasks 4 and 5 was to describe the existing inspection and monitoring techniques, and identify gaps between the reliable data needed for effective monitoring and the available inspection methods. There are large gaps in the inspection of permanent moorings. While limited measurements and inspection can be carried out by divers and ROVs, the most common inspection methods are simply visual. The standard requirement of dimensional measurements can be extremely difficult underwater, and the large measuring devices can be cumbersome for divers and ROVs to manage. Equipment exists to carry out three-dimensional (3-D) scans of the mooring system that can help find areas of excessive wear or corrosion, but they are not in common use. 3-D scanning equipment should be used for the baseline post installation survey.

Devices to monitor mooring line tensions exist, but there is limited evidence that the systems are robust enough for continued operation over the years. New techniques are being developed, but most are difficult to retrofit on an existing mooring system. With some additional development, reliable, robust MTMS could be applicable to new systems prior to installation.

Mooring line failure monitoring is easier, but still not simple. The system needs to be tailored to the facility, and needs to be carefully monitored to ensure that it is working properly and giving the results expected. As an example, it is relatively easy to determine that a windward mooring line on a catenary moored facility has failed through use of a simple GPS system. But in certain cases, the leeward lines are more prone to failure because they are subject to greater interlink wear due to the larger change in shape of the catenary on leeward lines. Therefore, GPS cannot identify leeward mooring line failure.

Part of the problem with mooring line tension monitoring, or even mooring line failure monitoring, is that each system tends to be unique. It is difficult to buy an off-the-shelf system that will match both the needs and details of a specific facility. This, in turn, means that any system will be custom-made with added cost and lead time.

The conclusion is that there are large gaps between the desired monitoring data and the practicable inspection technology to provide that data. The prospects for filling those gaps in the near future are limited. This, again, reinforces the need for pre-installation QA/QC.

Task 6 – New Technologies for Monitoring and Inspection

Few, if any, would argue that better subsea inspection technology is needed, but the willingness to financially support its development is scarce. For example, electromagnetic inspection of wire rope is an old technology in air, but there has yet to be any significant advance in underwater inspection of wire ropes. While the old techniques have limitations when it comes to subsea, and these limitations will slow or limit its implementation, few new techniques have been proposed in the meantime. This report outlines some of the techniques that are being considered, but until there is a stronger desire to develop them, most mooring inspections will continue to be visual by either ROV or diver.

Mooring line tension monitoring appears to be a more manageable issue. There are companies developing components that can measure mooring line tensions in real-time, and feed the information back to the facility. In addition, there are a number of systems in use that are designed to detect mooring line failures. There is an expectation that, in the relatively near future if given the right incentives, these systems will be further developed for use in operations. One of the drivers could be the realization that many of the installed mooring systems are reaching their original design life, and the operators lack the data to be able to demonstrate that the fatigue loading is as originally expected (or less). The safety factors incorporated into the standard fatigue curves are intended to cover lack of certainty in both the loading and resistance. If the loading side can be better confirmed, then the safety factor on past experience could possibly be reduced, thereby allowing an increased future life.

CONCLUSIONS

BSEE requirements for mooring monitoring and inspection are documented in API RP 2SK, API RP 2I, and API RP 2SM (by reference in U.S. CFR). These documents are quite useful but there are gaps when compared with other standards. Filling all or some of these gaps will improve safety and mooring integrity. The gaps include:

- No requirements for a MIM plan
- Insufficient requirements for a more thorough post installation survey that will give a detailed picture of the as-installed mooring and allow correlation between analysis and measurements
- Insufficient details and guidance on the requirements for mooring line failure detection equipment, and procedures regarding what actions should be taken

There are large gaps in the existing in-service inspection technologies. While studies exist to help fill some of these gaps, it appears unlikely that there will be large advances in the short term.

Mooring system tension monitoring has been reported to lack robustness in the past, but there are systems being proposed that could improve monitoring reliability if adequate funds are forthcoming.

RECOMMENDATIONS

Throughout this report there are numerous recommendations that will improve mooring system integrity. While recommendations have not been prioritized, clearly all recommendations are not of equal importance or value. Each recommendation should be evaluated for its importance to safety and integrity, as well as the effort required for implementation.

This report was based on current practices, available proven technology, and the referenced resources. Given the potential for improvement in techniques and practices, BSEE should continue to encourage input and feedback from industry and other stakeholders.

Table 1 provides a summary of recommendations based on this report. The following are the types of gaps:

- Type A: Level of Details – the topic is covered, but additional detail on what is required would improve the requirement
- Type B: Lack of Supplement Guidelines – the subject is addressed, but additional guidelines on application of the requirement is needed
- Type C: Subject Not Covered in Current Requirements

Table 1: Summary of Recommendations to BSEE					
Rec#	**Subject**	**Gap Type**	**Std. Ref.**	**Description**	**Sect/Page Ref.**
Mooring Integrity Management (MIM) Plans					
1	Develop MIM	C	API 2SK	A MIM plan should be developed. Currently there is no API document on this subject, but we understand that API will be developing API RP 2MIM. The MIM plan should set out what inspection and monitoring is required, and how the results should be managed.	Sect. 1.2.3 Page 13 Page 21 Sect. 3.3 Sect. 6.2.5
2	MIM update schedule	C	API 2 MIM	The MIM plan should include requirements that the MIM be updated based on the results of previous inspection and monitoring.	Sect. 3.3
3	Mooring risk analysis	C	API 2 MIM	The MIM should be based on a holistic mooring system risk assessment. The outcomes from the risk analysis should be reflected in the MIM (or DWOP) in terms of monitoring and inspection plan, spares, and emergency response plan.	Sect. 3.3
4	Mooring performance standards			While not a current requirement in the U.S. OCS, international operators may have adopted a Safety Case philosophy that identifies moorings as a safety critical element. Some guidance on this approach would be beneficial to the overall safety of the mooring systems.	Page 31
Installation Verification					
5	Pre-stretch all polyester	C	API 2SM	While pre-stretching polyester mooring systems is common, it is not specifically required and should be taken into account within design & deployment.	Page 19 Page 28
6	Detailed measurement of “as-installed” component lengths	A/B	API 2I	Installed lengths can be significantly different from “contract” or “certified” lengths and it is important that the post installation (baseline) survey accurately record the installed mooring system. API RP 2I provides some detail, but there are additional details that should be documented.	Pages 6, 11, 19, 28 Sect. 3.3
Mooring System Monitoring					
7	Failure detection and alarms	C/B	API 2SK	Effective mooring line failure detection and alarm warning should be installed. (There have been a surprising number of cases in which a failed mooring system has only been discovered during a mooring line inspection.)	Pages 4, 12, 20, 28 Sect. 3.3
8	Action on mooring line failure	C	API 2SK	There should be a formal set of procedures to be followed if a failed mooring line is detected. The actual actions to be taken will depend upon many factors, but offshore personnel need to know specifically what actions to take and the urgency.	Page 29
9	Mooring line load monitoring		API RP 2SK	BSEE should consider further study into the current benefits and reliability of mooring line load monitoring. It is currently omitted from the list of gaps to be filled in (see Section 3.3) because of questionable effectiveness.	Pages 20, 28, 31, 33, 47, 61 Sect. 3.3

Table 1: Summary of Recommendations to BSEE					
Rec#	**Subject**	**Gap Type**	**Std. Ref.**	**Description**	**Sect/Page Ref.**
Periodic Inspection					
10	Inspection methods	B	API 2I	API RP 2I provides more detail than other standards largely based on visual inspection. Informative guidelines on other methods should be provided. API RP 2I should continue to consider industry needs in terms of detailed specifications and guidance on effective methods.	Pages 4-12, 20-24, 30, 36, 41, 71
Additional Recommendations					
11	Management philosophy	C	API RP 2SK	A mooring system management philosophy document should be developed. It should be the foundation upon which the mooring system is designed, fabricated, installed, and operated. The MIM, emergency procedures, mooring line failure detection methods, and other documents should be based on this document.	Sect. 3.4.2
12	Operation guidelines	C	API RP 2SK	Specifications on Mooring System Operation Guidelines should be included in API RP 2SK. Experience suggests that a well-developed operations manual for a mooring system, especially for a complex system, will increase the effectiveness of MIM and reduce risk.	Sect. 3.4.5
13	Incident reporting	C	API RP 2SK	Key to improving mooring system integrity is to learn from past failures. BSEE does require incident reporting, but more detailed systematic incident reporting (e.g., incident trigger, failure mechanism) and information sharing is recommended.	Sect. 3.4.6
14	Planning and cost of MIM	B	API RP 2SK	The cost of both inspection and monitoring is not insignificant and should be considered carefully to determine optimum effectiveness. More detailed guidance on planning an effective MIM program should be provided.	Sect. 4.6
15	Data management	C	API RP 2SK	The amount of data gathered can quickly become burdensome. A guidance document is recommended on the effective use of computerized data management systems; allowing for a good assessment of the data to be made and identifying useless or questionable data.	Sect. 4.7
16	Competence & training	C	API RP 2SK	Everything from general visual inspection onwards, needs to be performed by competent people. A guidance document is recommended that details what knowledge, training, testing, and certification (where applicable/available) should be considered as additions to training programs.	Sect. 4.8
17	Life extension	C	API RP 2SK	A guidance document is recommended that details what needs to be considered, analyzed, and documented for a mooring system life extension.	Sect. 6.5

Table 1: Summary of Recommendations to BSEE					
Rec#	**Subject**	**Gap Type**	**Std. Ref.**	**Description**	**Sect/Page Ref.**
18	Requirements	B	API RP 2SK	The three API documents incorporated into the CFR by reference are not mandatory. BSEE should consider which recommendation should be mandatory for U.S. OCS (either now or in the future).	NA
Thruster-assisted Moorings (TAM)					
It is unlikely that there will be permanent TAM systems installed in the GoM. The following points only apply if TAM is to be considered in U.S. OCS.					
19	Capability in complete blackout	C	API 2SK	Blackout needs to be addressed, but the criteria need to be established from further study.	Page 23 Page 30
20	Thrusters considered a safety critical element (SCE)	C/A	API 2SK	The purpose of using thrusters needs to be clearly defined and performance standards developed.	Page 31
21	Verification and testing	C/A	API 2SK	There is a need for verification and testing procedures that are consistent with performance standards.	Page 31
22	Operations manual	C/A	API 2SK	Effective instructions and training for operators are important.	Page 31

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LIST OF ACRONYMS

ABS	American Bureau of Shipping
ACFM	Alternating Current Field Measurements
ACPD	Alternating Current Potential Drop
ADCP	Acoustic Doppler Current Profilers
API	American Petroleum Institute
BSEE	Bureau of Safety and Environmental Enforcement
CE	Circumferential Extent
CFR	Code of Federal Regulation
CSC	Cross-sectional Change
CT	Computed Tomography
DGPS	Differential Global Positioning System
DP	Dynamic Positioning
DWOP	Deepwater Operations Plan
EMD	Electro Magnetic Detection
FBG	Fiber Bragg Gratings
FBS	FBS Incorporated™
FLS	Fatigue Limit State
FPS	Floating Production System
FPSO	Floating Production Storage and Offloading
FSU	Floating Storage Unit
GoM	Gulf of Mexico
GPS	Global Positioning System
GUL	Guided Ultrasonics Limited™
GWT	Guided Wave Testing
GWU	Guided Wave Ultrasonics
HSE	Health and Safety Executive (UK)
IADC	International Association of Drilling Contractors
IMAS	Integrated Monitoring and Advisory System
IMO	International Maritime Organization
IMR	In-Service Inspection, Maintenance, and Repair
IMRR	Inspection, Maintenance, Repair and Replacement (plan)

LIST OF ACRONYMS

IMU	Inertial Measurement Unit
ISO	International Organization for Standardization
JIP	Joint Industry Project
MBL	Minimum Break Load
MBS	Minimum Breaking Strength
MIM	Mooring Integrity Management (plan)
MMS	Minerals Management Service
MOA	Memorandum of Agreement
MODU	Mobile Offshore Drilling Unit
MPI	Magnetic Particle Inspection
MTMS	Mooring Tension Monitoring Systems
NDE	Non-Destructive Examination
NDT	Non-Destructive Testing
NMD	Norwegian Maritime Directorate
NOPSEMA	National Offshore Petroleum Safety and Environmental Management Authority (Australia)
NTL	Notices to Lessees
OCS	Outer Continental Shelf
OIS	Offshore Information Sheet
OPB	Out Plane Bending
OSCR	Offshore Installation (Safety Case) Regulations (UK HSE)
OTC	Offshore Technology Conference
PFEER	Prevention of Fire and Explosion, and Emergency Response regulations (UK HSE)
Pi	Plant Integrity Limited™
PLB	Pencil Lead Break
PT	Dye Penetrant Testing
RAT	Rope Access Technology
RBI	Risk-based Inspection
ROV	Remotely Operated Vehicle
RT	Radiography Testing
SCE	Safety Critical Element

LIST OF ACRONYMS

SEMS	Safety and Environmental Management System
SHM	Structure Health Monitoring
SIM	Structural Integrity Management (plan)
SwRI	Southwest Research Institute™
TLP	Tension Leg Platform
UK	United Kingdom of Great Britain and Northern Ireland
ULS	Ultimate Limit State
USCG	U.S. Coast Guard
UT	Ultrasonic Testing
WSN	Wireless Sensor Network

INTRODUCTION

The U.S. Department of the Interior (DOI), Bureau of Safety and Environmental Enforcement (BSEE), Technology Assessment Program, has specific interest in Safety and Technology Verification in the U.S. Outer Continental Shelf (OCS). As the result of ABS Consulting's proposal entitled "Mooring System Integrity Management for Floating Structures," submitted in response to Broad Agency Announcement *E14PS00018, Safety and Technology Verification of Oil & Gas Operations in the U.S. OCS*, BSEE awarded contract E14PC00038 to ABS Consulting.

BSEE has a requirement for mooring integrity set out in Title 30, Code of Federal Regulations, Subparts G and I, and these, in part, rely on reference to requirements set out in various American Petroleum Institute Recommended Practices (API RP) and publications. Some of the API publications have been adopted, after modification, by other national and international organizations. As an example, the ISO 19901-7 standard on stationkeeping is largely based on API RP 2SK. However, the ISO standard has been reorganized and many of the details in the wording have changed. As standards get accepted through the ISO process, other changes are incorporated into the standard. There can be significant differences between two standards or RP's initially based on the same original document, resulting in different international requirements. In addition, other nations develop and update their codes and regulations, taking advantage of advances in technology and addressing issues that may not currently be applicable to BSEE's OCS jurisdiction. BSEE wants to ensure that the current U.S. requirements for mooring integrity and monitoring represent the safest reasonable approach for its OCS jurisdiction, using the most appropriate and modern technology.

Mooring systems are an integral and sophisticated component of offshore assets. When mooring systems are compromised, they can present significant risks to asset integrity and personnel safety. BSEE aspires to reference and rely on a set of mature standards that are founded on sound engineering principles and validated with extensive in-service history, exact design criteria, and a history of reviews for compliance. However, these standards don't necessarily exist for all components of mooring systems. This report will assist BSEE in determining how its regulations for *Mooring Integrity Management* compare to other worldwide regulations, what gaps exist in the regulations, and what inspection techniques are currently available. ABS Consulting, in conjunction with our parent company, the American Bureau of Shipping (ABS), prepared this report with the goal of improving BSEE and industry understanding of global mooring standards, inspection techniques, and risks.

ABS Consulting and ABS have extensive experience that add value to this project, including:

- ✓ We work closely with oil companies, drilling contractors, mooring installation contractors, inspection companies, trade organizations, equipment manufacturers and regulatory agencies.
- ✓ We act as a certified verification agent, and/or Class Society of permanent and mobile floating offshore units.
- ✓ We develop and review mooring system In-Service Inspection Plans.
- ✓ We attend offshore mooring inspections Developing design guides and standards, including ISIP rules for mooring components.

- ✓ We monitor mooring systems' continued integrity after installation (per ABS class requirements).
- ✓ We work with BSEE on related technical studies.
- ✓ We participate on industry committees on the development and maintenance of related standards.
- ✓ We are active in ongoing Joint Industry Projects (JIP) related to moorings.

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The scope of this study encompasses only post installation monitoring and inspection, and does not address fabrication and installation quality control and quality assurance (QA/QC). Both are vital to integrity management of the mooring system.

While this report for BSEE is concerned with U.S. OCS, international standards and practices that were reviewed address issues that may not currently be relevant or applicable to the U.S. OCS. These issues are included because they have the potential to become relevant in the future.

1.0 LITERATURE REVIEW OF CODES, STANDARDS AND OTHER RELEVANT DOCUMENTS (TASK 1)

1.1 OVERVIEW

The objectives of this project were to (1) perform a state-of-the-art review of existing industry and national offshore codes/standards with respect to mooring integrity aspects; (2) produce a comparison report identifying gaps between the codes; and (3) provide recommendations on which of the gaps identified between the codes merit consideration for changes to U.S. regulations to fill those gaps. Relevant codes and standards were researched, gathered, and reviewed. **Table 2** lists all documents reviewed as part of this study. Only current revisions in use were considered.

The three main mooring standards incorporated into regulation by reference within the U.S. Code of Federal Regulations (CFR) are the API RP 2SK, API RP 2I, and API RP 2SM. In addition to these, there are a number of Notices to Lessees (NTLs) that were reviewed. The Memorandum of Agreement (MOA) OCS-04 Floating Offshore Facilities dated 28 February 2008, between the Mineral Management Service (MMS) and the U.S. Coast Guard (USCG), was reviewed and discussed with the USCG. The results of that discussion have also been included in this report.

The main relevant International Standards are the ISO 19900 series of standards developed by ISO TC67/SC7, "Petroleum and Natural Gas Industries – Offshore Structures." Of this series of standards the primary mooring standard is ISO 19901-7:2013 "*Petroleum and Natural Gas Industries – Specific Requirements for Offshore Structures – Part 7: Stationkeeping Systems for Floating Offshore Structures and Mobile Offshore Units*."

Polyester moorings, the primary offshore synthetic mooring component, is one of the many manmade fiber ropes included in API RP 2SM. Polyester moorings are covered under ISO 18692:2007 "*Fiber Ropes for Offshore Stationkeeping – Polyester,*" and ISO 19901-7 has limited discussion on synthetic fiber ropes.

Regulations from the United Kingdom (UK), Norway, Australia, and Canada were reviewed, and there was investigation to determine if any other countries had specific requirements for monitoring/ inspection. It was thought that Brazil, with its large amount of deepwater offshore floating facilities, may have some requirements; however, it was found that there were no specific regulations covering monitoring and inspection. Brazil relies on the API standards. Canada references ISO 19901-7 for stationkeeping and states in its regional Annex B.3 that most of the requirements of the Norwegian Annex B.2 apply to Canada. The Norwegian NORSOK standards present high-level requirements regarding in-service inspection programs. The relevant standards are general in nature, applying to all types of offshore facilities.

Classification society requirements were not included in the scope of this project because of the number of classification societies and an assumption that the class requirements for mooring integrity would not be significantly different than the documents reviewed.

There tend to be two types of national regulation: (1) those that are actually passed into law and (2) those that are issued as "Safety Notices" or "Guidance Notices." Governments use items such as

Safety Notices (UK Health and Safety Executive [HSE]) or BSEE NTLs to “require” other actions. As an example, UK HSE required operators to inspect the chain in trumpet bells’ mouths to ensure that there was no damage after a specific case was identified. These “one off” notices tend to be very specific for a particular item and are not necessarily part of any code or standard. The expectation is that, should the cause be found to be prevalent, the codes will eventually be updated to include the item. A number of these specific Safety Notices/NTLs have been included, but the list is unlikely to be complete. There could be a large number of Safety Notices/NTLs that are extremely specific and of no real relevance to this report.

Table 2: Main Codes/Standards Reviewed

Number	Revision	Title
API RP 2I	3rd Edition, 2008	In-service Inspection of Mooring Hardware for Floating Structures
API RP 2SK	3rd Edition, 2005 (Addendum, 2008)	Design and Analysis of Stationkeeping Systems for Floating Structures
API RP 2SM	2nd Edition, 2014	Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring
API RP 2FPS	2nd Edition 2011	Recommended Practice for Planning, Designing, and Constructing Floating Production Systems
ISO 19901-7	2nd Edition, 2013	Stationkeeping systems for Floating Offshore Structures and Mobile Offshore Units
ISO 19904-1	1st Edition, 2006	Floating Offshore Structures – Part 1: Monohulls, Semi-submersibles and Spars
ISO 18692	1st Edition, 2007	Fiber Ropes for Offshore Stationkeeping – Polyester
NORSOK N-001	2012	Integrity of Offshore Structures
NORSOK N-005	1997	Condition Monitoring of Load Bearing Structures
HSE Offshore Installation Moorings (IS 4/2013)	2013	UK HSE Offshore Information Sheet No. 4/2013
HSE Research Report 444	2006	Floating Production System (FPS) Joint Industry Project (JIP) FPS Mooring Integrity
HSE FPSO-Mooring Inspection (SN-3/2005)	2005	Floating Production Storage and Offloading (FPSO) – Mooring Inspection
UK Mooring Integrity Guidance (MIG)	2008	UK Mooring Integrity Guidance
NOPSEMA	2010	Offshore Petroleum and Greenhouse Gas Storage (Safety) Regulations 2009
BSEE NTL 2008-G09	2008	Guidelines for Moored Drilling Rig Fitness Requirements for Hurricane Season
BSEE NTL 2009-G03	2009	Synthetic Mooring Systems

1.2 Outline of the Codes and Standards

The following sub-sections give a high level overview of the codes and standards that were reviewed as part of this study. Additional details are provided in the code-specific **Tables 16 through 24** (provided in Appendix A) for API RP 2SK, API RP 2SM, API RP 2I, ISO 19901-7, ISO19904-1/API RP 2FPS, HSE IS 4/2013, UK MIG, NORSOK N-001, and N-005, respectively.

1.2.1 API RP 2SK

API RP 2SK (stationkeeping) is one of the three main mooring standards incorporated into regulation by reference within the CFR. It is the basic design document for mooring systems and can be used for both temporary (MODU) and permanent moorings. It is primarily a design document that gives little information or requirement for post installation inspection or monitoring. The first reference is in subsection 2.5.6, which states that "A regular inspection program is essential to monitor the integrity of the moorings." However, the main reference to system monitoring is the statement in Section 8, "Monitoring Equipment" subsection 8.4.1, "Line Tension":

> "Moored floating units should be equipped with a calibrated system for measuring mooring line tensions if the operation requires mooring line adjustment, and line tensions should be continuously displayed at each winch. For units that do not require a tension measurement device, a device for detecting mooring failure should be considered."

When mooring line adjustment is required, monitoring of the mooring line tensions is also required, but the practicality of this monitoring is not considered. There is no requirement to monitor mooring line tensions if adjustment is not required.

Some newer systems could provide the needed accuracy and reliability, but sufficient evidence is not currently available. Discussion in the API RP 2SK working group has tended to move away from "requiring" active mooring line tension monitoring unless absolutely necessary. The main requirement should be detection of mooring line failure. There have been a number of cases of permanently moored floating systems with broken mooring lines that have gone undetected until a periodic mooring inspection was done. If a monitoring system cannot even detect a broken mooring line, then perhaps the emphasis should be taken off the details (*what is the tension?*) and put onto the fundamentals (*has a mooring line actually failed?*).

ISO 19901-7 is an international equivalent to, and largely based upon, API RP 2SK, but is reformatted into an ISO "normative-informative" structure. In addition, ISO 19901-7 has incorporated some limited advice and requirement for inspection, as is covered in API RP 2I.

1.2.2 API RP 2SM

API RP 2SM is the second of the three main mooring related standards incorporated into regulation by reference within the CFR. It covers the design, manufacturing (including manufacturing inspection), installation and maintenance of synthetic mooring lines. Section 10 covers in-service inspection, but is only a few paragraphs long, and mainly points to API RP 2I. The only unique part of API RP 2SM concerning monitoring is the following:

> "**10.3 Operations:** During operations, mooring line tensions or geometry should be monitored regularly, and the mooring lines should be adjusted, if needed to maintain stationkeeping performance."

1.2.3 API RP 2I

Overview: API RP 2I is the third of the three main mooring related standards incorporated into regulation by reference within the CFR. It covers the inspection of mooring lines and mooring jewelry. It was originally written for the inspection of MODU moorings, and largely relied on "in-air" inspections. The 2008 third edition of API RP 21 incorporated inspection of permanent mooring systems, giving guidance on underwater inspection techniques.

The RP is prescriptive and gives actual discard criteria for certain types of defects (e.g., cracks on chain, broken wires on wire rope). In other cases it states that the discard criteria should be determined in consultation with the original equipment manufacturer. It also specifies exactly what inspection intervals should be used, the extent of the inspection, the speed of the mooring line (for in-air inspections), and that there should be a fully implemented material traceability program (more likely applicable to MODU moorings than to fixed installations). This RP is the only mooring inspection standard that gives strong and explicit criteria and/or guidance. However, it has its limitations.

Content: The scope of API RP 2I is set out in Section 1, which contains some excellent guidance on the purpose of the inspection, life safety during inspection (Section 1.3.3), philosophy, etc., but does not specifically require a holistic MIM plan. Section 1.3.1 outlines the inspection philosophy, basing the RP on the acceptability of a 10% loss of breaking strength, and Section 1.3.2 addresses the potential for changing this value. Although "risk-based inspection" is not specifically discussed, the topics covered suggest a risk-based approach. For example, there is discussion on the acceptability of certain degradation depending on the consequences of the component's failure. Other documents discussed in this report are explicit in the requirement for risk-based inspection and its tie-in with the MIM, but API RP 2I is not as explicit on this topic.

Section 1.4 establishes that there shall be a material traceability program, and that the service history of all components shall be tracked. While this is important for MODU moorings, it is also important that the history, manufacturing, certification, etc., of the components in a permanent mooring system are maintained. This is particularly important if components get changed out or taken out of service for in-air inspection. Annex A of the RP contains a detailed list of what should be maintained within the component history record.

The details of inspecting MODU mooring chain are discussed in Section 2 and wire rope in Section 3. It is assumed in these sections that the mooring can be inspected in-air, but gives specific acceptance criteria for defects and loss of strength. Section 2 discusses the types of defect that can be found and their relative significance, including the use of the "go-no go" gauge for chain geometric properties. It states that 100% of chain should be visually inspected for defects, and that measurements should be taken every 100 feet. Section 3 on wire rope gives similar guidance as to what to inspect, what defects can be found, acceptance criteria, etc. The two sections are detailed and informative.

Section 4 covers inspection of steel components in permanent moorings. It relies on similar acceptance/ rejection criteria to the chain and wire rope sections for MODUs, but expects that the vast majority of the inspection will be visual and underwater.

Section 4.5.2.1 states that there should be an as-built survey, and goes into some detail as to what this should entail. One of the reasons for the as-built survey is to ensure that there has been, for example, no damage during installation and no unacceptable twist in mooring components. The as-built survey also establishes the baseline against which subsequent surveys can be carried out. A good baseline survey is invaluable for documenting the performance of the installed system and comparing it to the expected performance. If differences are found, they can be investigated. The RP does state that in many cases an ROV can document the exact location of each component and that the metocean, draft, trim, etc., conditions of the facility at the time of the inspection should be recorded. These data should allow a good baseline recording of the mooring system and performance expectations.

Section 4.5.3 establishes the inspection schedule, giving specific criteria for when inspections should be carried out. Section 4.6 on inspection and discard criteria discusses the different areas that are subject to degradation and how they differ from MODU moorings (e.g., splash zone, touchdown point).

Section 5 covers the inspection of fiber ropes for both MODUs and permanent installations. Section 5.2.2 discusses the destructive inspection and testing of insert pieces, but recommends against including them because they have been found to be of limited benefit, and can potentially increase the risk of a mooring failure. The section goes over the types of damage that can occur and that the discard criteria need to be agreed upon with the manufacturer. It also discusses other potential damage mechanisms such as soil ingress, twisting, marine growth, etc. Additional information is given on the as-built survey, and how it is important to estimate the elongation of lines due to the installation tension. Here it explicitly mentions the use of these data to compare against future measurements.

Probably the biggest drawback of the RP is that it is not particularly helpful on what to do in an underwater inspection. It is primarily a MODU mooring inspection document, based largely on in-air inspection of moorings, which has been extended to the underwater inspection of permanent systems. It covers the same type of ground (e.g., chain dimensions over a number of links, inspection of the jacketing of sheathed wire rope, looking for corrosion) but that guidance is of extremely limited value when the inspection relies on an ROV, or when there is very limited visibility. What it tends to lack is an overall holistic view of mooring integrity monitoring.

1.2.4 International Standards

The main relevant International Standards are the ISO 19900 series of standards developed by ISO TC67/SC7, "Petroleum and Natural Gas Industries – Offshore Structures." Of this series of standards the primary mooring standards are the following:

- ISO 19901-7:2013 "Petroleum and Natural Gas Industries – Specific Requirements for Offshore Structures – Part 7: Stationkeeping Systems for Floating Offshore Structures and Mobile Offshore Units"
- ISO 19904-1:2006 "Petroleum and Natural Gas Industries – Floating Offshore Structures – Part 1: Monohulls, Semi-submersibles and Spars" (very similar to API RP 2FPS published in 2011)

Polyester moorings – the primary offshore synthetic mooring component, but only one of the manmade fiber ropes covered in API RP 2SM – are covered under ISO 18692:2007 "Fiber Ropes for Offshore Stationkeeping – Polyester." ISO 19901-7 has limited discussion on synthetic fiber ropes.

1.2.5 ISO 19901-7:2013

ISO 19901-7 is largely based on API RP 2SK, but has been completely reformatted into a "normative/ informative" structure. (Note that API RP 2SK is currently under revision with a 4th Edition publish date of December 2016. Although it will be reformatted to be similar to the organization of the ISO standard, it will have more up-to-date content than the ISO standard.)

The monitoring requirements in ISO 19901-7 (Clause 11.3) are very similar to the requirements in API RP 2SK. Whereas API relies mainly on API RP 2I for inspection of moorings, there is no equivalent in the ISO series. However, 19901-7 does include a clause dealing with in-service inspection of moorings, which is not covered in 2SK. The philosophy is covered in Clause 5.4, which specifies that:

> “At the planning stage, a philosophy for inspection and maintenance shall be developed and documented, to ensure full consistency with the design of the stationkeeping system and its components. A critical assessment shall be made of the ability to actually achieve the intended objectives through inspection and maintenance efforts.”

Clauses 12 and A.12 then cover the details of such a plan under the heading “In-service inspection, monitoring and maintenance.” The clause is not as prescriptive as API RP 2I in that it leaves it to the dutyholder to develop a Structural Integrity Monitoring (SIM) plan and decide on the frequency and scope of inspections (less monitoring and more inspection, or vice versa). However, it is explicit in stating that the purpose of the SIM is to ensure the integrity of the stationkeeping system throughout its design service life. It strongly suggests that a third-party review of the SIM should be undertaken.

A requirement of the SIM is the development and maintenance of a database on the mooring system. In addition to the database, there should be an evaluation that is continually updated to reflect the current condition of the mooring system and provide assurance that it is fit for purpose. Based on the information gained from the database and evaluation, parts plans are developed and implemented.

The informative Annex A in this ISO standard gives additional details of some of the other inspections that should be carried out. The 2013 edition of 19901-7 was not modified to account for the 2008 inclusion of permanent mooring system inspection covered by the 3rd Edition of API RP 2I; however, 19901-7 does reference RP 2I for the “above water inspection” of certain components.

Annex A gives more details than API RP 2I on the inspection of fairleads, and the change out of, for example, liners on large bending shoes. Other top components that interact with the mooring system are also included (e.g., linear winches, chainstoppers, roller fairleads).

ISO 19901-7 Annex A gives limited discussion on inspection of subsea components. While far less extensive, it follows the basic outline approach used in API RP 2I.

1.2.6 ISO 19904-1 (2006)/ API RP 2FPS (2011)

API RP 2FPS (2nd Edition) is merged with ISO 19904-1. The philosophy of the in-service inspections and maintenance of the floating installations presented in the API RP 2FPS and ISO 19904-1 (Clause 18 of the both standards), follows the philosophy presented in the ISO 19902 (2007) for fixed structures. The ISO approach to in-service inspection requirements adopts the SIM methodology and also applies risk-based Inspection (RBI) procedures. The inspection types for planning and implementing inspection programs are given in Section 18.4.3 of both standards.

The default inspection intervals and scope for the main structures are also presented. However, similar to ISO 19902, the API RP 2FPS/ISO 19904 focuses on the requirements for the SIM program. It is also states that the requirements of the Recognized Classification Society which classified the unit should be implemented in the inspection program.

In both ISO 19902 and API RP 2FPS, the high-level schematic of the SIM cycle is provided. As illustrated in **Figure 1**, the four stages of the SIM are shown to involve data collection, evaluation and development of inspection strategy, and a detailed inspection program.

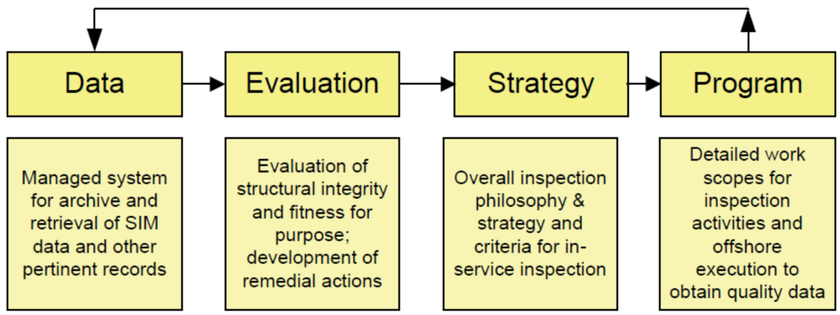

Figure 1 – Four Stages of the SIM

For stationkeeping systems, Clause 17.2.3 recommends that:

> "Monitoring of mooring line tension or line angle should be performed to detect line failure, for example, by instrumentation, remotely operated vehicle (ROV) inspection or underwater cameras. Local winch and chain-stopper control shall be specified, and can involve remote control and monitoring of winch, chainstopper and line parameters."

Some typical monitoring programs that have been implemented for different structural configurations are also presented in Clause A.18.4.7:

a) Monohull:

- forces in critical mooring hardware and angle of departure of mooring lines
- motion response monitors to support helicopter operations
- ballast level monitors in the control room
- motion monitoring in waves and swell (measurement can be a requirement of helicopter operation support)

b) Semi-submersible:

- forces in critical mooring hardware and angle of departure of mooring lines
- crack growth and development in a critical structural member or brace
- leak detection in non-flooded members
- weight growth, weight distribution and stability
- ballast level monitors in the control room
- motion monitoring in waves and swell (measurement can be a requirement of helicopter operation support)

c) Spar:

- humidity detectors where leak before break strategy has been adopted, as appropriate
- tension in mooring lines

1.2.7 ISO 18692:2007

ISO 18692 is very limited in its scope and contains little additional information. It was incorporated by reference into API RP 2SM first edition, but all the relevant or needed clauses have been directly incorporated into API RP 2SM third edition, without need for referencing the ISO.

1.3 Overview of National Regulatory Requirements

Regulations from the following countries have been reviewed:

- United States of America (NTLs only in this section)
- United Kingdom of Great Britain and Northern Ireland (UK)
- Norway
- Australia

A number of other countries were investigated to determine if they had monitoring or inspection requirements of their own (in particular Brazil, with its extensive deepwater moored offshore infrastructure). It was found that there were no specific regulations covering monitoring and inspection in Brazil; it relies on API standards.

Canada was also investigated, but they reference ISO 19901-7 for stationkeeping. The Canadian regional Annex B.3 states that most of the requirements of the Norwegian Annex B.2 apply to Canada.

The following sub-sections give a high level overview of the regulations in each of the countries identified above (as opposed to the standards that have already been addressed).

1.3.1 United States – BSEE and USCG

BSEE NTLs were reviewed. The following were identified as being relevant to the scope of this report:

1. BSEE "Synthetic Mooring Systems," Notice to Lessees (NTL) No. 2009-G03, http://www.bsee.gov/Regulations-and-Guidance/Notices-to-Lessees/2009/09-g03/, Effective Date: January 27, 2009, Expiration Date: January 27, 2014, Date Accessed: December 15, 2014
2. BSEE "Guidelines for Moored Drilling Rig Fitness Requirements for Hurricane Season," http://www.bsee.gov/Regulations-and-Guidance/Notices-to-Lessees/2008/08-g09/, Effective Date: June 1, 2008, Expiration Date: December 1, 2013, Date Accessed: December 15, 2014

Those two NTLs refer to guidance contained in the following documents:

- API "Design, Manufacture, Installation and Maintenance of Synthetic Fiber Ropes for Offshore Mooring," API RP 2SM, 2nd Edition, July 2014
- API "In-service Inspection of Mooring Hardware for Floating Structures," API RP 2I, 3rd Edition, April 2008
- API "Design and Analysis of Stationkeeping Systems for Floating Structures," API RP 2SK, 3rd Edition, October 2005 (Addendum May 2008)

It should be noted that although both NTLs are past their expiration date, they are listed on the BSEE website, and NTL 2014-N01 eliminated all expiration dates for NTLs listed on the BSEE website. The current Information to Lessees (ITL) are not applicable to this report.

In addition to the BSEE NTLs, the 28 February 2008 MOA between MMS and USCG on the subject of Floating Offshore Facilities (MOA: OCS-04) was reviewed and discussed with CDR Tracy Phillips of USCG in order to determine if there were any additional USCG requirements.

1.3.2 BSEE NTL 2009-G03

This NTL sets out requirements for the deepwater operations plan (DWOP) (pursuant to 30 CFR 250.287) specific to the use of synthetic mooring systems in deepwater operations. In this context, synthetic mooring systems are considered new technology, which involve alternate procedures and equipment to gain BSEE approval for use in operations. The NTL states the requirement for an Inspection, Maintenance, Repair and Replacement Plan (IMRR) also known as an additional or supplement DWOP. For permanent production facilities with moorings comprised of synthetic rope of unproven design, a supplement DWOP must be submitted containing a QA plan and a discussion of the new technology. The NTL provides guidance on what should be included in the DWOP, particularly associated with design considerations and inspection acceptance criteria. The NTL also provides guidance on appropriate inspection methods and when these should be carried out, and guidance on retirement criteria for inadvertent line drops to seafloor. The NTL encourages the use of new inspection technology as it becomes available.

Guidelines are also provided for the use of synthetic mooring systems in Permanent Production Facilities and MODUs. Specific requirements for length of test inserts and instrumentation that the mooring system should be furnished with to monitor condition are provided. In addition, guidance is provided on the content of a sub-rope test plan. Appendix B provides more detailed guidance on the inspection, testing and retirement criteria for synthetic mooring lines pre-laid on the seafloor. Reference is made to API RP 2SM regarding design and testing criteria, and the development of a QA manual. Reference is also made to API RP 2SM regarding retirement criteria on inadvertent drop to seafloor, visual inspection acceptance criteria of the filter barrier, and minimum breaking load (MBL). API RP 2I is referenced regarding requirements for recordkeeping of the operational history of individual ropes; guidelines on damage assessment; and guidance on additional inspection, testing, replacement and repair.

1.3.3 BSEE NTL 2008 G09

This NTL applies to all moored rigs, including drilling, workover, and completion operations conducted by moored rigs. The NTL provides guidance for assessing/ensuring a rig's fitness or survivability during a hurricane. Specific to the scope of this report, the NTL recommends that a risk assessment be completed and mitigation measures be implemented to ensure the rig's "fitness." The NTL makes reference to guidance contained in API RP 2SK Appendix K.

1.3.4 MMS/USCG MOA: OCS-04

The purposes of the MOA, written before the split of the MMS into a number of independent organizations (which includes BSEE), was to (1) identify and clarify responsibilities of the MMS and the

USCG and (2) provide guidance for the appropriate agency approval of systems and sub-systems for floating offshore facilities. It is understood that this MOA, dated 28 February 2008, is being updated. The proposed contents of the revised MOA are not yet available for review.

Item 4 of the MOA delineates the responsibility for the stationkeeping system between BSEE (referred to as MMS) and USCG, but this item is more related to the design rather than to monitoring and inspection. Plans Item 25j covers “Mooring Inspection Maintenance Repair Replacement Plan” and states that the responsible agency is split between BSEE and USCG, with USCG taking the lead. However, the last column of comments states that “[the plans] must be submitted any time a company wants to use synthetic moorings...” thereby implying that plans do not need to be submitted in other cases. Since this MOA was drafted, there has been an increased use of synthetic moorings, along with increased confidence in their viability and survivability – to the extent that they are not subject to the special treatment that they used to have (e.g., there is no longer a requirement for insert test pieces).

In discussions with CDR Tracy Phillips of USCG, it was stated that USCG had few requirements for the moorings of permanent floating installations. However, there could be a requirement that foreign flag vessels meet IMO MODU Code, Chapter 4.12 (anchoring arrangements for surface and column-stabilized units). That chapter contained no discussion of mooring system monitoring or inspection, beyond a basic requirement that the as-installed be confirmed as in compliance with the as-designed.

1.3.5 UK – HSE

The UK operates under a Safety Case system that is overseen by the UK HSE. The basic regulations are the Offshore Installations (Safety Case) Regulations (OSCR) [2005]. These are, in turn, based on the 1992 regulations of the same name. Supplementing the OSCR are the Offshore Installations (Prevention of Fire and Explosion, and Emergency Response) (PFEER) [1995] regulations. The following lists the relevance of these regulations to mooring monitoring and inspection:

- There are limited prescriptive requirements for monitoring or inspection of the mooring system, except through the specific design codes (in this case ISO 19901-7) and by reference to documents such as Oil & Gas UK “Mooring Integrity Guidance.” There is also reference to guidance given in API RP 2I and API RP 2SM.
- The mooring system is a Safety Critical Element (SCE) and thus must have a developed Verification Scheme to demonstrate that it will be available when needed (in the case of a mooring system, continuously available) and will meet its predefined performance standard. Performance standards should be measureable and auditable, as expressed in the following quote from the HSE guidance on PFEER regulations: “Setting performance standards for measures is a crucial aspect of the assessment process. Performance standards should relate to the purpose of the system, item of equipment, procedure, etc., which they describe. They may be described in terms of functionality, survivability, reliability, and availability. They should be measurable and auditable…”
- It is the responsibility of the dutyholder (i.e., the operator for a permanent moored offshore floating facility) to develop the performance standards and verification scheme for the mooring system, but taking “… into account Oil & Gas UK Mooring Integrity Guidance...”

In addition to the coverage of the mooring system under the OSCR, there have been a number of other HSE documents that also give guidance as to what is expected of the dutyholder. Some of these guidance notes are simply covering a specific problem found in the past (e.g., specific mooring failures, loss of dynamic positioning). In many respects, these are similar to the BSEE NTLs that are issued periodically. One specific to moorings is the Offshore Information Sheet (OIS) No. 4/2013 “Offshore Installation Moorings” (an 8-page document).

UK HSE Safety Notice 3-2005 FPSO Mooring Inspection: This safety notice is applicable to weather vaning monohulls only (e.g., FPSOs, FSUs) and addresses a specific problem discovered on a UK continental shelf-based FPSO. There was chain wear that resulted in loss of chain cross sectional area. The safety notice does not give a cause for the excessive wear, but does require operators to inspect chain in the bell mouth and take corrective action if necessary.

UK HSE Research Report 444 Floating Production System, JIP FPS Mooring Integrity: Research Report 444 is the final report of a JIP organized and run by Noble Denton Europe. The JIP had participants from most of the relevant sectors of the industry and looked at all types of permanently moored units, with a heavy primary focus on FPSOs. There was a heavy North Sea bias, in part because of who responded to the JIP questionnaire about in-service damage and failures.

The results of the JIP are summarized in Offshore Technology Conference (OTC) paper 17499 (2005). The report and OTC paper largely present results assessing the causes and consequences of failure rather than specifically looking at the methods of monitoring and inspecting mooring systems. Nonetheless, about 10% of the report in Chapters 17 and 18 do address methods of monitoring for mooring line tensions/ failures and inspection, respectively.

Chapter 17 goes through some of the available, and potentially available, mooring line tension/failure monitoring equipment. It does not make any solid recommendations; but states that having such a system is advantageous.

Chapter 18 contains little by way of recommendations, mainly discussing the types of inspection techniques available. One point made in Chapter 18 is that the leeward mooring lines may be subject to worse wear than the windward lines. This is because of the large change in catenary shape for small changes in load when loads are low. This large change in catenary shape tends to lead to large interlink movements. When mooring line loads are high, the lines tend to be taut, so there is little change in catenary, hence little inter-link movement. Chapter 18 also suggests that an optical “caliper” may be a better method of determining chain link size/shape than the classic “go-no go” gauge suggested in API RP 2I.

Research Report 444 was used during the development of the Oil & Gas UK Mooring Integrity Guidance document.

UK HSE Offshore Information Sheet No. 4/2013 “Offshore Installation Moorings”: OIS 4/2013, which supplements UK HSE Research Report 444, states that ISO 19901-7, including the Norwegian regional Annex B.2, should be used as the basis for mooring system design where reasonably practicable and that existing systems should be reviewed for compliance with 19901-7. The main significance of Annex B.2 from the standpoint of monitoring and inspection is that there is an increased corrosion allowance requirement in B.2.3.16 (0.8mm per year in the splash zone and 0.2mm per year elsewhere). It also states that there should be an assessment for possible bacterial corrosion at the seafloor.

Paragraph 10 of OIS 4/2013 states that the dutyholder is expected to identify critical areas for inspection using the guidance of the Oil & Gas UK Mooring Integrity Guidelines in addition to classification society requirements – the frequency increasing with age (paragraph 11). The dutyholder is then to develop "…clear acceptance and rejection criteria..." for the inspection of mooring components (paragraph 12). Guidance is given in API RP 2I, but the source of the acceptance/rejection criteria is often considered to be the original manufacturer.

The dutyholder is encouraged to monitor mooring line tensions and to retain the data for at least 30 days. Where this is not practical, there must be a system in place to ascertain when a mooring line has failed. OIS 4/2013 points to the Oil & Gas UK document for suggestions and allows other techniques, but they must be appropriate for the mooring system.

Paragraph 19 states that, at intervals set by the dutyholder, data should be gathered to confirm that the mooring system is behaving as predicted by the mooring analysis under different metocean and other conditions.

Oil & Gas UK Mooring Integrity Guidance: This document is not a formal code or standard, but is included in this report because it is specifically referenced by UK HSE in OIS 4/2013, as discussed above. The scope of this guidance document states that it was originally conceived to cover FPSOs, but can be applied to all moored vessels. It covers all direct mooring components and their interface structures (e.g., fairleads). Fundamental to the document is the development of a MIM system. While the API document suggests developing a MIM, the MIM is an integral part of the Oil & Gas UK document; the executive summary is almost exclusively about the aims and content of the MIM. The MIM should include at least the following philosophical aspects (paraphrased from the document):

- Recognition that manufacturing is critical and QA/QC is fundamental to reliability
- A holistic view of the purpose and limitations of the mooring system, including what actions should be taken if its integrity is impaired
- Detailed risk study assessing the likelihood and consequences of any component/system failure that can be used to help develop an intelligent inspection and maintenance plan
- Monitoring of mooring (to some degree)
- Inspection scope driven by the risk study
- Data gathering, codifying, use, and identification of anomalies

The details of the MIM components (e.g., system description, performance standards, failure philosophy) are provided in Section 2 of the Oil & Gas UK Mooring Integrity Guidance document.

1.3.6 NORWAY

The primary Norwegian standards relevant to monitoring and inspection of permanent offshore floating facility mooring systems are the NORSOK standards, two of which are described below.

NORSOK N-001 "Integrity of Offshore Structures": This standard covers all types of offshore structures, including bottom founded and floating. It is mainly about the design, and that the integrity of the facility is ensured through the correct use of load and resistance factors. As such, the document has little to do with monitoring or inspection, but does give some general guidance (particularly on what should be done if defects are found).

NORSOK N-005 "Condition Monitoring of Loadbearing Structures": This NORSOK standard describes principles, functional requirements, and guidelines for condition monitoring of the loadbearing structures throughout their operative lifetime until the decommissioning. This standard is applicable to all types of offshore structures used in the petroleum activities, including bottom founded structures and floating structures. It is applicable to condition monitoring of complete structures, including substructures, topside structures, vessel hulls, foundations, and mooring systems.

> "The Operator shall monitor the condition of the operated offshore installation in a systematic manner. This may include development of an overall philosophy and strategy for condition monitoring, establishing in-service inspection systems and long term inspection programs, in-service inspection planning, offshore execution, data logging, evaluation and assessment, implementation of repair and mitigation measures, emergency preparedness, etc. The structural integrity may be considered based on component check, system capability assessment or / and system safety assessment."

The N-005 standard presents only high-level requirements regarding an in-service inspection program. The platform operator is responsible for preparing this program based on the characteristic of the structure, loading history, and inspection findings. No specific requirements regarding the inspection intervals are presented. However, Section A3.2 of the standard includes details regarding preparations for inspection and underwater inspection methods. More detailed guidelines regarding the in-service inspection of various types of structures (jackets, column stabilized units, ship-shaped vessels and concrete structures) are presented in the normative Annexes C through F of the standard.

Section D.2 discusses the platform integrity. The position keeping system is part of overall integrity. Section D.4 recommends that conditions of the mooring system, including lines, fairleads, winches, stopper etc., should be systematically monitored. It also states that, for the mooring system, a separate document describing inspection, maintenance, and replacement philosophy should be established. This should include inspection methods and frequencies, fabrication and installation data, acceptance data, and replacement procedures.

> "The integrity of the position keeping system, normally consisting of mooring lines, is important with respect to avoiding escalating events such as riser failures. The integrity is normally secured by a redundant design which includes allowance for a certain number of line breakages. This is documented in the design of the system."

In addition to the NORSOK standards, Norway has mandated a regional annex to ISO 19901-7. The regional annex requirements are not relevant to monitoring and inspection.

The Norwegian Maritime Directorate (NMD) has issued local regulations, including the 'Anchoring Regulations of 10 July 2009, No. 998' (NMD 998) concerning positioning and anchoring systems on mobile offshore units. The 2013 version of ISO 19901-7 Annex B.2 has been updated to reflect NMD 998.

The following are the particular points of difference to the main text, and to other mooring design codes, in 19901-7 Annex B.2:

- Enhanced test load requirements for drag anchors
- Increased corrosion and wear allowance in the splash zone
- Assessment of a two-line failure case for a 10-year return period storm condition (permanent and production unit moorings only)
- Assessment of transient motion after line failure for permanent moorings, irrespective of proximity to other installations
- Increased safety factors when connected to risers, or when in proximity to other installations (consequence class)
- 100-year return period storm condition applied (with slightly reduced safety factors) to the mooring systems of mobile offshore units. (The main ISO code applies a 5- to 10-year storm for mobile offshore units.)
- Additional requirements for drag anchors as further detailed in DNV-RP-E301
- A check (accidental limit state) on mooring line integrity for a single extreme event (typically a 100-year return period, with a safety factor of 1 applied)

1.3.7 Australia NOPSEMA

The Australian Government has instituted a Safety Case regulatory framework similar to the UK regime. The body responsible for Safety, Well Integrity, and Environmental Protection in the Australian offshore petroleum industry is the National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA). The *Offshore Petroleum and Greenhouse Gas Storage Act 2006* (Offshore Petroleum Act 2006) underpins the regulatory framework. The act is applied through the following regulations:

1. *Offshore Petroleum and Greenhouse Gas Storage (Safety) Regulations 2009* (Offshore Safety Regulations 2009);
2. *Offshore Petroleum and Greenhouse Gas Storage (Environment) Regulations 2009* (Offshore Environment Regulations 2009);
3. *Offshore Petroleum and Greenhouse Gas Storage (Resource Management and Administration) Regulations) 2011* (Resource Management and Administration Regulations 2011); and
4. *Offshore Petroleum and Greenhouse Gas Storage (Regulatory Levies) Regulations 2004* (Regulatory Levies Regulations 2004).

The Offshore Safety Regulations 2009 sets out expectations for the development, submission and maintenance of an installation's Safety Case. Part 3 of the regulations describes the process of validation of design, construction and installation, and significant modification or decommissioning of a facility. (Validation is also known as verification in other regions of the industry.) The Resource Management and Administration Regulations 2011 are associated with ensuring that the execution of offshore oil & gas operations are compatible with the optimum long-term recovery of petroleum, and sets out the expectations for well integrity management. NOPSEMA is a cost recovery agency and this is described in how levies are applied in the last of the four regulations listed above.

The *Occupational Health and Safety (Maritime Industry) Act 1993* (Maritime Industry Act 1993) is complementary to the Offshore Petroleum Act 2006. It applies to prescribed ships that are engaged in trade or commerce. The Offshore Petroleum Act 2006 applies to floating offshore installations involved in petroleum exploration and recovery, and injection and storage of greenhouse gas substances in offshore areas. NOPSEMA provides no specific technical reports or notices providing guidance on mooring integrity management for permanently moored systems, but the operator has to nominate their Performance Standards and SCE in their Safety Case. In this case, the mooring system is an SCE. The operator of a facility must submit the safety case to NOPSEMA. NOPSEMA has developed a policy on Validation.

1.3.8 CANADA

No Canadian-specific inspection and monitoring regulations have been identified for Canada, although there is a Canadian Annex within ISO 19901-7, Annex B.3. This basically states that they are the same technical requirements as for Norway.

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2.0 GAP ANALYSIS FROM REVIEW OF CODES, STANDARDS AND OTHER RELEVANT DOCUMENTS (TASK 2)

The mooring integrity not only depends on inspection and monitoring but also design, manufacture, installation, and operation in terms of project phases. This section encompasses a gap analysis of the main aspects of a permanent mooring system that may have influence on mooring integrity based on the literature review of the codes, standards and regulations.

2.1 Summary of Gaps Between API Documents and Other Referenced Documents

There is little doubt that API RP 2I gives some of the most detailed information on inspection and acceptance/rejection criteria for offshore mooring components, albeit more heavily biased towards MODU moorings and inspection in-air. The places that API RP 2I and API RP 2SK tend to be lacking are in some of the more philosophical aspects of planning and checking. Some of the areas that are better covered in other documents include:

- Post installation mooring inspection – increased description of what should be inspected and why would be of benefit
- Failed component monitoring – there is a requirement for both mooring line tension monitoring and failed component/mooring line detection for certain situations, but no general requirement. While mooring line tension monitoring can be difficult, there is significant merit in knowing when a line has parted.
- There is little information or requirement for developing a MIM plan. API RP 2I requires inspections, but there is merit in planning and timing those inspections based on a detailed review (likely a risk-based review) of the mooring system capabilities, failure probabilities, and failure consequences.

The above is not a complete list, but gives a high-level overview of some of the areas not well covered in the API suite of Recommended Practices.

2.2 Details of Gaps Between Referenced Documents

In order to help the reader interpret *Table 15: Subject Matter Table Gap Analysis* (provided in Appendix A), **Table 3** was developed to explain the different "subjects" included in the left column of ***Table 15: Subject Matter Table Gap Analysis***. In many cases the description of the subject is self-explanatory, but in other cases there could be some confusion. The intent is that Table 3 help clarify the issue.

Table 3 shows what is included in each of the codes and standards assessed as part of this study. The left hand column of the table gives a "subject" that may be addressed within the codes (e.g., type of floating facility). The right hand column provides a few details of what is included in the code subject.

In **Table 15**, the left hand column of the table again gives a "subject" and the other columns list the codes. The column for the specific code will be marked if the particular subject is addressed within that specific code/standard. In some cases, if the subject is addressed within the code, then there will be a reference section within the code quoted and there may be a very brief outline of what could be required. The intent of Tables 3 and 15 is not to repeat all that is in the codes, but to give the reader an indication if the specific subject is addressed/discussed in that particular code.

Table 15 acts as a clear gap analysis between the codes and standards. If a subject is not covered within a specific standard, then there is a gap. The table does not comment on the gaps, or whether they should be filled. In some cases there could be a gap, but a similar subject is addressed through a different approach. For example, the extent of mooring inspection can be prescriptive or it can be determined through use of risk analysis. There are advantages to both approaches. A risk-based approach allows for better use of resources; however if the risk assessment is poorly interpreted, it can lead to certain components not being suitably inspected – a prescriptive regime mandates what is to be inspected.

The gaps identified within the table were assessed as part of Task 3 of this study, with recommendations as to if and how they should be filled.

Table 3: Expanded Description of Items/Subjects Contained in Subject Matter Table (Table 15)

Item (as listed in detailed Table 15)	Discussion/Expanded Description of Items
General Description	This contains a very brief description of what is contained in the document of relevance to monitoring and inspection. It is not intended to be a complete description
Type of Floating Facility Covered	
All permanent	Marked with an "x" if the document is applicable to all type of moored floating offshore facility (not TLPs)
Ship-shaped only	Marked with an "x" if the document is applicable to only ship-shaped vessels
MODU	Marked with an "x" if the document is applicable to MODUs. While not relevant to the current study, this can help give insight to the document
Installation	
Compare installed to design	Does the standard state that the installed mooring system needs to be compared to the design condition? This is particularly important if the installation is complicated, or the design is sensitive to small changes.
Pre-stretch all polyester	While it is common practice to pre-stretch polyester moorings when they are installed so that the installed length matches the design length, not all standards require or specify that it be done.
Look for installation damage	Does the standard require a post installation inspection to check for installation damage?

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Table 3: Expanded Description of Items/Subjects Contained in Subject Matter Table (Table 15)	
Item (as listed in detailed Table 15)	**Discussion/Expanded Description of Items**
Detailed 3-D location of points on mooring system	There can be merit in carefully plotting the mooring system in full 3-D so that the exact location of each component (or the end termination of each component) is known. This can only be done accurately if the metocean conditions at the time of the measurements are known because the components will "move" as the forces on the facility change. If this initial survey is carried out carefully, it can give excellent information to be used for comparisons later in the field life.
Detailed measurement of "as-installed" component lengths	The "as-installed" length can be different from the "certified" delivery length because of stretching and bedding in. Knowledge of the as-installed length can help interpret future survey results
Track metocean conditions, draft, etc., during survey	This is critical if detailed information is recorded.
Seabed sections pulled straight	Does the code require a check to ensure that the grounded section of mooring line is pulled straight? If it is not, it can affect the mooring system response. There is likely to be a significant grounded length on catenary moored facilities in hurricane areas.
Component twist	Is there a requirement that any twist within the mooring system be noted, and does the standard contain any specific limits of twist (e.g., some allow 5 degrees of twist per link of chain)?
Monitoring	Does the standard require monitoring of the following parameters?
Line load	Is there a requirement that all the mooring line loads are monitored on a regular or continuous basis?
Position or vessel offset	Does the facility position have to be monitored and recorded (in the moored condition)? This is not the same as: Does there have to be a location tracking system installed in case the facility suffers complete mooring system failure?
Maintenance of records for defined period (normally 30 days)	If line loads or position are monitored, do the records have to be kept? If so, for how long?
Failed component	Is there a requirement that the mooring system be monitored to determine if one or more of the mooring lines has failed?
Time to detect failed component	If mooring integrity is to be monitored, then how quickly does an "alarm" need to be raised when one of the lines fails?
Failure response procedures and response plan	Is there a requirement for formal response plans of action in the event of a mooring line failure?
Failed mooring lines/components to be reported	Is there a requirement in the standard that all mooring component failures be reported?
Specific operating limits on line failure	Does the code establish specific operating limits when a mooring line fails, or is there a specific set of criteria that must be met in order to keep operating in the event of a mooring line failure?

Table 3: Expanded Description of Items/Subjects Contained in Subject Matter Table (Table 15)	
Item (as listed in detailed Table 15)	**Discussion/Expanded Description of Items**
Design verification: Compare vessel offset (under known metocean) to the calculated offset	Is there a requirement that the facility motions be monitored, or measured, to compare the predicted offsets with those measured under the specific metocean conditions? This comparison can be a way of determining if there has been a change or any damage to the mooring system.
Behavior	Does the standard require that the behavior of the facility is monitored and recorded?
Compare behavior to design expectations	Does the behavior of the facility match the expected behavior as defined in the design documents?
Mooring Integrity Management (MIM) Plans	
MIM required	Does the standard require that a specific MIM plan be developed?
Detailed description of MIM	Does the standard give a detailed description of what is expected in a MIM Plan?
MIM based in part on Mooring Integrity Risk Review (or similar)	Some standards require/suggest that the MIM be based on a detailed mooring risk assessment that should be carried out prior to installation. The risk assessment should be more than a simple HAZID-type assessment, but also consider a broader range of risks. The MIM can then be targeted particularly at the most likely failures, the highest consequence failures, etc. Through this type of targeting, efficiency can be obtained.
Require "consequence based" MIM	Similar to the above, but is the MIM to be based on the consequences of certain components failing?
Performance standard and verification scheme for mooring	In Safety Case regimes the mooring system will almost certainly be classified as an SCE. In such a situation, there is an expectation that a Performance Standard would have to be developed for the mooring system and a method established for ensuring that the performance standard be met (the Verification Scheme)
MIM should be continually updated based on past experience	Does the standard require that the results of inspections be compared to the expectations of those inspections, and if there is a mismatch, that the MIM be updated to become more in line with expectations? For example, if specific components are subject to more corrosion than originally expected, is there a requirement that the MIM be updated to require more frequent inspection of those components, to align with what would have been stipulated had the actually corrosion rate been anticipated?
Acceptance/Rejection Criteria	Does the standard specify, or require the dutyholder to develop, specific acceptance/rejection criteria for mooring components?
Inspection Schedule	
Inspection Interval	Is there a specified inspection interval?
Annual Inspection required	Is an annual inspection required?

Table 3: Expanded Description of Items/Subjects Contained in Subject Matter Table (Table 15)	
Item (as listed in detailed Table 15)	**Discussion/Expanded Description of Items**
Detailed Inspection approximately every 5 years	Is there a requirement for a more detailed inspection on, for example, a 5-year basis?
Inspection after severe event	Is there a requirement for inspection after severe event such as hurricane, collision, falling objects?
Frequency of inspection increases with age	Is there a requirement that the frequency of inspections increase with age of the mooring system?
Identify specific components for monitoring	Does the standard require that certain component (either specified or at the discretion of the dutyholder) be identified and monitored in detail? For example, is there a requirement that a specific chain link be monitored over time so that there is a clear indication of change over time? If random links are inspected, then small dimensional changes can be masked by manufacturing differences.
Track finding to compare with previous survey	Is there a requirement that results of inspections be reviewed before the next inspection, or compared to the results of the next inspection, to determine if everything is as expected?
Inspection Type	
Visual	Almost all the codes state that underwater inspections should be "visual," be it by diver or ROV.
Change out mooring leg	Does the standard specify that a mooring line should be changed out for onshore, in-air, or inspection, or does the code allow for such a change out? (Note that there can be significant risks associated with changing out a mooring leg.)
Inspection – Components Covered – Mooring Line	Does the standard give details for inspecting the following components, and if so, are there specific acceptance/rejection criteria?
Chain	
Steel Wire Rope	
Polyester	
Other synthetic	
Clump weights	
Buoys	
Standard manufactured connectors (e.g., Kenter)	Kenter links and the like are not normally allowed within permanent mooring systems.
Purpose built connectors	
Wire rope terminations	
Fiber rope splices	
Inspection – Components Covered – Facility	
Winches	
Fairleads	
Anchors	

Table 3: Expanded Description of Items/Subjects Contained in Subject Matter Table (Table 15)	
Item (as listed in detailed Table 15)	**Discussion/Expanded Description of Items**
Chainstoppers, Trumpet, bell mouth	There have been some experiences over the last few years where chain has been damaged around the trumpet bell mouth. The two main problems have been out-of-plane bending fatigue and local chain wear.
Inspection – Areas of Particular Interest	Are any of the following areas specifically mentioned for detailed inspection within the standard?
Fairlead, Trumpet Bell Mouth	
Splash zone	
Touchdown point/Thrash zone	
Below Seabed	
Trenching	
Thruster-assisted Moorings	
Thruster-assisted monitoring of mooring line tension, position, etc.	Is there a specific requirement that mooring line tensions be monitored on thruster-assisted mooring systems?
Mainly based on Class for survey	Is the inspection of the thruster, drives, power generation, control, etc., mainly based on the normal Classification Society machinery inspection extent and schedule?
Extent of thruster failure from FMEA	Does the standard require any specific FMEAs or other failure scenarios when assessing the thruster-assist system?
Failure the same as a mooring line	Most mooring standards have a failed mooring component criteria, be it single or multiple lines. This question addresses if a thruster-assist failure is treated the same way as a mooring line failure. It is relevant because it has been suggested that thruster-assist failures could be more common than mooring line failures, so possibly should be operated at a higher level of reliability, or with a more stringent failure criterion
Capability in complete blackout	Is there a specific requirement for mooring system capability in the case of a complete blackout (i.e., with no thruster assist)? An example could be that the mooring system be capable of holding the facility without directional control in an xx year return period storm.
Thrusters considered SCE	Are thrusters considered SCE (as discussed for the mooring system above) and thus subject to the development of performance standards and a verification scheme?

3.0 RECOMMENDATIONS ON GAPS BETWEEN CODES, STANDARDS AND OTHER DOCUMENTS (TASK 3)

3.1 OVERVIEW

Tasks 1 and 2 of this project included a review of existing industry, national, and international offshore codes and standards addressing mooring monitoring and inspection of permanent floating offshore installations. The codes and standards given in **Table 4**, in general, cover the regulatory requirements on the mooring systems worldwide and they are the focus of the gap analysis of this project. This section provides a comprehensive assessment of identified gaps between the BSEE requirements and the codes and standards studied in Tasks 1 and 2, and makes specific recommendations to BSEE on the gaps deemed to be important.

Table 4: Worldwide Standards for Mooring Systems that Discuss In-service Inspection or Monitoring

USA Standards:	API RP 2SK	API RP 2FPS	API RP 2SM	API RP 2I
ISO Standards:	19901-7	19904-1		
UK Documents:	SN-3/2005	RP 444	IS 4/2013	MIG
Norway Standards:	NORSOK N-005	NORSOK N-001		

While the focus of this particular study is on mooring monitoring and inspection, it is important to realize that mooring integrity is related to every phase of a project: from design, specification, manufacture, quality assurance, pre-delivery inspection, installation, post installation verification, through to in-service monitoring, inspection and operations. All of these phases are integral to ensuring a reliable mooring system. There is room for significant improvement in the stages prior to mooring installation, but the scope of this gap analysis is to determine where there is room for improvement in the areas of ongoing monitoring, inspection, and mooring system in-service management. The recommendations will be focused in those areas.

3.2 WHY THE GAPS NEED TO BE FILLED: OVERVIEW OF INTEGRITY ISSUES OF MOORING SYSTEMS

To improve the integrity of mooring systems, there is a lot that can be learned from past failures[1]. Several publications provide reviews of various mooring incidents. Some of the most recent publications include the following:

- *A Historical Review on Integrity Issues of Permanent Mooring Systems*, by Kai-tung Ma, Hongbo Shu, Philip Smedley, Didier L'Hostis, Arun Duggal (OTC 24025, 2013)
- *Application of Lessons Learned From Field Experience to Design, Installation and Maintenance of FPS Moorings*, by Richard D'Souza, Sai Majhi (OTC 24181, 2013)
- *Mooring Integrity JIP Reports* (Phase 1, 2005; Phase 2, 2012)

[1] The term "failure" here is being used in a general sense. For all moored floating systems, the one line damage case is part of the design. But when discussing mooring integrity (as opposed to facility integrity), a mooring line parting can be considered as a failure. It is this sense of failure that is generally used in this report.

The first of the references covers 21 incidents that occurred worldwide between 2001 and 2011. The incidents included eight that were major (e.g., involved multiple line failure, loss of stationkeeping, emergency production shutdown, damage to risers with associated small amount hydrocarbon leak). The information was obtained largely from public domain.

The second of the references reported failures during the same period (2000 to 2011) based on the studies conducted by ExxonMobil. It reported 23 documented FPU mooring failures. Twenty FPUs required partial or complete mooring replacements and repair. The paper also reported cases where preemptive actions were taken due to concerns about the mooring system integrity.

The third of the references represents the industry effort on mooring integrity (mooring integrity JIP). The number of participants reached 38 for Phase 2 of the JIP. The Mooring Integrity Guidelines of Oil & Gas UK were developed largely based on the outcomes of the JIP. A custom designed questionnaire was developed during the JIP to undertake an international survey of worldwide FPS operations including FPSOs, production semis and Spars. However, the response to the questionnaire was not given a high priority by hard pressed offshore and office-based personnel. The reported failures are mostly from the North Sea where there are statutory requirements for reporting mooring incidents to the UK HSE. It is reported that, on average, an FPU will experience a mooring line failure every 9 years, based on the available data for the period 1980 to 2001. Appendix B provides the HSE UK sector and Norwegian mooring incident statistics.

Although the causes for the incidents are quite scattered, the following factors are noticed:

1. At least six of the failures resulted in complete failure of the mooring system, with the facility going adrift.
2. None of the failures resulted in significant loss of hydrocarbon to the environment.
3. In the majority of instances, failures occurred at an interface or discontinuity (e.g., connector, spelter socket, splice).
4. A new failure, mechanics of Out-of-Plane (OPB) of chain links, was identified that caused failure of, or damage to mooring links in a hawse pipe. Section 6.2.2 of this report provides detailed information on the OPB study.
5. Installation damage to multiple lines required preemptive actions, including rebuilding wire rope sheathing, trimming specific line, re-socketing, and using bandit collars for repairs. Close monitoring of affected lines and improved installation method were also necessary.
6. The lower end of mid-water wire rope contacting the seabed introduced compression and bird caging into the wire rope.
7. Twists in the pigtail chains (running from the buried pile padeye to a connector on the seabed) led to two failures (albeit not within the chain, but in components above the chain). In this instance a hockle is believed to have formed in the chain, which ordinarily would simply pull out. However, it was within the seabed and there was sufficient soil resistance to prevent it from pulling out. Therefore, tension loading was taken across a link rather than the normal end-to-end. This led to early fatigue failure in a very difficult location to repair.
8. Improper weld repairs of chain links were undertaken during manufacturing (no welding is allowed on any chain component).

9. Mistreatment or poor handling of mooring lines during transportation and installation led to failure or damages. Uncontrolled welding heat onto a chain link while on the anchor handling vessel can introduce very high local residual stresses that can led to premature chain fracture.
10. Operation problems occurred, such as failure to disconnect in time for a sudden typhoon, or relying on active heading control thruster systems to prevent vessel turning beam into storm.
11. Corrosion has been a major contributor to several incidents.

These incidents reinforce the need to further improve the reliability of mooring systems. Improvement in each related aspect (e.g., design, installation, maintenance, inspection, monitoring, operation) could positively contribute to greater reliability of the mooring systems. This report is focused on improvements in the areas of mooring integrity management, inspection, and monitoring programs. A rigorous MIM plan, improved inspection, and monitoring program by owners and operators could greatly help improve reliability.

It is imperative, however, to understand the limitations of an in-service inspection system. Improved quality of mooring components, installed as per the design, is a more effective way to improve reliability than the current – relatively poor, mainly visual – underwater inspection techniques. These techniques will likely improve over time, and the value of current visual techniques at finding excessive corrosion and mechanical damage should not be dismissed, but there are significant limitations as to what can currently be achieved.

3.3 Assessment of Gaps Between BSEE Regulations and Other Standards and Codes

In Task 2 of this project, gaps between BSEE regulations and other standards and codes were provided (see Appendix A, Table 15). The more important subjects selected in the gap analysis include:

- Installation verification
- Monitoring and mooring line failure detection
- MIM plans
- Periodic inspection
    - Schedule
    - Inspection method
    - Mooring line coverage
    - Mooring facility coverage
    - RBI
- Thruster-assisted mooring system

In general, API RP 2I provides more detailed information on inspection and acceptance/rejection criteria for offshore mooring components than any of the other codes reviewed. However there are areas (i.e., gaps) where other documents provide better coverage than is provided by the codes incorporated by BSEE. This section provides an evaluation of these gaps and recommendations to fill them. The types of gaps, shown in **Table 5 and Table 6**, are categorized as follows.

- Type A: Level of Details – the topic is covered, but additional detail on what is required would improve the requirement
- Type B: Lack of Supplement Guidelines – the subject is addressed, but additional guidelines on application of the requirement is needed
- Type C: Subject Not Covered in Current Requirements

Most of the Type B gaps are in reference to UK documents and, to a lesser extent, ISO documents which include both normative and informative sections. For example, the UK HSE document RP 444 (an informative document that resulted from a JIP) and the Oil & Gas UK Mooring Integrity Guideline document provide extremely useful guidelines and recommendations, but they are not mandatory. ISO 19901-7 is divided into both normative and informative sections, but much of the valuable information it contains is in the informative – not mandatory – Annex A. ISO 19901-7 also contains an Annex B on Regional Information which is not generally mandatory, although it can be within its specific area of applicability.

The level of importance and the need to fill the gaps are evaluated based on an overview of recent industry experiences, industry feedback (such as mooring integrity forums), and JIPs (such as Mooring Integrity JIP project). Table 5 and Table 6 provide comments on filling some of the gaps identified, and the contents are summarized in Section 3.4.1 of this report. In addition, other areas are also recommended for BSEE consideration as detailed in Sections 3.4.2 through 3.4.6.

Table 5 provides the assessment of the gaps identified from previous sections, with some detail items consolidated (see also Section 3.4 for additional recommendations). The reference column suggests which standard may need to be revised to include the recommendation. For example, the need to pre-stretch all synthetic mooring lines is not clearly detailed in the BSSE referenced codes. Table 5 suggests incorporating this requirement in a future revision to the referenced code API 2SM.

Table 5: Assessment of Important Gaps Between BSEE Regulations and Other Standards

Subject	Gap Type	Ref.	Gap Assessment
Installation Verification			API RP 2I and 2SK provide some detail, but there are more useful requirements in other standards such as UK Oil & Gas MIG (see detailed gap table in *Appendix A – Summary Tables of Codes/Standards Reviewed*)
Pre-stretch all polyester	C	API 2SM	While pre-stretching polyester mooring systems is commonly carried out, it is not specifically required within any of the current BSEE referenced standards. Unless pre-stretched, polyester rope will creep over time, with the amount of creep depending on the load. A change in mooring line length affects the overall mooring system response. Creep also causes a substantial change in the rope stiffness properties which will also change the mooring system response. Prior to pre-stretching, the ropes are considerably more elastic. Pre-stretching should be taken into account within deployment.
Detailed measurement of "as-	A/B	API 2I	Because installed lengths can be significantly different from "contract" or "certified" lengths it is important that the post installation survey accurately record the exact details of the

Table 5: Assessment of Important Gaps Between BSEE Regulations and Other Standards			
Subject	**Gap Type**	**Ref.**	**Gap Assessment**
installed" component lengths			mooring system that was installed, including a detailed measurement of component length. In addition, there should be full documentation on the mooring system installed, including reference to the specific certificates for each component and, ideally, the location of all terminations and connectors.
Mooring System Monitoring			API documents provide very limited specifications on monitoring. UK HSE OIS No 4/2013 supplemented with UK Oil & Gas MIG has more requirements and provides more details.
Failure detection and alarms	C/B	API 2SK	Effective mooring line failure detection and alarm warning should be installed. The combination of line failure detection, MIM plan, and pre-installation risk analyses can help avoid or reduce the likelihood of progressive failures. (There have been a surprising number of cases in which a failed mooring system has only been discovered during a mooring line inspection.)
Action on mooring line failure	C	API 2SK	There should be a formal set of procedures to be followed if a failed mooring line is detected. The actual actions to be taken will depend on many factors, including mooring system robustness and redundancy, but the offshore operating personnel need to know specifically what actions to take, including if production should be shut-in and the urgency with which the action should be taken.
MIM Plans			Currently there is no API document on this aspect (see also additional discussion in Section 3.4, Recommendations to BSEE). Based on the latest information, API will develop API RP 2MIM using Deepstar's *Mooring Integrity Management Guidelines*.
Develop MIM	C	API 2SK	A MIM plan should be developed. It should formally set out what inspection and monitoring is required, and how the results should be interpreted. UK Oil & Gas MIG and Deepstar MIM Guidelines provide guidelines for MIM. It is important for the improvement of mooring system integrity. UK HSE refers to UK Oil & Gas WIG. Effective MIM plans could improve the reliability of a mooring system.
Mooring risk analysis	C	API 2 MIM	The MIM should be based on a holistic mooring system risk assessment. The assessment should account for factors such as mooring system robustness, novelty of the design, types of mooring components used, likely effects of errors in analysis (e.g., consequences of a small change in the input parameters, small changes causing a disproportionate effect on the response), component inspectability, likelihood of defect detection, consequence of component failure, likelihood of escalation from single component to system failure, etc. The risk analysis should include the hazards

Table 5: Assessment of Important Gaps Between BSEE Regulations and Other Standards			
Subject	**Gap Type**	**Ref.**	**Gap Assessment**
			identification, effect criticality, and recommended actions to mitigate the risk. The outcomes from the risk analysis should be reflected in the MIM (or DWOP) in terms of monitoring and inspection plan, spares, and emergency response plan.
MIM update schedule	C	API 2 MIM	MIM should include requirements that the mooring system inspection and monitoring program be updated based on the results of previous inspection and monitoring. For example, if a specific type of defect is occurring more often than expected, then the inspection interval should be shortened. If the defect is less common, then possibly the interval can be increased. The plan should be reviewed to determine if new technology should be employed for inspection or monitoring. In effect, the MIM should allow and mandate learnings from past findings.
Periodic Inspection			API RP 2I provides more detail than other standards for periodical inspection in term of inspection interval, coverage of inspections, focus areas for inspection, etc. It is largely based on visual inspection which is used in general and is acceptable for underwater inspection. Informative guidelines on other inspection methods should be provided.
Inspection methods	B	API 2I	API RP 2I should be more open to industry needs in terms of detailed specifications and inspection methods. It is one of the most challenging area subjects for further development. Tasks 4 and 5 give more details on techniques currently available and under development.

Table 6, and the paragraphs below it, address some additional items that should be considered, but do not necessarily require modification at this time.

Table 6: Assessment of Other Gaps Between BSEE Regulations and Other Standards			
Subject	**Gap Type**	**Ref.**	**Gap Assessment**
Thruster-assisted Moorings (TAM)			While current requirements are comparable with other standards, some additional topics should be addressed if TAM facilities are to be used in U.S. waters. It is, however, unlikely that there will be permanent TAM systems installed in the GoM on which thrusters are an integral part of the hurricane survival condition (due to the evacuation needs). Following points only apply if TAM is to be considered.
Capability in complete blackout	C	API 2SK	UK HSE recommends that, as a minimum, a thruster-assisted mooring should be able to survive a 10-year storm in a blackout (i.e., with loss of all thrusters). Blackout needs to be addressed, but the criteria need to be established from further study.

Table 6: Assessment of Other Gaps Between BSEE Regulations and Other Standards			
Subject	**Gap Type**	**Ref.**	**Gap Assessment**
Thrusters considered SCE	C/A	API 2SK	The purpose of using thrusters needs to be clearly defined (heading control, reduce mooring load or combination of both) and performance standards developed for their operation.
Verification and testing	C/A	API 2SK	N/A Verification and testing. For thrusters to assist mooring system through automatic controls, calibration of the control system is necessary during the sea trial.
Operations manual	C/A	API 2SK	Since thrusters are active systems, operator's knowledge and the effective instructions for operators are important.

Mooring Line Load Monitoring: Mooring line load monitoring has been omitted from the list of gaps to be filled in Table 6. Effective monitoring should be encouraged, but there is little merit in specifically requiring it at this time. The current requirements in API RP 2SK for mooring line load monitoring only apply when the design incorporates active line winching. It has been suggested that general mooring line load monitoring is advantageous, but there are complications. Many of the currently installed systems, and those currently marketed, have been reported to be insufficient regarding accuracy and reliability. There appears to be little value in requiring the installation of a system whose accuracy and service life are questionable. Requiring failed line detection is, in many respects, more important, and certainly more practical. However, if a mooring line load system is installed, the records should be maintained for some time (e.g., 30 days) so that, should there be an anomalous mooring system response identified, there is a possibility it can be back-calibrated to past experience.

It is likely that industry, over time, will increasingly see the advantages of mooring line tension monitoring. For example, the results can be used to help justify reducing the amount of fatigue life used up during operations, thereby helping to justify a "life extension" should one be needed. Once the value of the monitoring is seen, the money and research will be expended to develop operational systems that have the accuracy and life needed to gather the relevant data.

3.4 Recommendations for BSEE

Among others, one of the lessons learned is that the mooring systems have been evolving in terms of numbers, size, water depth, new materials, operation conditions, etc. These factors would increase the uncertainties of the performance of the mooring systems. The prescribed standards, with supplement of performance-based guidelines by BSEE, would be beneficial to the improvement of overall safety of the mooring systems.

3.4.1 Summary of Issues in the Gap Assessment (Tables 5 and 6)

The following items are recommended in the tables:

- Pre-stretch synthetic fiber ropes
- Detailed "as-installed" inspection and mapping of the mooring system
- Mooring line failure monitoring (see additional comments below)
- Action on mooring line failure (see additional comments below)

- Develop a MIM (additional discussion below)
- Improved incorporation of new inspection methods (see results from Tasks 4 and 5)

3.4.2 Document of Mooring System Management Philosophy

It is recommended that a mooring system management philosophy document be developed. It should be the foundation upon which the design is undertaken, fabrication specifications are developed, installation carried out, and the facility operated. Many of the other documents needed to help ensure a reliable mooring system will inherently grow from this base document (e.g., the MIM, emergency procedures, mooring line failure detection method). It should include at least the following aspects:

- Design philosophy
    - Recognition that manufacturing is critical and QA/QC is fundamental to reliability
    - A holistic view of the purpose and limitations of the mooring system
    - Expected performance of the mooring system
- Installation verification, both the methods to be used and the results of the surveys
- Monitoring of mooring system to ensure that the system response is as expected from the analyses undertaken during the design stage
- Inspection scope driven by the risk study
- Data gathering, codifying, use, and identification of anomalies
- Emergency response
- Methodology for determining when the MIM document should be updated

BSEE can refer to Oil & Gas UK Mooring Integrity Guidance Document or Mooring System management Guidelines by Deepstar for guidelines.

3.4.3 Mooring System Risk Assessment

It is recommended that a mooring system risk assessment be carried out during design, and updated, if necessary, as the design changes. This requirement can be incorporated through the update of API RP 2SK. Based on available information, the 2SK group is considering this item for the upcoming update of the RP 2SK document. One part of the study should be an assessment of the mooring failure modes in conjunction with the potential consequences. This type of study is particularly important for a complex mooring system. The study should be holistic and account for, or include the following:

- Mooring system robustness – One-line failure consideration is common practice, but potential for multi-line failure depending on the system and expected performance should be included. The common causes for potential multi-line failure (such as corrosion, etc.) should be evaluated and necessary emergency response plan should be in place if needed.
- Novelty of the design (if the design is highly novel, then it is more likely that it will be subject to novel failure mechanisms; the unknown unknowns)

- Types of mooring components used, if they are fabricated from commonly used materials or higher strength, if their sizes are within the previous experience range, if the manufacturer is experienced with these components, etc.
- Experience of the manufacturer
- Slope of the hazard curve and consequences of errors/inaccuracies in the analysis (e.g., underestimation of metocean conditions, vessel response more than anticipated – generally the consequences of the known unknowns)
- The availability of components in the mooring system for inspection, if a leg can be *safely* rotated out of service for onshore inspection (unlikely, but has been suggested), and the likelihood that defects will be detected
- Parting, or significant impairment, of a mooring line due to corrosion and wear (e.g., uniform/pitting corrosion, adequate corrosion allowance, reasonable corrosion rates based on past experience in the area)
- Chain in/out plane bending
- Mooring component parting, or significant impairment (accessories, etc.)
- Degradation due to installation and handling
- Degradation of anchor holding capacity due to trenching or others
- Failure modes for thruster assisted mooring

Appendix 6B of the Oil & Gas UK Mooring Integrity Guidance Document provides a list of failure modes by category at a detailed level. BSEE may refer to it for guidelines on the consideration of failure modes of a mooring system.

3.4.4 Mooring System Monitoring

A carefully selected monitoring system with warnings upon mooring line failure should be required to help improve the integrity of a mooring system. The chosen system will depend upon many of the details of the specific mooring system. The system should be chosen, and validated, taking into full account the mooring system response. As an example, it may be possible to simply calibrate a thruster assist system, which includes a simple feed from a wind monitoring device, to warn when unexpectedly high thrust is required. Conversely, for a grouped mooring system, when a single line failure could result in very little offset, it may be necessary to monitor the mooring line angle at the fairlead. Choosing a viable system will require desktop calibration with computer simulations combined with onsite monitoring of system response during the early periods of operation. The system must be reliable. Also, it is important that the offshore personnel have clear instructions of what to do in the event of a failure. For reference, **Figure 2** shows the statistics of mooring system monitoring in North Sea for a turret mooring system.

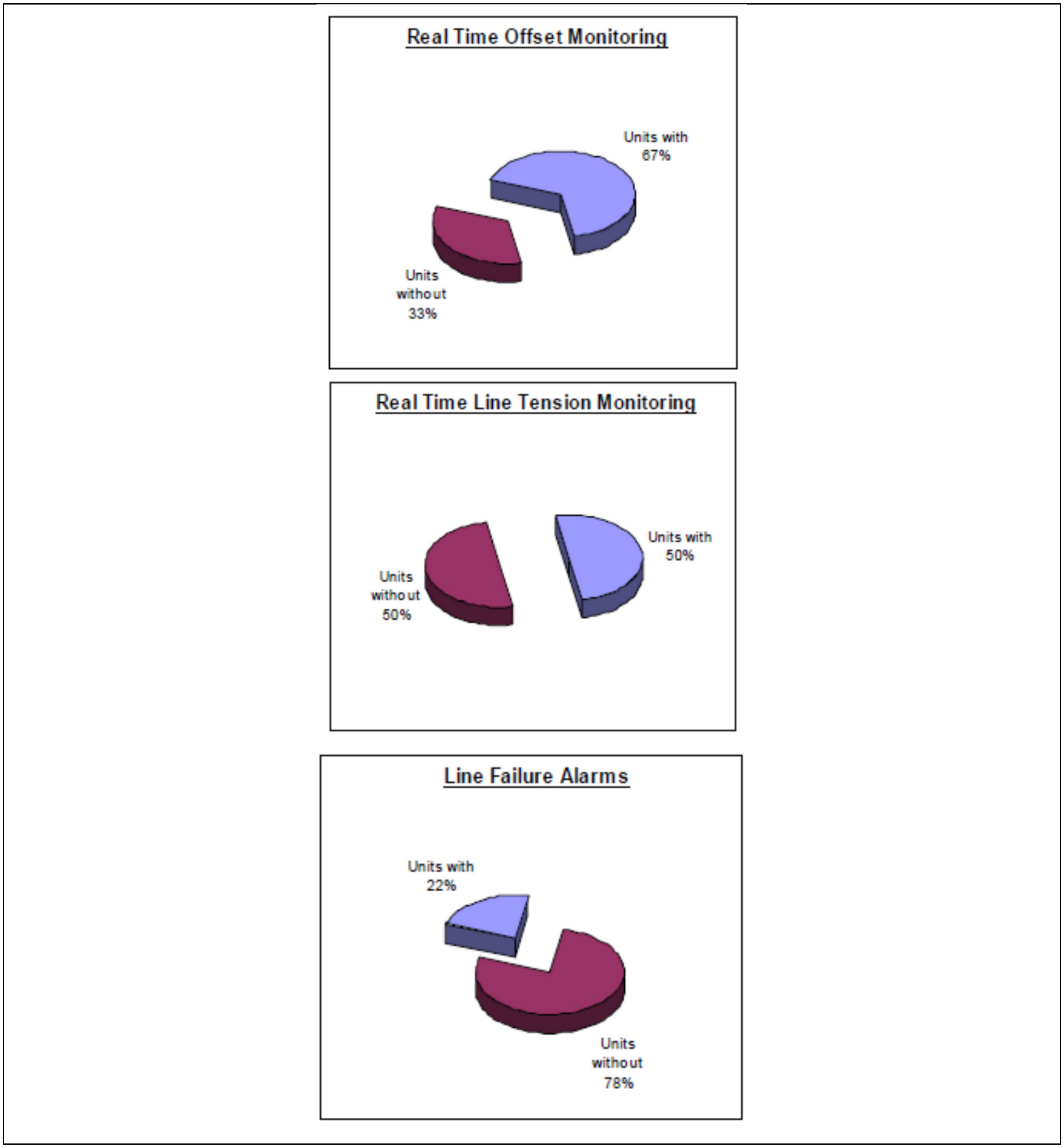

Figure 2 – Monitoring Statistics for Turret Mooring in North Sea (courtesy of Mooring Integrity JIP)

3.4.5 Mooring System Operation Guidelines

Specifications on mooring system operations manuals should be included in API RP 2SK. A mooring system is considered a passive stationkeeping system in comparison with a dynamic positioning system. Often there is no detailed operations manual developed for the mooring system. However, experience suggests that it is important to have a well-developed operations manual for a mooring system, especially for a complex system. The following items may be included in the operations manual:

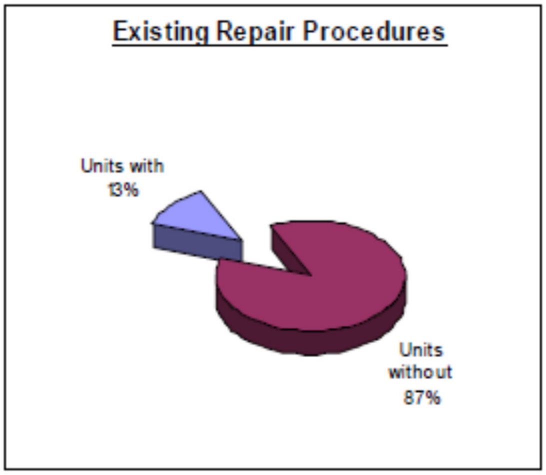

Figure 3 – Statistics of Having Repair Procedure of Turret Mooring in North Sea (*courtesy of Mooring Integrity JIP*)

- Capability of mooring system under different conditions (intact, one-line failure, or other degraded cases)
- Expected response of the system under the same conditions (vessel offset, motions, etc.)
- Mooring risk studies should be kept on board for reference when untoward event occur
- Response to monitoring status or alarms
- Emergency response
- Data records
- Incident report

Figure 3 shows the statistics of turret moored systems in North Sea that have existing repair procedures.

3.4.6 Incident Reporting

The key to improving mooring system integrity is to learn from past failures. BSEE does require incident reporting (CFR Title 30 Part 250.188), but mainly on the incidents that involve personal, property and environment damages. Systematic incident reporting (such as incident trigger, failure mechanism, etc.) and information sharing is highly recommended. Unless industry is given the opportunity to learn from its mistakes, it is difficult to understand how progress can be made in mooring system reliability. Because there is no current reporting requirement, and no formally established method of determining what problems have been encountered in the past, companies continue to make the same mistakes, and fail to learn from the experiences of others.

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4.0 REVIEW OF EXISTING INSPECTION & MONITORING TECHNOLOGY (TASK 4)

4.1 OVERVIEW

In general the purpose of inspection and monitoring is to provide information that aids the integrity assessments from the manufacturing stage through to end of life of the asset.

The terms monitoring and inspection are sometimes used interchangeably, which can lead to misunderstandings and errors. To help avoid misunderstanding, this report defines monitoring as using information to determine the status or response of the mooring system, a mooring line, or occasionally a mooring component. Monitoring is normally continual. Effective monitoring can provide extremely valuable information on the performance of the mooring systems, such as verification of design model, mooring line break, or excessive creep in synthetic mooring lines. In addition, mooring line tension monitoring can be invaluable in understanding the fatigue life usage of an installed mooring. This, in turn, can help determine at what point the fatigue life has been, or will likely be, fully used. A number of different monitoring systems have been deployed, but in many cases without sufficient thought about what is to be monitored, the need for customization, and the need for a robust design.

This report defines inspection as the determination of the condition of a mooring component, or occasionally the mooring system, at a specific point in time. It normally involves the active participation of inspectors for the relevant point in time. Mooring line inspection includes manufacture inspection and in-service inspection. While manufacture inspection is focused on the detection of defects and quality controls, in-service inspection is focused on anomalies due to any incidents, degradation due to wear and corrosion, and the exacerbation of manufacturing defects. Inspection consists of visual examination, or the examination of specific characteristics of the materials of construction using some form of technology, normally referred to as non-destructive examination (NDE). All of this is performed intermittently either periodically or on ad-hoc basis. To do this effectively it is necessary to first identify the degradation mechanisms and rates of deterioration that could credibly occur, which forms the basis of selecting the frequency of inspection and the technologies to be used. The value of these inspections, in terms of ensuring the continued integrity of the mooring system, is dependent on a number of factors, such as inspection methods, locations of mooring systems, planning, experience of inspectors, seabed properties and conditions, underwater visibility, sea currents, etc. In addition, the inspection can be hazardous to the divers (having to inspect continuously moving components) and can be hazardous to some parts of a mooring system (e.g., if the inspecting ROV collides with the mooring system), and particularly to any synthetic components.

Degradation of mooring system components can be the result of: corrosion, wear, installation damage, flaws in manufacturing, material incompatibility, design errors, etc. Industry has come to rely on regular in-service inspection of mooring systems as part of the integrity assurance program, but the available processes and tools are not always suitable, reliable, or sensitive enough. MODU mooring systems can be inspected in-air as they are retrieved or deployed, but that option is not normally available on an FPS. Not only is it difficult to recover an FPS mooring leg, it can also be very high risk.

Offshore floating structure moorings have very discrete structural forms and this limits both the inspection and monitoring techniques that can be applied usefully. This section describes the commonly applied methods and technologies and looks at new and emerging technologies that may be applicable in the future providing there is research and development.

The data obtained from either inspection or monitoring needs careful interpretation to understand the state of the degradation at the time of data capture and the extrapolation needed to understand the overall impact on the mooring integrity. Frequently there are multiple types of data from the variety of inspection and monitoring tools used. The possible interactions of multiple data types from the different techniques can complement each other but there is always the real risk that they conflict, or at least appear to conflict. This needs to be taken into account in the evaluation to provide the most credible assessment of current and future condition.

There is a broad range of underwater/in-service inspection techniques used in the industry. They range from a simple ROV visual inspection to high tech 3-D mapping technology. It is important to understand the advantages and disadvantages of each technique and when each can best be applied. This section provides an overview of inspection technology and current practice of mooring system inspection during manufacturing and while in service.

In this project, the mooring system inspection technologies are categorized into four different groups in terms of the technical readiness and matureness:

- **Approved:** Approved inspection technologies in-air and underwater are accepted by Code, Rule, or Guidance.
- **Implemented:** Implemented inspection technologies are adopted by offshore industries. However these technologies need approval in Code, Rule or Guidance (in term of class acceptance).
- **Mature:** Mature inspection technologies are valid through laboratory test/ other industry applications. However, further technology feasibility study is required in the field test. Task 6 of this project provides more information in this area.
- **Emerging, novel, or experimental:** This includes technologies either in some stage of development for subsea use either on moorings or other applications, or already developed and used elsewhere or above water offshore that may be feasible for subsea mooring applications

4.2 WHY THE NEED FOR INSPECTION AND MONITORING OF MOORINGS

The drivers for inspecting and monitoring mooring systems range from regulatory compliance to dutyholder-driven activities that are integral to an integrity management plan.

4.2.1 REGULATORY REQUIREMENTS

Both 30 CFR 250.901 and 30 CFR 250.198 refer to API RP 2I. Periodic surveys should be conducted no less than once every five years. A visual inspection should be conducted annually for the above water mooring components, including chain or wire rope, winches or windlasses, deck sheaves, stoppers, and fairleads or bending shoes.

The inspection is mainly visual with photographs, video, and inspectors comments taken. The inspection can also include measurements of component diameter or depth based on the inspection plan. It is sometimes desirable to measure the potential across various mooring components to provide some insight into the possibility of corrosion occurring.

4.2.2 Existing Codes and Practices

As discussed in Section 1, there are three API RPs referenced in the CFR. Of these only API RP 2I relates directly to the inspection of moorings. But, as discussed in Section 2 of this report, it is really intended for MODUs where the moorings can be inspected in-air. In part, this RP is practical and applicable to in-service inspections, while other aspects, such as the requirements to take measurements every 100 feet, are just not practical or achievable. The main inspection objectives, for permanent mooring systems, that are given in API RP 2I are:

1. To confirm that the wear and corrosion is within the design values over the life of the facility. (Note: Permanent mooring components are normally designed with a wear and corrosion allowance.)
2. To inspect the integrity of the connections of the individual components

4.3 Mooring Component Degradation Mechanisms as Related to In-service Inspection

A key aspect of developing inspection plans is having a good understanding of the credible degradation mechanisms and where on the length or component of the mooring system this is likely to occur. Another important aspect to understand is the rate of degradation as this can impact both the types and frequencies of inspection and monitoring. For the purposes of this study, these characteristics are focused primarily on moorings in the Gulf of Mexico (GoM) but degradation mechanisms that occur elsewhere in the world are included because they could possibly occur at some time in the GoM.

Table 7 briefly highlights the areas that need to be inspected, what is being looked for, and some of the difficulties of inspecting those areas. **Figure 4** has been included to help explain the tension-tension fatigue crack locations on a common (stud link) chain. The locations are similar on a studless link.

Table 7: Outline of Mooring Components for Inspection

What to Inspect	Where to Inspect	Difficulties with Inspection
Chain		
General inspection	All over chain	Need to clean chain Access difficulties at and below mudline
Tension-tension fatigue	Half crown intrados (most common location)	Very difficult to see or get any access to the area as it obstructed by the adjacent link
	Crown extrados (another relatively common location)	Reasonable access, particularly in studless chain when the adjacent link is not as obstructive
	Flash butt weld (occasional location for fatigue)	Good access to outside, but more difficult on intrados.

Table 7: Outline of Mooring Components for Inspection		
What to Inspect	**Where to Inspect**	**Difficulties with Inspection**
Out-of-plane Bending Fatigue	Chain link at the bellmouth	Access impaired by bellmouth in most cases. Can be either in-air or under water, depending on the design.
General corrosion	All over chain	Visual gives some information. Measurements can be taken if needed.
Pitting corrosion	All over chain	Good from visual
Interlink wear	Contact point between links	Need to measure the double diameter of the two links at the contact point. Need baseline dimensions. Chain bar stock ovalizes during fabrication.
Dimensional anomalies	Length over a number of adjacent links	Need baseline for results to be meaningful. Can be difficult to measure relatively large distances with sufficient accuracy
Mechanical or installation damage	All over chain	No significant problems if there is sufficient visibility
Twist in chain	All over chain	Need reasonable visibility to be able see twist over number of links
Synthetic		
Mechanical damage	Splice	Generally good visual, but access to termination limited
	Body of rope	No significant problems if there is sufficient visibility
Internal damage		Not possible with available technology
Wire rope		
Fatigue of wire rope	All over – sheathed rope	Not currently technology, but possible in the future
	All over – un-sheathed rope	Visual of surface only
Corrosion	All over	Visual, but can be difficult to interpret. Measurements of diameter feasible if wire not sheathed
Fatigue of rope termination	Body of termination	Similar access problems as with chain
Connectors		
Misalignment	Between connector and connected components	Visual normally adequate (see also discussion below this table)
Corrosion	All over	Similar to chain (see also discussion below this table)
Inter-component wear		Similar to chain interlink wear
Loose pins, lost retainers, etc.	Visual	Inspectors need to know what the component should look like (in order to see defective condition)

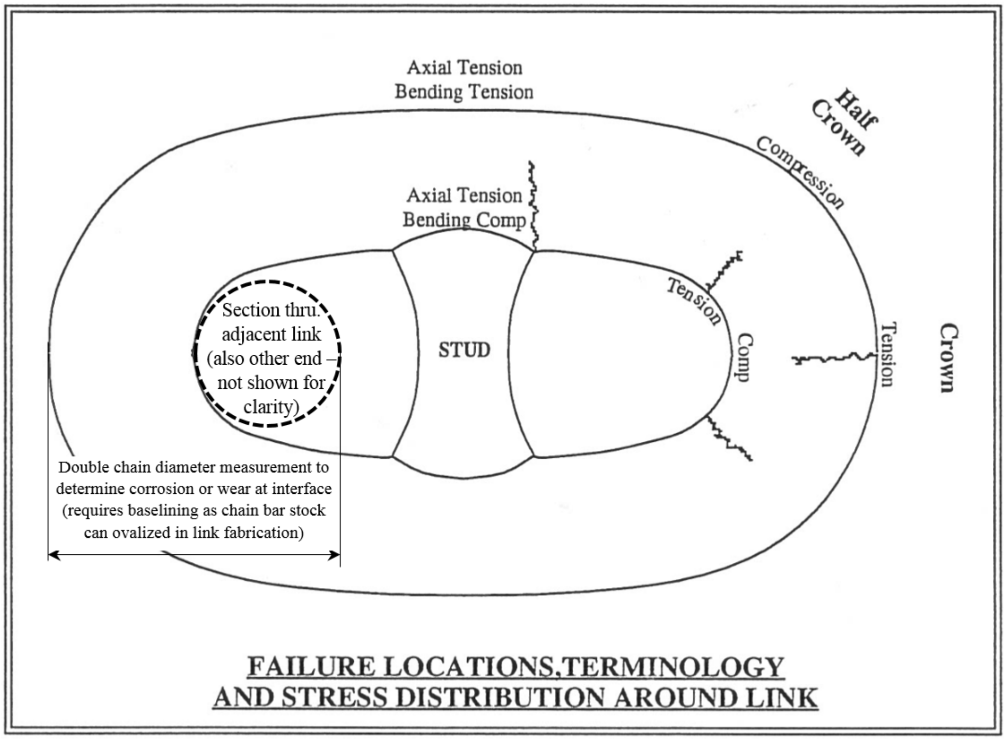

Figure 4 – Terminology and Tension-Tension Fatigue Crack Locations on Common (stud link) Chain

Connectors are potentially subject to the same degradation as other steel components, but there are additional failure/degradation modes. OTC 24025 (2013) identifies a disproportionate number of failures in connectors. A new draft API is being developed to try to prevent the recurrence of these failures, but there is merit in understanding some of the issues to help in defining an inspection strategy for existing facilities. The following are some of the reasons that connectors are of special interest during inspections of existing installations:

- **Tolerances:** Connectors are designed and fabricated within specified tolerance limits to help ensure that the components being connected will fit into the connector. However, if the connector tolerances are, for example, at their maximum, and the components being connected are at their minimum, then there can be appreciable play in the system, potentially leading to out of alignment loading. This issue is being considered for inclusion in a new draft API document, but there are currently no industry-based guidelines.
- **Materials:** Another issue that has been discussed at some length by the group developing the draft connector guideline is that of material compatibility: different types of steel have resulted in increased corrosion rates.
- **Design Details:** Missing retaining pins, nuts, etc. has been a problem on connectors, often due to failure of design details.

4.4 INSPECTION OF MOORINGS

The inspection techniques used and the qualifications of the people performing the work are going to vary, depending primarily on whether the part of the mooring under consideration is above or below water. For the below-water section there will be differences in techniques and personnel depending on water depth.

4.4.1 Above Water Inspections

Above water inspections typically are performed by inspectors working on permanent access flooring or on correctly installed temporary staging (e.g., scaffolding). These qualified inspectors conduct the inspections using a range of technologies and methods. Typically, but not universally, they are not qualified engineers and therefore do not complete the analysis and assessment of data.

Where staging is impractical to install, qualified rope access technology (RAT) inspectors are employed. RAT inspectors use mountain climbing techniques and equipment to reach otherwise inaccessible locations. This climbing technique has been used internationally in a number of different work environments since at least the 1980s. As well as the RAT qualifications, the personnel need to have the appropriate qualifications and/or training to perform tests. It should be noted that for some tests the qualified inspector can be positioned remotely on a safe access point and the RAT inspector simply applies the probe to the test surface under the direction of the qualified inspector.

4.4.2 Below Water Inspections

Below water inspections require the use of divers or ROVs to access the inspection site and to perform the work. Depending on the inspection technology used, the diver may or may not need to have appropriate qualifications. If the recording instrument remains above water, the diver will only deploy the probe (exactly as described above for the RAT inspections).

Below water inspection of moorings is normally limited to visual (e.g., for gross defects and unusual corrosion) and some measurement of material loss. While both divers and ROVs are capable of carrying out some NDT, there is generally limited access to the areas of chain and connectors most likely to suffer cracking (e.g., the half-crown intrados on chain), so frequently there is no NDT carried out.

One area of the mooring system that can be difficult to inspect is any component that actually breaks the waterline. On a semi-submersible it can be difficult to significantly change the vessel draft, making it nearly impossible to carry out inspections of this zone. On some FPSOs, where the moorings come above water, it may be feasible to alter the draft to allow access to the normal waterline zone.

4.4.2.1 Diver Inspections

Setting aside the depth limitations and cost impacts, diver inspections are generally better than those preformed using an ROV. This is because of the clarity of vision and depth of field perception of the human eye, plus the diver’s greater dexterity. Divers generally can perform the same tasks to the same level of competence as topside inspectors. Where applicable, they would be required to have comparable training and certification to be allowed to perform inspection tasks.

While there are risks associated with diving, which are well managed by the industry, the greatest impediment is the depth limitation. There are a range of well proven and safe diving technologies used in the offshore industry, ranging from shallow water (air) diving to deep water (saturation) diving. Shallow water (air) diving is the most commonly used practice but this has an industry-imposed depth limit of 150 feet maximum, which is reduced to 100 feet by some safety standards[2] There are diving systems onboard specialist support vessels that have permanently installed saturation diving systems, meeting class and USCG requirements, with an operational depth limit of 1,000 feet. The cost of diving operations generally increases exponentially with depth. Therefore, the benefits of diver inspection need to be weighed against cost.

4.4.2.2 ROV Inspections

ROVs range in size and sophistication from those that are compact and capable only of visual inspection through large (motor vehicle size) units capable of performing complex tasks. Most ROVs are capable of performing some type of NDT activities. The extent and complexity of tasks is largely a function of vehicle size and power. ROVs generally do not perform well right at the water line because of the turbulence, but other than this there is no practical hard limit on water depth. Particular ROV systems may be depth limited by design or attributes of the deployment methods but it should be noted that ROVs have been successfully working at depths of greater than 2.5 miles (e.g., on the Titanic wreck). As is to be expected the costs will increase with the size, sophistication, and working depth of the ROV system selected. Overall, it will generally be less expensive than using divers for comparable working depth and tasks performed.

Developments are continuing on autonomous underwater vehicles (AUV) that are self-powered and use wireless telemetry systems. Once commercially available, AUVs will overcome some of the existing limitations with ROVs created by the need to have an umbilical to provide power and telemetry.

Industry studies and reports have indicated that ROVs are capable of damaging the sheathing on synthetic ropes through accidental impact, which raises the question of what the real advantage is if the act of inspection can actually cause damage. Conversely, if ROVs are not used for the inspection, how can there be reasonable assurance that there has not been some significant damage to the mooring lines? The answer is not simple, but the situation is improved by an increased awareness of the risks and benefits of an inspection. If visibility is good, can the separation distance between ROV and mooring line be increased? It depends on the mooring problems to be inspected. Some pre-inspection assessments may be able to devise a more logical program for inspection that minimizes the risk of damage while maximizing the likelihood of finding the most probable defects.

4.4.3 When to Inspect

Inspection is beneficial at several life-cycle stages. While this study is focused on the in-service phase, inspection needs and justifications of the other life-cycle phases are at least briefly discussed.

[2] CFR 1910.410 allows surface supplied commercial air-diving (the norm in offshore work) to a depth of 190 feet, but with a variety of limitations commonly employed by all competent diving operators. Depending on operational and safety constraints, this may be reduced to 100 feet.

4.4.3.1 Inspection During Manufacturing

Inspection during manufacturing is critical in many cases. Chain dimensions are not necessarily as expected because the bar stock deforms during chain formation. Therefore, if you don't know what the as-manufactured product was, you have no idea what has changed. Wire rope generally is less of a problem as is synthetic (almost exclusively polyester). Another aspect is that steel wire can be sheathed and synthetic rope can have different jackets/filters, making it hard to see the "real" component.

4.4.3.2 Inspection During Installation

Inspection during installation is hugely beneficial as it is the primary means of verifying that the mooring has been installed in accordance with the limits defined in the project specification, and for corrective action to be taken if necessary.

4.4.3.3 Base-Line Inspection

At the earliest opportunity and preferably before the facility experiences major environmental events, a baseline survey should be completed as it confirms the initial "as-is" condition. This may differ in reality from the survey issued for construction or even the as-built documentation. Successive inspections would then allow the deviations from the original condition to be estimated, measured, and/or assessed.

4.4.3.4 Periodic In-Service Inspection

Depending on expected degradation types and rates, and regulatory requirements, it is usual to inspect offshore facilities, including the moorings, on a periodic basis. To meet U.S. regulatory requirements, the interval between inspections needs to be no greater than 5 years. In some parts of the world predominantly using RBI methodologies, this interval could be either less or greater than 5 years.

Based on the survey conducted by Mooring Integrity JIP, it is interesting to know that in the North Sea, turret mooring systems were inspected more frequently than the arbitrary nominal used generally for offshore facilities (see Figure 5).

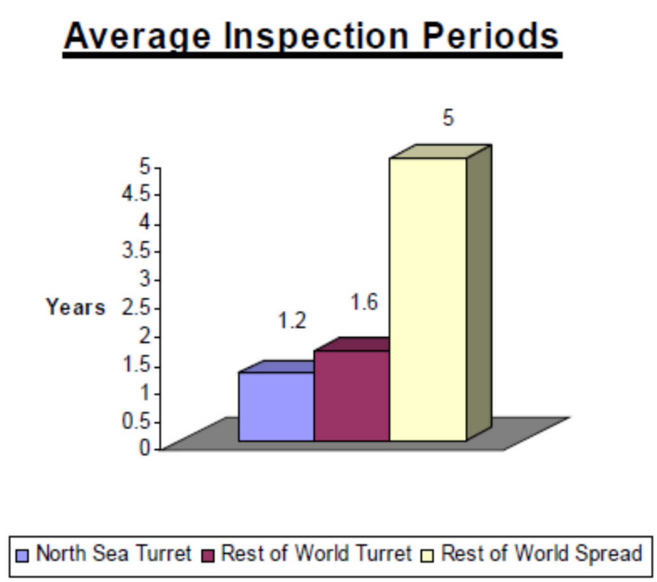

Figure 5 – Average Inspection Period (*courtesy of Mooring Integrity JIP*)

4.4.3.5 Ad-Hoc Inspections

The need for ad-hoc inspections over and above the periodic events can be generated by a number of different situations, such as after a major event such as a storm, a structural failure or ship impact.

Other examples include maintenance of the moorings, or construction work in the vicinity of the moorings, that could potentially impact the moorings.

4.4.4 WHERE AND HOW OFTEN TO INSPECT

API RP 2I, class rules and other standards provide guidelines on the inspection interval, extent of the inspection, discard criteria and required documentation. Major class societies, in general, also follow IACS recommendation 38 "Guidelines for the Survey of Offshore Mooring Chain Cable in Use" (1995/2010) for the in-service inspection. In addition some operators may inspect the mooring system after large storms or other events that warrant inspection (dropped objects, phased installation of risers, etc.).

In general, the periodic inspections include annual inspection and special periodic (5 years) inspection. The annual inspection is to be carried out at approximately 12-month intervals, with the vessel at operational draft range, and the position mooring system in use. The annual inspection is normally carried out through visual inspection to confirm that the mooring system will continue to carry out its intended purpose until the next annual survey. The scope of the annual inspection is limited to a visual inspection for the above water mooring components, including chain or wire rope, winches or windlasses, deck sheaves, stoppers, and fairleads or bending shoes.

Special periodic inspection is to be carried out at approximately 5-year intervals and requires extensive inspection in addition to addressing the overall mooring performance. Certain measurements and detailed inspections of the mooring components are required for the critical areas, such as the fairlead region, splash zone, touch-down region, and connectors. API 2I Section 4.6 provides detailed information on where to inspect as well as discard criteria.

A survey of operators conducted through FPS mooring integrity JIP (see report Section 6.2) revealed that there is significant variation in the frequency of mooring inspection. There are some operators who visually inspect their mooring systems each year, possibly supplemented by additional surveys after significant events such as storm conditions. However, there are others who only visually inspect their mooring systems once every 5 years.

Although the value of information gained from visual inspection is debated, it can be argued that it increases the chance of finding some of the potentially systemic problems within the mooring system before there is a complete mooring system failure. Examples include localized high rates of corrosion (e.g., by galvanic action), component misalignment, loose pins in connectors, etc. In addition, there may be other conditions that could affect the integrity of the mooring system, such as installation status, anchor scour, and trenching.

API RP 2I requires an as-built inspection to confirm that the anchor legs are connected as designed, to check or monitor damage during installation, and to ensure that the permanent twist in the anchor legs is within the design/installation margins. API RP 2I also requires the documentation of as-built inspection on a detailed listing of all components in each mooring leg, such as manufacturer, serial number or other identification. In addition, the document should include any information available on mooring system modifications made during installation. However, the level of implementation on as-built inspection may vary across the industry. As recommended in Section 4.4, a detailed, as-installed survey can be of considerable value. If it can be confirmed that the mooring system has been installed as designed, or the details of the installed mooring system can be ascertained, then it is possible to use mooring monitoring to help calibrate the analytical models, improve fatigue life predictions, better understand the consequences of a single line failure, and generally improve the overall reliability of the installed system. The installation survey is something that may easily be skimped on, but the later cost to the facility owner can be considerable. High quality installation information can help in the justification for continued operations beyond the original design life by allowing far better understanding of the actually experienced in-service loadings.

Based on the survey conducted by Mooring Integrity JIP, it is interesting to note that in the North Sea, turret mooring systems were inspected more often than required (as illustrated in Figure 5, above).

4.4.5 Existing Inspection Techniques (Focusing on Mooring Inspections)

There's a range of inspection technologies used with varying levels of success on offshore floating installations. Some, but certainly not all, of these may be applicable for inspection of mooring inspections. There are several reasons for knowing or doubting the applicability of NDE techniques, with the main ones being the following:

- Physical shape/ geometry of mooring components are quite different than offshore structures. Generally for structures, we are dealing with large scale features and components and the inspection technologies have been developed/ improved with these configurations in mind.
- On structures, inspection programs are not guaranteed to find all degradation and/or failure. This usually does not have a catastrophic consequence as loads will distribute out to other paths.
- Moorings have many single points of potential failure with no alternative load path – when the component fails the mooring line fails. The only distribution is onto adjacent mooring lines.
- The known failure points on moorings are often inaccessible, or at best have limited access or geometry incompatible with the NDT tools developed for structures.
- Defects, particularly in rope, tend not to at or near the surface. Buried or hidden defects are usually difficult to detect.
- Some or all of the mooring on the seabed may be buried. In theory it could be exposed but in practice it is doubtful if this will be achievable.
- Mooring lines are dynamic because of the floating structure movement making contact difficult or impossible to achieve

Inspection techniques used offshore that may have some use on moorings include the following:

- **Close Visual Inspection (CVI)** is the most common and powerful method for detection of gross defects. It can also be used for close up examinations of welds, etc. It can be performed both above and below water and by divers or ROVs.
- **Mooring Line Dimension Measurement**. Certain measurements of the mooring components are required during the 5-year interval inspection. Mooring chain measurement systems that have been used include simple diver-deployed manual calipers, a prototype stand-alone robotic system, and ROV-deployed systems. Some dimensional checks, particularly those that involve

measurement over multiple chain links, become difficult or impossible to perform underwater. But some ROV-deployed systems include both mechanical caliper and 'optical caliper' systems that appear to be practical and effective.

- **Magnetic Particle Inspection (MPI)** is commonly used during manufacture and installation, including most of the chain surface if equipment is supplied to move adjacent links around (allowing good access to the chain intrados). MPI is normally used to detect surface breaking or near surface breaking crack indications but it should be noted that the rough surface of most chain links may create false indications. Common practice is to inspect the flash butt weld of every link and to inspect 10% of all accessible surfaces of the links. In-service inspection could include MPI as explained above, but noting that moving components around to allow thorough inspection is generally not feasible. For most chain, MPI of the flash butt welded area would be possible, but only for surface breaking or near surface breaking cracks. MPI is feasible underwater but the specific geometry of chain links may restrict its use.
- **Ultrasonic Testing (UT)** is often used to examine the flash butt weld area of chain. The great advantage that UT has is that it can detect both surface breaking and subsurface defects. This is particularly important in the flash butt weld area where incomplete fusion can result in subsurface defects. The technique is straightforward to use above water and underwater with divers. For ROV applications, it may be necessary to develop a special tool to hold the probe(s).
- **Electro Magnetic Detection (EMD)** method is an old technology that has been used for many years for the inspection of wire ropes. Devices exist for inspecting ropes of diameters of up to approximately 150 mm (6 inches). The method can detect surface breaking defects through non-conductive coatings. One of the biggest problems with the technology is that it is not good at detecting defects close to the wire rope termination, probably the area of greatest interest in mooring wires. For many years there has been discussion about moving the existing, relatively mature, technology underwater, but so far little progress has been made.
- **Dye Penetrant Testing (PT)** can be used on metallic and non-metallic materials, provided the product is virtually non-porous. This inspection method has been used for inspection of mooring chain. Only surface breaking defects can be detected. PT requires the surfaces and possible surface-open discontinuities to be clean. It is only applicable above water.
- **Radiography Testing (RT)** for mooring chain and wire rope produces a "picture" of mainly volumetric discontinuities, provided these are favorably oriented with respect to the direction of the applied X- or gamma radiation. "Two-dimensional" flaws can be difficult to reveal and the defect height, which often is the most critical parameter, is normally impossible to assess by radiography. The great advantage is the permanent record (the radiogram, the film), but the radiation hazard can limit the applicability of the method.

4.5 Monitoring

Monitoring, as described above, is using information to determine the status or response of the mooring system, a mooring line, or occasionally a mooring component. Monitoring involves the continual or intermittent gathering of direct or indirect data. It is intended to indicate specific properties (e.g., mooring load), changes in properties (e.g., a change in mooring load), or some other effect that, either alone or in conjunction with other data or observations, indicates a change in status of the mooring system (e.g., mooring line failure).

4.5.1 Overview

Effective real time mooring monitoring can supplement periodical inspections to provide information on mooring system performance, anomalies, mooring line loading for fatigue assessment, etc. Effective mooring monitoring methods depend on the characteristics of a mooring system, objectives, and other conditions. In-service system monitoring for mooring systems is implemented for various reasons, in particular for mooring leg failures.

The JIP of FPS mooring integrity has gathered information on existing mooring failure detection systems. There are also more comprehensive monitoring and advisory systems that have been reported as being in use in exiting mooring systems. Those methods are summarized in this section of the report.

In addition to the monitoring technologies discussed in this section, the following technologies being developed are discussed in Section 6.3:

- Direct in-line Tension Monitoring (Inter-M Pulse)
- Sonar based system for real-time feedback on the status of mooring lines

There has been considerable discussion in industry meetings about the lack of success in monitoring mooring lines, and particularly in determining mooring line tensions. The consensus tends to be that industry should require, and be able to monitor, if a mooring line fails. The failure should be detected in real time so that the FPS crew can take the appropriate action (assuming suitable plans have been developed). There are a number of systems that have been proposed to detect line failure, and some have been deployed. It is important to realize that not every system will work on every type of mooring system. As an example, a monitored GPS-based system will be able to detect windward line failures quickly on a conventional catenary moored facility. The same GPS system may not be able to quickly detect a windward line failure on a taut moored grouped system, and could completely fail to identify a leeward mooring line failure. It is important to decide how quickly a failure needs to be detected, under what circumstances, what plans the crew have for acting on failure detection, the type of mooring system, etc. Once the details are understood (and for many systems this needs to be during the design stage), a suitable system can be chosen and installed.

Actually monitoring mooring line tensions, either continually or intermittently, and either with real-time surface readout or recoverable data from subsea equipment, is considerably more complex. Systems have been installed on a number of FPS, but with extremely limited success in most cases. There have been many reasons given for the limited success (e.g., strain gauging a winch can give good data on the line tension at the winch, but does not account for friction losses over the sheaves and fairleads). Discussion with a number of the consultants and contractors involved in installation of the monitoring equipment suggests that part of the problem is the client expectation that an “off the shelf” system can be developed and used on a range of mooring types. In reality, it is likely that a good quality, successful monitoring system is going to have to be customized – designed for the actual facility, mooring type, and mooring line size. Such a system is not going to be inexpensive. In addition, early models could prove to be less effective than hoped. The end result is that companies are reluctant to expend the required money with limited expectation of success. In reality, however, there are well-established methods for determining loads and tensions; the difficulty is in ensuring they are correctly calibrated, and installed in such a way that they are sufficiently sturdy to have a useful life. In addition, sturdiness is a serious problem offshore; cabling can easily get damaged; power is neither clean nor necessarily entirely reliable; crews are not necessarily trained to understand the importance of monitoring equipment; etc.

The following descriptions of monitoring technologies have been included to help create and improve understanding of what is being done at present, and proposed for the future. In many respects, mooring line monitoring, even real time tension monitoring, is an easier problem to solve than mooring line inspection.

4.5.1.1 Simple Sonar Probe

A simple sonar probe system has been used on a North Sea FSU. The sonar head is deployed through the center of the chain table to approximately 15 to 20 meters below the hull. The head is deployed every two weeks in calm weather or after a storm to confirm that all the mooring lines are present. The illustrated system is fairly simple and is easy to repair if something does go wrong with it. But if a line breaks in the mud, still having some tension/catenary, the signals from the sonar probe may not be sufficient to indicate that a line has failed.

Simple Sonar Probe	
Maturity:	Has been used in a limited number of applications
Intent:	Detect failed mooring line only – no tensions. If not permanently deployed, then no real time feedback on a failure
Application:	All types of facility, but easiest on a turret moored system
Deployment:	New and existing units
Advantages:	Can be retrofitted; low technology; probes easily repaired if damaged
Disadvantages:	Only failed line detection when system deployed. Possible problems detecting failure on seabed if it does not result in significant mooring line angle change at turret. No mooring line tension data gathering

4.5.1.2 Inclinometers

A simple inclinometer could measure mooring line angles. In calm weather, if any of the mooring line angles have changed to a significant extent, there is a possibility of a line failure. Such inclinometers could be checked using “football” sized ROVs, which can be deployed directly from the deck of the FPS itself. These small ROVs can be stored on the FPS itself or can be sent out by a helicopter as the need arises. Simple inclinometers overcome the difficulties sometimes encountered with damage to power and signal distribution cables on more complex systems. But the readings are not continuously monitored.

Inclinometer	
Maturity:	Has been used in a limited number of applications
Intent:	To measure mooring lines angles for the use of detecting line failure or as inputs to the mooring lines load assessment
Application:	All types of mooring systems
Deployment:	New and existing units
Advantages:	Direct measurement of line angle and not affected by other parameters. Relatively simple system with low cost
Disadvantages:	No continuous monitoring. Line angle for each mooring line may be recorded at different times and could cause inaccurate line load assessment

4.5.1.3 Load Cell

In theory, mooring line load monitoring is the most straightforward way to detect mooring line failures. There are systems that use fixed chainstoppers, which have been outfitted with load cells underneath their base. Figure 6 illustrates a load cell at chainstopper. There are also load cells installed in mooring lines. Figure 7 shows an instrumented load pin. However, experience has indicated that the accuracy, reliability and robustness are major issues using load monitoring system, especially for underwater where access to the mooring line and instrument, is very difficult if not possible. The power and signal transmission cables are areas of particular weakness for systems exposed to long term offshore loading conditions. A new development in recent years is the use of in-line load cells, such as Inter-M Pulse with a load cell housed in a protective casing, making it better suited for offshore installation. Data transfer is conducted via an acoustic transmitter. Section 6 of this report provides more discussions on this topic.

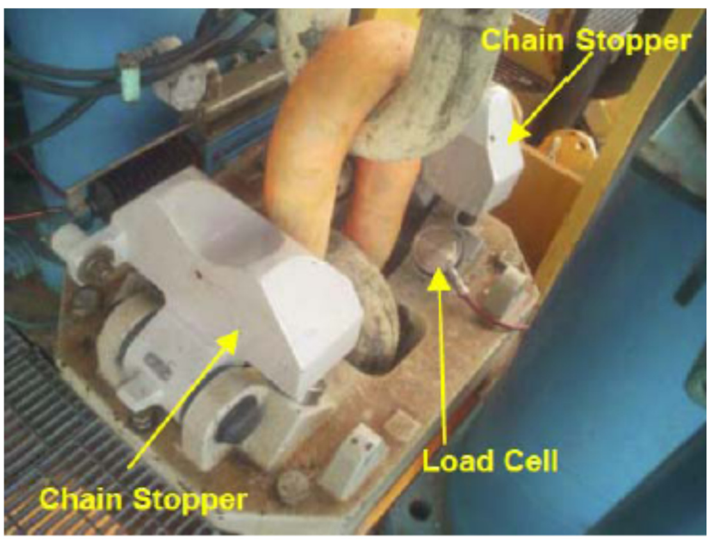

Figure 6 – Instrumented Load Cell at Chainstopper (*courtesy of FPS mooring integrity JIP*)

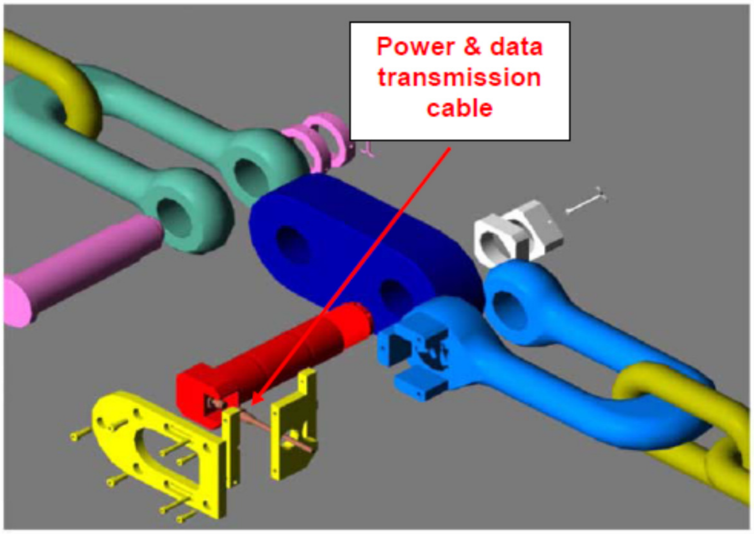

Figure 7 – Instrumented Load Pin (*courtesy of BMT/SMS*)

Load cells are old technology, but have been found to be unreliable when used in mooring system monitoring. Part of the problem is that they are required to be operational for extended periods of time with little opportunity for recalibration. Signal drift can be detected up to a point; however, it is not always possible to determine what is due to instrument drift versus what is a slow change in the real mooring line load. Another problem can be the system losses between the chainstopper, where the load cell is installed, and the mooring line tension away from the facility. Not only is it difficult to ascertain the frictional losses, but they may not be fixed over time. Again, this can introduce an unexplained signal drift.

Load Cell	
Maturity:	Has been used in number of applications
Intent:	Monitor mooring line load for the detection of line failure, over loading, or fatigue assessment
Application:	All type mooring systems; difficulty for submerged turret mooring system
Deployment:	New and existing systems. For inline load cell; retrofit is relatively difficult
Advantages:	Long time, very well used method for load measurement. Relatively simple system, low cost.
Disadvantages:	Measurement is not reliable especially when the mooring line load is not very high. Many other factors affect the output of the measurement, such as frictions, temperature, signal drafting, recalibration, durability of transmission cables, etc.

4.5.1.4 Global Positioning System (GPS) and Gyro

Figure 8 illustrates a global positioning system. Theoretically, the abnormal changes of the offset of a FPS should be able to indicate the failure of a mooring line. Some units have installed GPS/ Differential Global Positioning System (DGPS) for position monitoring. However, the effectiveness of using offset monitoring to detect mooring line failure depends upon many factors, such as the characteristics of the mooring system, water depth, monitoring of environmental conditions, and reliability of GPS and Gyro. But in general, overall offset monitoring and recording using GPS and Gyro is cheap. The offset information combined with knowledge of environment and mooring system behavior could, at least, provide triggers for further inspection.

Global Positioning System (GPS) and Gyro	
Maturity:	Has been used in a number of applications
Intent:	To monitor and measure FPSO locations and hence to derive the mooring line load
Application:	All types of mooring systems
Deployment:	New and existing systems
Advantages:	Easy to install and relatively low cost. Equipment on board the vessel and easy to maintain
Disadvantages:	The relationship between vessel's position and mooring line load needs to be carefully studied to have a clear understanding between the measured positions and mooring line load. Environment measurement (wind, wave, and current) may be necessary.

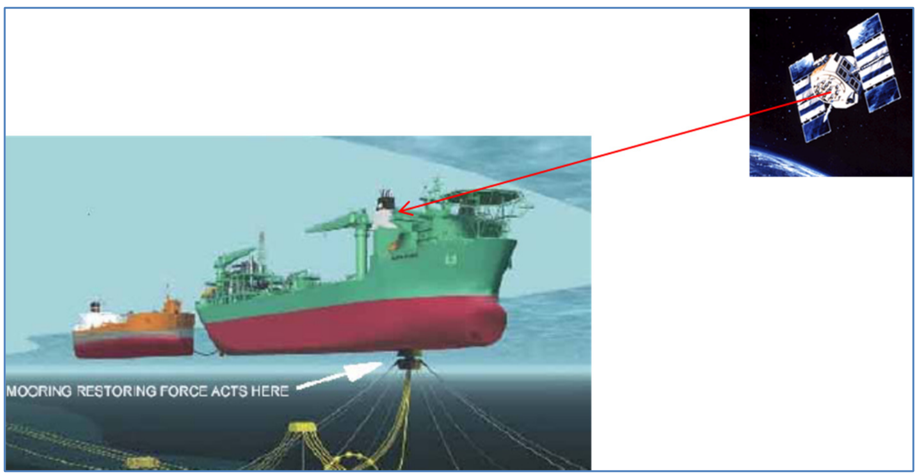

Figure 8 – Global Positioning System (*courtesy of FPS mooring integrity JIP*)

4.5.1.5 Indirect In-line Tension Monitoring (moorASSURE)

The moorASSURE monitoring system monitors the mean angle of mooring lines and vessel's position. On each mooring line, an inclinometer is attached to measure its mean angle. The measured angle is periodically transmitted to vessel mounted acoustic receivers using hydro-acoustic data link. The acoustic inclinometer is placed in a holder to allow its retrieval and installation by ROV or diver. The logger holders can be attached to chain links or on the chain follower below the chain table. A number of hull-mounted acoustic receivers are connected using electrical cables to an industrial rack mounted data acquisition system located on the topside (see Figure 9).

The measured mooring line angles are collected by a topside data acquisition system. The mean mooring line tension is derived using the measured mooring line angles and vessel's position data. The calculated mooring line tension is displayed and compared with preset thresholds. Where measurements exceed predefined threshold, alarms are raised by the software. The system was installed on the Espírito Santo FPSO, in Campos Basin block BC-10, offshore Brazil in 2009.

Indirect In-line Tension Monitoring (moorASSURE)	
Maturity:	Used in limited number of applications
Intent:	Continues monitoring and measuring mooring lines angles and predicts mooring line load based on line angles or detects mooring line failures
Application:	All type of mooring systems
Deployment:	New and existing units
Advantages:	Real time monitoring, acoustic transmission, less maintenance
Disadvantages:	Need careful calibration for the model of mooring line angles and mooring line load. Data management and alarm setting criteria

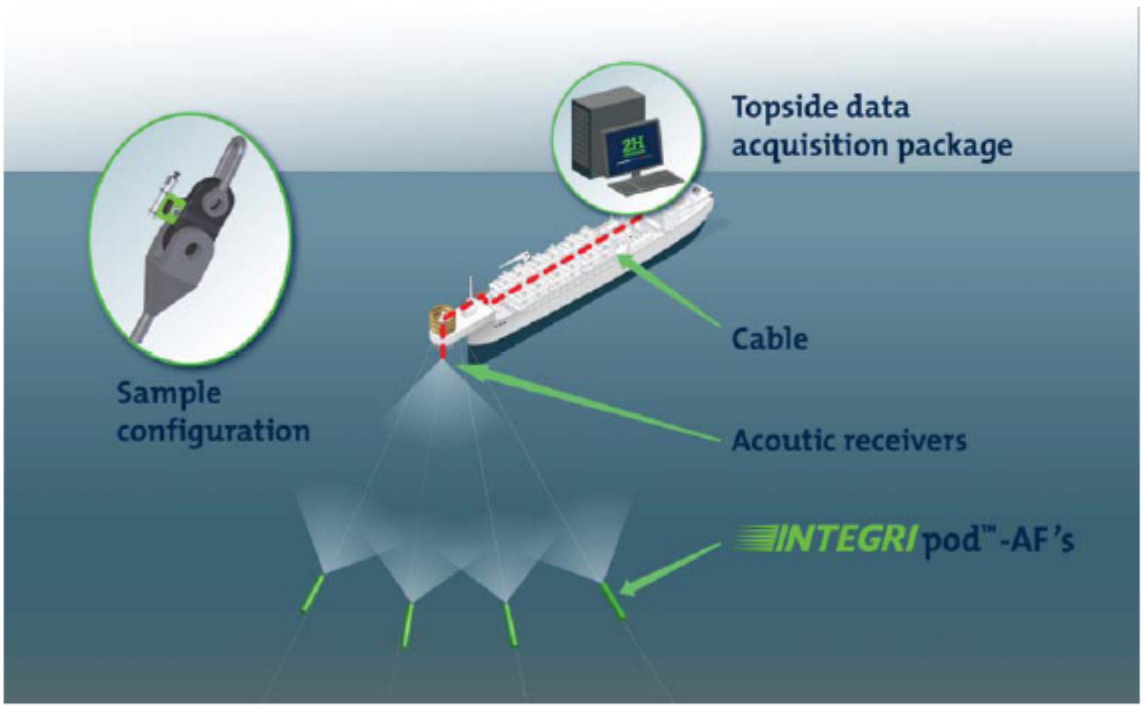

Figure 9 – Indirect Line Tension Monitoring System (*courtesy of 2H*)

4.5.1.6 Integrated Monitoring and Advisory System (IMAS)

Recently, an Integrated Monitoring and Advisory System (IMAS) has been designed and installed on an FPSO with submerged soft yoke mooring system. It includes monitoring system, forecast system, and data acquisition system. The monitoring system monitors wind, wave and current conditions, FPSO motions, and mooring load. The forecast system includes the prediction of FPSO motions and mooring line load. It also provides advisory on optimum loading conditions. The data acquisition system uses a central server on the FPSO to collect, process, and store the data from the various instruments. Most instruments on the FPSO are connected directly to the server by TCP/IP and Modbus protocols, while wave and current measured data could be transmitted to the main server through the oilfield network. The hardware used includes DGPS, Inertial Measurement Unit (IMU), Acoustic Doppler Current Profilers (ADCP), inclinometers, accelerometers, Fiber Bragg Gratings (FBG) sensors. So far, feedback on the effectiveness of the system are not available. Perhaps more information on the performance of the system will be available in a couple of years.

Integrated Monitoring and Advisory System (IMAS)	
Maturity:	Has been used in a limited number of applications
Intent:	Monitor and detect mooring line overloading, failure, and provide operation advisory
Application:	All types of mooring systems
Deployment:	New and existing units; could be difficulty for existing unit
Advantages:	Comprehensive system for real time monitoring and provide advisory for operations
Disadvantages:	Relatively expensive with the measurements systems. The system is relatively new and the effectiveness of the advisory system is not yet known.

4.5.2 Challenges of Monitoring Systems

Real time mooring monitoring system can have many benefits to the integrity of the mooring system, including the following:

- Revealing anomalies of mooring system for further investigation
- Providing warnings on mooring line failures
- Providing information for RBI, modification of inspection and repair plans
- Verifying numerical model for mooring strength analysis and understanding mooring system performance
- Assessing fatigue damage using measured mooring line load, verifying against fatigue analysis and condition assessment for possible life extension

However, it should be understood that, at this time there is no single mooring monitoring system that can effectively work for all mooring systems and for all objectives. The objectives and requirements for mooring system monitoring should be carefully planned.

Much progress has been made in terms of the number of installed monitoring systems and the technical advancements of monitoring systems.

4.6 Planning and Cost of Inspection and Monitoring

The cost of both inspection and monitoring is not insignificant and, therefore, both methodologies have to be considered very carefully to determine how to achieve the optimum useful information at the lowest practical cost. For both inspection and monitoring to be effective, the following aspects should be considered at the beginning:

1. Information needed to understand performance (e.g., extent of corrosion, fatigue tensions, mechanical damage, extreme storm tensions, loss of line)[3]
2. What to inspect and monitor to provide the understanding needed
3. What inspection technologies can be applied to obtain the answers to 1 and 2, above

[3] This is the most fundamental question that must be addressed. Without doing so, it is very likely that data will be gathered that do not contribute to an understanding of the underlying issues.

4. Reliability and accuracy of the related equipment and systems
5. Determination of good inspection intervals, noting that different degradation process and different inspection techniques could have different useful intervals, based on their characteristics[4]
6. Establishment of baselines
7. Effective method of data processing, reporting, and alarming to indicate degradation or failure of monitored system
8. Effective method of data processing and reporting for the purpose of condition assessment and remaining fatigue life, if needed
9. Interface design for ease in understanding the monitoring parameters by operational personnel

Inspection is not a one-size-fits-all solution and for each application the technologies used, the methods of deployment, the procedures used, and the assessment of data is somewhat unique for each application. Many of the inspection technologies used in the offshore industry were developed for use on structures, both floating and fixed, and in particular many were intended for examination of welds. The components that make up a mooring system generally are quite different to structures and the implication of this is that specific inspection tools used successfully on structures will either not work or will have very limited application on moorings.

A monitoring system is most easily incorporated into a facility at the design and construction phase. It appears that more operators are realizing the benefits of having such a monitoring system for an FPS; therefore, new builds now tend to include this in the design. The most challenges are for existing units to be retro-fitted. The cost of retro-fitting not only includes the cost of monitoring systems, but also the cost of installations, which is often expensive (especially for underwater installation). The cost and the effects of the monitoring system will continue to be challenging topic.

The measurement equipment for a mooring monitoring system is subject to harsh environments, especially for underwater installations. The equipment is often out of reach for inspections and maintenance. It could be difficult to determine the source of an abnormal signal (e.g. failure of the instrument, or the system) without redundancy, or a lot of troubleshooting. A possible solution may be to use multiple monitoring methods – almost the case of one system monitoring the other.

Experience indicates that there are many uncertainties associated with the monitoring system using mooring line load measurements, due to the friction in the fairleads/chainstopper, sensitivity of load cells, temperature effect on load cells, possible plastic deformation of load cell, the ability to detect line failures in mud, and others. If a mooring line fails in mud, the line will drag through the mud until the friction exerted by the soil surrounding the chain matches the tension in the chain at its sea bed

[4] Prescriptive intervals in industry standards/recommended practices tend to be conservative, but nevertheless robust, particularly for the actual floating structures. But they are not optimized for specific applications and the unique characteristics of moorings.

touchdown point. Anchor handling experience and calculations has shown that very high line pulls are required to drag large diameter chain through the sea-bed.

In general, using GPS/DGPS for position measurement is reliable, provided some redundancy measurement is considered. However, it is not quite straightforward to interpolate the measured positions for the indication of mooring failures. Experience indicates that if a mooring line fails in moderate weather conditions, it is difficult to distinguish the change in offset from the normal offset changes due to wind, wave, and current effects. In addition, the direction from which the weather comes may influence the effectiveness of offset monitoring for line failure detection. For example if a line fails and the weather pushes the unit in the direction of the failed line, the offset from the equilibrium position will be small compared to the weather pushing the unit in the opposite direction of the failed line.

It is also necessary for a GPS/DGPS monitoring system to monitor the environmental conditions and to carry out calibration study for the monitored mooring system. In addition, so that operating personnel understand and effectively use the monitoring system, training and onboard support must be provided.

4.7 Data Processing and Data Management

Inevitably over many years and for the multiple parts of an offshore facility, the amount of data gathered becomes substantial. Therefore, it is important that computerized data management systems be used to store, analyze, interrogate, and trend the captured data. In many cases it is the comparison of different data that allows a good assessment to be made and the data management system must allow this to be done.

Data processing and data management may have often received less attention than basic requirements during the planning and design process. This could have resulted in large volumes of data generated but not used, or an overwhelming amount of data that takes a long time to sort out. For example, on one instrumented North Sea FPSO a mooring line failed; it took two weeks of data processing from the other lines to reveal the tension spike that confirmed it was a real failure rather than an instrumentation fault.

No sensors can be 100% accurate, and thus modeling tools are necessary to discard useless information and extract meaning out of the useful data. It is equally important to interpret the results in a way that is easy to understand. Visualization through visual imagery has been regarded as an effective way to communicate both abstract and detailed analysis.

4.8 Competence and Training

Although largely outside the scope of this study, it should be highlighted that everything, from general visual inspection onwards, needs to be performed by competent people, with training and certification where applicable/available. For some systems, particularly for monitoring, it is not practical to always have trained and qualified people in attendance at all times.

Mooring is a passive stationkeeping system, and the operations personnel, in general, do not seem to have an active role in mooring system management. However, providing knowledge and training to operations personnel regarding the mooring system is important even for a passive stationkeeping system, especially with monitoring system on board. Operations procedures and failure response procedures should be clear and easy understood by the operation personnel, and should be kept onboard, preferably within the maintenance and emergency response manuals.

5.0 GAP ANALYSIS ON INSPECTION AND MONITORING TECHNOLOGY (TASK 5)

5.1 GAPS IN MOORING INSPECTION TECHNOLOGY

Given that the main inspection technology currently used is a combination of visual by diver and visual by ROV, there are significant gaps in industry's ability to inspect the moorings of floating offshore installations. There are some potential inspection technologies being developed, but most will still suffer from the disadvantages of requiring an ROV (with the potential to damage the mooring system) or diver (with risks to the diver). Moorings may also require cleaning of marine growth, which exposes the mooring components to potentially increased corrosion. Table 8 shows the areas of the mooring system, in conjunction with the potential failure mechanism, and the available inspection technologies (see also Table 6). It can reasonably be argued that whenever no viable inspection technology is given, there is an identified gap. It is extremely unlikely that these gaps will all be filled in the near future. However, identifying the gaps, reinforces the importance of an extremely high quality manufacturing QA/QC program to ensure that the integrity of the product installed is completely unimpaired.

Table 8: Gap Analysis of Mooring Inspection Technology

Failure Mechanism	Is cleaning required?	Diver (w Depth Limits ~150 feet*)	ROV	ACFM or Equivalent ROV & Diver	MPI	UT	Physical "Go-No Go" Template	Rope Access Inspectors
Below the Seabed	Currently no viable or likely viable inspection techniques for below the seabed							
Material loss								
Cracks								
Thrash Zone	Difficult to access all sides of mooring components because seabed gets in the way							
Material loss	Y	Y	Y	N/A	N/A	N/A	L	N/A
Erosion	Y	Y	Y	N/A	N/A	N/A	L	N/A
Interlink wear	Y	L	L	N/A	N/A	N/A	L	N/A
Birdcaging of wire rope	N	Y	Y	N/A	N/A	N/A	N/A	N/A
Trenching	N	Y	Y	N/A	N/A	N/A	N/A	N/A

Table 8: Gap Analysis of Mooring Inspection Technology								
Failure Mechanism	**Is cleaning required?**	**Diver (w Depth Limits ~150 feet*)**	**ROV**	**ACFM or Equivalent ROV & Diver**	**MPI**	**UT**	**Physical "Go-No Go" Template**	**Rope Access Inspectors**
Free Hanging Zone below Waterline	There is good access to all sides of the mooring line, although in grouped moorings there could be limited space closer to the water surface. Almost all connectors will be in this zone. While one of the most accessible areas of the mooring, it is also one of the least likely to have a mooring failure, except due to connector failure.							
Fatigue (tension tension) – Chain	Y	LL	LL	LL	LL	LL	N/A	N/A
Fatigue (tension tension) – wire rope	Y	N	N	N	N	N	N/A	N/A
Fatigue (tension tension) – Connectors	Y	LL	LL	LL	LL	LL	N/A	N/A
Mechanical damage to Synthetic	N	Y	Y	N/A	N/A	N/A	N/A	N/A
Mechanical damage to sheathing	N	Y	Y	N/A	N/A	N/A	N/A	N/A
Wire or other component fouling mooring lines	N	Y	Y	N/A	N/A	N/A	N/A	N/A
Corrosion	Y	Y	Y	N/A	N/A	N/A	L	N/A
Connector misalignment or out of tolerance	N	Y	Y	N/A	N/A	N/A	N/A	N/A
At the Waterline	This is a particularly difficult area as it cannot be accessed by divers, boats, or ROVs. On certain units it is possible to change the draft to move waterline components either above or below the waterline so can be accessed by either rope access or diver, respectively							
Fatigue (tension tension) – Chain	Y	LL	N/A	LL	LL	LL	N/A	LL
Corrosion	Y	Y	N/A	N/A	N/A	N/A	Y	Y
Above the Waterline	Generally covered by rope access technology (RAT)							
Fatigue (tension tension) – Chain	N	N/A	N/A	LL	LL	LL	N/A	LL
Fatigue (tension tension) – wire rope	N	N/A	N/A	N	N	N	N/A	N

Table 8: Gap Analysis of Mooring Inspection Technology								
Failure Mechanism	**Is cleaning required?**	**Diver (w Depth Limits ~150 feet*)**	**ROV**	**ACFM or Equivalent ROV & Diver**	**MPI**	**UT**	**Physical "Go-No Go" Template**	**Rope Access Inspectors**
Fatigue (tension tension) - Connectors	N	N/A	N/A	LL	LL	LL	N/A	LL
Mechanical damage to Synthetic	N	N/A	N/A	N/A	N/A	N/A	N/A	Y
Mechanical damage to sheathing	N	N/A	N/A	N/A	N/A	N/A	N/A	Y
Corrosion	N	N/A	N/A	N/A	N/A	N/A	N/A	Y
At Vessel Interface	The vessel/mooring interface can be either underwater or above the water surface.							
Fatigue (tension tension) – Chain	N	LL	LL	LL	LL	LL	N/A	LL
Fatigue (bending tension) – Chain	N	Pos/LL	Pos/LL	Pos/LL	Pos/LL	Pos/LL	N/A	Pos/LL
Fatigue (OPB) – Chain	N	Pos/LL	Pos/LL	Pos/LL	Pos/LL	Pos/LL	N/A	Pos/LL
Abrasive damage	N	Y	Y	N/A	N/A	N/A	N/A	Y
Corrosion	N	Y	Y	N/A	N/A	N/A	N/A	Y

Y = Yes, this technique can be effectively used
N = Not possible with current technology
L = Limited capability depending on access around the component being inspected
LL = Very limited possibility, in most cases because critical area is unlikely to be accessible (e.g., half crown chain intrados)
Pos/LL = Possibility that there could be good access to the critical area, but in most cases there will be very limited access.

Notes on Gap Analysis	
Is Cleaning Required?	Cleaning is time-consuming and can result in increased corrosion
Diver (Depth Limit = 150 feet)*	*While the industry limit for diving is 1,000 feet the costs increase exponentially with depth because of the increasingly complex diving systems needed. Given the sophistication of today's ROVs and the limited mooring integrity risks in this mid-water range, a practical solution is to use these ROVs for inspections below 100 to 150 feet, noting that 150 feet is the limit for the lower cost air-diving.
UT develops a ROV deployable probe array for specific chain size	Has to be capable of operating with a corroded, and potentially pitted, surface
Phased array Build for ROV deployment	Must be capable of operating with a corroded, and potentially pitted, surface

5.2 GAPS IN MOORING MONITORING TECHNOLOGY

There are a limited number of properly monitored mooring systems currently in existence. There are different views as to why this is the case. Some say that monitoring is not yet technically viable while others contend that there has been insufficient impetus for industry to deploy suitably robust and customized systems to work effectively. Nonetheless, there is a much better chance that suitable systems will be developed and deployed in the near future. The first gap most likely to be filled is the real time detection of failed mooring line(s). A system that manages to detect a mooring line failure in real time absolutely should be required on all permanent floating facilities. While there are difficulties with certain systems (e.g., GPS may not work effectively with taut moored units), it should not be beyond the capability of any reasonable organization to install such a system in the near future.

Monitoring mooring line tensions, particularly real time, could be a more difficult nut to crack, but certainly not impossible. As with failed line detection, it is unlikely that there will be an off-the-shelf solution available that is generally applicable to many installations, but if there is a real need to monitor mooring line tensions (e.g., for verifying fatigue life usage for potential "life extension"), then the technology will be forthcoming.

6.0 INDUSTRY ADVANCEMENTS AND RECOMMENDATIONS (TASK 6)

6.1 OVERVIEW

There are ongoing JIPs, many in which ABS is a participant, that have identified a number of different issues (e.g., excessive pitting corrosion of chain, problems with connectors). There are also companies developing techniques and technologies to either overcome those problems, or find them quickly enough so they do not become an unexpected in-service problem. ABS has a dedicated research & development group that has been involved in reviewing the testing results of some of these techniques. Others are presented at industry meetings. Our team is in communication with most of the companies that are developing new technologies for mooring line integrity monitoring. These companies are generally willing to assist by supplying information as it helps in their marketing efforts. The project team has searched literature and talked to industry vendors about what technology is being developed, when it can be applied, and what problems it will help solve. Section 6.2 provides overviews of recent JIPs, and Sections 6.3 and 6.4 provide the development of inspection and monitoring technologies.

There are many units operating in the GoM with mooring systems that are approaching the end of their original design life, and there has been considerable discussion as to how this should be addressed by industry. There are many facets to the problem, including:

- What is the current condition of the mooring system, how has it been monitored during its life, and are there any increases/decreases in the corrosion rate by comparison to design?
- How much of the original design fatigue life has been depleted by exposure to actual metocean conditions?
- What are the metocean conditions to which the unit was exposed?
- Have the unit's motions been as predicted, or was the original analysis conservative/ unconservative?
- Has there been additional information on the expected fatigue life of the mooring components used for the actual installation?
- Do mooring line tension monitoring, or unit motions monitoring results exist that can be used to reassess the fatigue life used so far?
- What are the consequences of a single mooring line failure and its effect on the survivability of the remaining lines?

The project team members, who have been involved in mooring system life extension projects around the world, used past experience and information available to them to develop a plan on the assessment of mooring system remaining life. The assessment also draws on a number of studies in which the formal structural reliabilities of mooring systems have been assessed using intact, single, and multiple line failures as inputs. Through use of the plan, it can sometimes be possible to ascertain if a mooring system can reasonably be expected to be used safely for service beyond its original design life. Section 6.5 provides recommendations for mooring system life extension

6.2 Review of Related Mooring System Joint Industry Projects (JIPs)

6.2.1 FPS Mooring Integrity JIP

Table 9 provides a brief summary of the FPS Mooring Integrity JIP, which was completed in 2010. The participants included operators, floating production contractors, regulatory authorities, equipment suppliers, and inspection companies, which provided access to a significant pool of data. The first part of the JIP was focused on the overall review of mooring integrity issues, case studies, and current status on the management of mooring integrity. The second part of the JIP was focused on guidelines for monitoring and inspection using ROVs. The second part also included the studies on break testing of worn mooring components, proof load on fatigue endurance, and material compatibility. The JIP reports are available to public. The report of the first phase of the JIP was also published (2006) by UK HSE as Research Report 444 titled as "Floating Production System, JIP FPS Mooring Integrity."

Table 9: FPS Mooring Integrity JIP Summary	
JIP run by:	Noble Denton
Start and end dates:	• Phase I (2003-2005) • Phase II (2007-2010)
Number and type of participant (for example):	• Phase I: 23 participating organizations • Phase II: 38 participating organizations • Participating organizations include operators, floating production contractors, regulatory authorities, equipment suppliers and inspection companies
Approximate cost of project (to get an idea of magnitude):	• Phase I: about £200,000 • Phase II: about £350,000
Published public documents (for example):	• HSE Research report 444 • Floating production system • JIP FPS mooring integrity
Published papers:	• Floating Production Mooring Integrity JIP – Key Findings, OTC 17499, 2015 • Phase 2 Mooring Integrity JIP – Summary of Findings, OTC 20613, 2010

The JIP work mainly includes data collections (testing if necessary), industry feedback gathering, cases study, data analysis and digesting, and workshop discussions. The outputs of the JIP may be summarized as following:

Publicizing the Importance of Mooring Integrity. The collected data and survey feedback indicate that the safety of a mooring system is not only determined by the design environment criteria and mooring line safety factors, but also by many aspects associated with the mooring system, which should be considered during design, installation and operation stages. Among others, the JIP report provides discussions on the following aspects that may not get enough attention or could be further improved:

- **Consequences of mooring line failure.** Analysis of consequence failure should include possible triggers to the one line failure or multi-line failure, and the management of the operations after failure. While one line failure could be caused by many reasons (e.g., overload, fatigue), multi-line failure may be due to the common weakness of the mooring lines, corrosion, or progressive failure after one line failure. Consequence assessment is necessary after one line failure to evaluate possible operation under reduced environment conditions.

- **Transportation/transfer and installation.** A few instances of improper handling of transportation and installation were discussed in the JIP report. There are different specifications on the installation of chain, wire rope, fiber rope and anchors, and the detailed instructions by the manufacturers for the transportation and installation of their products should be followed.
- **Turret mechanical implications for mooring integrity.** One failure mode of a turret mooring system is that the turret fails to rotate, which could result in the FPSO becoming partially or totally beam on to storm conditions and lead to twisting of the mooring system and high load on mooring lines. For both passive and active turret mooring system, the JIP report recommends that a check should be made on a turret FPSO to see how great the increases in line tension are if the vessel cannot weathervane to the weather.
- **Line status monitoring and failure detection.** The JIP indicates that it is clearly not appropriate to rely on annual ROV inspection to check if a mooring line has failed. It also indicates that there are still uncertainties associated with current available monitoring systems of specific types. However, an effective use of a monitoring system can improve mooring system integrity. UK HSE does mention that operators should have a suitable measurement on failure detection of mooring lines. However, the JIP reported that for the North Sea FPSOs, 50% of units cannot monitor line tensions in real time and 78% of units do not have line failure alarms.
- **Inspection.** The JIP reports that the important areas to inspect include the fairlead/ chainstopper, touch down and any discontinuity locations. In situ inspection is challenging even for in-air inspection due to difficulty in having access to the locations, such as in the trumpet area. Visual inspection is the main approach for underwater inspection. Currently, any underwater dimensional measurement requires the prior removal of marine growth, which could accelerate the corrosion by exposing fresh steel to the corrosive effects of salt water. A new technology in this area should be further investigated.
- **Sparing options.** The JIP discussed that having sparing mooring lines, connectors, and replacement procedures available is a good practice to minimize the risk and nonproductive time after one line failure. However, attention should be paid to the maintenance of the sparing. Previous experience has shown some problems of maintaining the sparing, such as lost connectors and deteriorated mooring lines when placed in an unfavorable environment.
- **Importance of a comprehensive mooring design specification.** The JIP emphasizes the importance of a comprehensive mooring design specification that may prevent potential problems from happening. The JIP recommends that the mooring design team should work with the installation team and the mooring system operators to understand installation and life cycle maintenance practice and to keep those in mind during the design process.

Guidance on the Improvement of Mooring Integrity. Among others, the JIP has produced guidance on the following subjects:

- **Guidance on how to monitor stationkeeping performance**. Guidance is provided on monitoring for the purpose of verifying mooring system analyses and for the purpose of mooring system integrity monitoring. For each purpose, the JIP provides the list of parameters, such as FPSO motion, environment conditions, and mooring system structure conditions to be monitored. Some guidance on data management is also provided.

- **Inspection guidance for ROV operators**. The purpose of the guidance provided is to enhance the knowledge of all those involved in specifying, preparing and undertaking the survey of an FPS mooring system, thus improving the overall standard of surveys and the interpretation of the result. Guidance is provided in the areas of selecting proper ROVs, understanding the surrounding environment (in terms of visibility, recent weather conditions, marine growth, trenching, etc.), as well as knowledge of mooring systems and the inspection equipment (such as what to look for, and how to make the best use of the inspection equipment). Specifications for the needed ROVs and an inspection sheet should be carefully developed before the inspection.

6.2.2 Chain Out of Plane Bending (OPB)

Table 10 provides a summary of this JIP, which was finished in 2012. The main driver for this JIP was the mooring leg failure of the Girassol deepwater CALM offloading system offshore West Africa. The failure of multiple legs occurred in the hawses of the buoy chain attachment system. These failures happened less than one year after the CALM had been installed. The investigation has suggested that the OPB is the cause of the mooring line failures, which was not included in the design criteria. The JIP was to develop design guidance for the mooring system against OPB failure through chain testing, data analysis, and finite element numerical simulations. Significant amount of effort has been put on chain testing, especially fatigue testing.

Table 10: Chain Out of Plane Bending (OPB) JIP Summary	
JIP run by:	SBM Offshore
Start and end dates:	2006-2013
Number and type of participant:	• 27 participants • Participating organizations include operators, floating production contractors, regulatory authorities, equipment suppliers
Approximate cost of project:	$1.8 million USD
Published public documents:	JIP report is confidential until July 2016
Published papers:	• *Methodology to Account for Corrosive Environment on Accelerated Fatigue Test on Mooring Chains Within the Chain Out Of Plane Bending (OPB) Fatigue Joint Industry Project (JIP)*, Fatigue Design, Nov. 2011, Vol 23&24 • *Chain Out of Plane Bending (OPB) Joint Industry Project (JIP) Summary and Main Results*, OTC 25779, 2015

Although the main work of this JIP is not closely related to the scope of the work of this project, the purpose here is to bring attention to the OPB failure mode, which should be considered not only in the design, but also in the inspection and monitoring if necessary. OPB introduces additional chain stress in addition to the mean (tension-tension) stress. It occurs when the movement of the chains is constrained by other components, such as hawses (see Figure 10). For the chains that are located at those locations where the chain's movement is constrained, they should be inspected for damages due to OPB and they should be rotated to different location if possible, such as periodically adjust mooring line length, to mitigate the OPB damage.

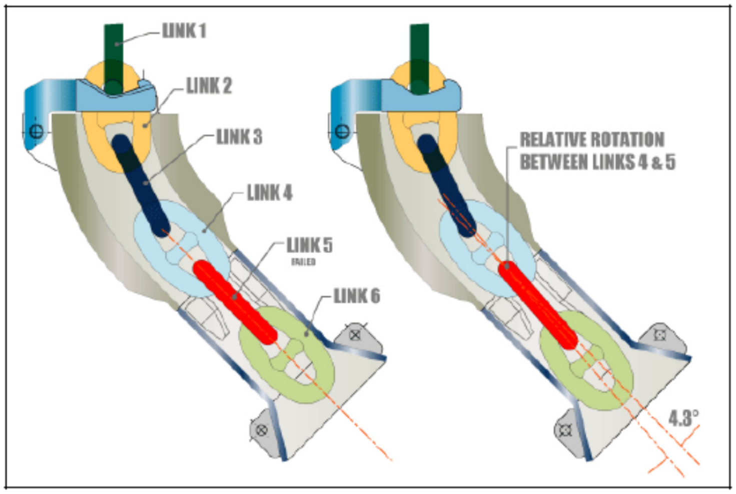

Figure 10 – Illustration of Chain Hawse Arrangement (*from HSE Research Report 444*)

6.2.3 Seawater Corrosion of Rope and Chain (SCORCH, completed 2014)

This JIP was finished in 2014 and the JIP reports will be available to public in 2017. A few papers have been presented at conferences such as OTC and ISOPE to provide JIP activities and qualitative findings form the JIP work. There have been discussions about releasing some of the JIP information to the industry for the guidance of corrosion consideration for the design of the mooring lines. A high-level of summary of the JIP, which is open to public, is provided in **Table 11**.

Table 11: Seawater Corrosion of Rope and Chain (SCORCH) JIP Summary	
JIP run by:	AMOG Consulting
Start and end dates	2010-2014
Number and type of participants:	27 participants; included operators, floating production contractors, regulatory authorities, equipment suppliers, inspection companies and universities
Approximate cost of project:	$2 million AUD
Published public documents:	JIP reports are confidential until 2018
Published papers:	• SCORCH JIP – Examination and Testing of Severely-Corroded Mooring Chains from West Africa, OTC 23012, 2012 • Investigation of Severe Corrosion of Mooring Chain in West Africa Waters, ISOPE 2012 • SCORCH JIP – Feedback on MIC and Pitting Corrosion from Field Recovered Mooring Chain Links, OTC 25234, 2014 • SCORCH JIP – Feedback from Field Recovered Mooring Wire Ropes, OTC 25282, 2014 • MIC and pitting corrosion on Field Recovered Mooring Chain Links, Australian Corrosion Association, 2014 • SCORCH JIP – Findings from Investigations into Mooring Chain and Wire Rope Corrosion in Warm Waters, OTC 26017, 2015

The scope of the JIP was to investigate the characteristics of corrosion of steel chain and wire rope moorings in warm waters and then offer design guidance on the consideration of corrosion. The JIP work mainly includes the development of a corrosion database, field and laboratory tests, data analysis, and the development of corrosion models. As shown in Figure 11, the corrosion database includes the measurements from engineering literature and the corrosion measurements from over 30 facilities (in-service and retired mooring chain and wire ropes from warm waters of Southeast Asia, West Africa, the GoM, Brazil and the North West Shelf of Australia). The tests were carried out to investigate the impact on corrosion due to sea temperature, water velocity, depth and oxygenation, steel grade and wire rope blocking compound. The laboratory tests were also conducted to assess the effect of Microbiologically Influenced Corrosion (MIC).

Figure 11 – Locations Included in Corrosion Database (*courtesy of FPS mooring integrity JIP*)

The JIP raised a number of operational considerations, including updated design guidance for corrosion allowance and operational considerations to maximize the life of chain links. Some related points are summarized below:

- Inspection plan should focus on high nutrient concentration in high temperature seawater where chains could have greatest likelihood of accelerated degradation.
- The seawater temperature and nutrient concentrations should be periodically assessed, including taking into account any discharges from the floating facility to get certain indications about potential susceptibility to pitting corrosion.
- Current industry practice during mooring inspections involves cleaning of the outer surface of the chain or wire rope using brushing or high pressure jetting. The findings of SCORCH indicate that such practices are likely to substantially reduce corrosion endurances through removal of the oxide and biofilm layers, resulting in the re-activation of a higher aerobic rate of corrosion. Consideration should be given to cleaning methods that do not result in such deleterious outcomes.
- The service lives for wire ropes vary significantly by the zone of the mooring systems in which they operate.
- Splash zone and thrash zone close to sea bed are critical locations for inspection programs. Steel wire ropes in the thrash zone have a propensity for birdcaging damage, as well as accelerated corrosion due to high flexure of the rope construction, loss of blocking compound, and abrasion of the zinc coating from interaction with entrapped sediments. In the design of new mooring systems, where practical, the use of steel wire ropes in the thrash zone should be avoided.

6.2.4 Mooring Integrity Users Group, FPSO Forum (since 2011)

Since the completion of the FPS Mooring Integrity JIP, there has been a lot of interest in the topic of mooring integrity. A mooring integrity user group was formed in 2011 (see **Table 12**) to facilitate the ongoing work in this subject. The group meets every six months for a 1-day forum, which is open to anyone interested. The main objective of the forum is for industry to share information, and to learn to improve mooring system integrity. The attendees for the previous forums include oil majors, contractors, mooring system designers, manufacturers, mooring system service companies, class societies, etc.

Table 12: Mooring Integrity Users Group	
Open public forum run by:	SOFEC
Start and end dates:	Since 2011
Number and type of participants:	Public Forum
Approximate cost of project:	N/A
Published public documents:	N/A
Published papers:	N/A

A lot of topics have been covered in the forums, with the following topics frequently discussed:

- Lessons learned
- Repairing/replacing experiences
- Inspection and monitoring
- Mooring system management
- Installation experiences
- Life extension

Many experiences have indicated that a safe mooring system operation requires the following:

- Robust mooring system design
- Quality manufacture
- Mooring systems installed as designed
- Safe operation by trained and competent operators
- Inspection, monitoring, maintenance, and repair to maintain the mooring system in the as-designed condition

Experience also indicates that there are many challenges and areas that need to improve, such as the following:

- There is a need for reliable technology for wire rope inspection.
- There is a need for training on how to inspect anchors for life extension
- Permanent magnet wire rope inspection techniques do not work well near terminations where they are needed most.
- There are no commercially available underwater wire rope inspection tools.

- Industry needs to develop a mooring system wire rope inspection guideline.
- Class/Company should require a baseline inspection of the mooring system after installation.
- There is a need for better visual inspection defect recognition guidelines to help reduce the amount of time spend looking at good equipment and to reduce inspector fatigue.
- There is a need for additional guidance on implementing a RBI system
- There should be a requirement to ensure basic operator competence through facility-specific training programs and annual training.
- There is a need for mooring/riser systems designed for easy field replacement.
- Unsheathed wire does corrode, resulting in lost material.
- Socket at touch down area introduces instant tension reductions, bending, and rotation in wire.
- Damaged outer layers in wires significantly reduce MBL (15 – 20 % per layer).
- There is a need for a robust tension monitoring system. Mooring line monitoring revealed most electronic monitoring systems do not work and 5 years is the maximum expected service life.
- Operators need to utilize vessel position monitoring systems.

The discussions have also pointed out that mooring system integrity can be improved through good practices, such as:

- Having a well-developed mooring system management plan
- Being aware if the conditions that are simplified or neglected in the design, such as:
  - Wire rope going slack in storms
  - Bending of chain links
  - Fatigue strength of corroded chain
  - Abnormal chain corrosion (chain corrosion in the splash zone and in-air, corrosion at the touch location and on bottom)
  - Abnormal chain wear (chain shoulder and interlink grip wear at the fairleads)
- Taking proactive actions such as:
  - Using cut-resistant jackets on synthetic ropes (protects against fishing damage and adds installation robustness)
  - Using sheathed steel wire ropes
  - Keeping the wire-chain connection either above seabed or on seabed
  - Avoiding spiral strand wire rope in areas subject to bending
  - After the repair or replacement of a mooring line, inspecting the adjacent mooring lines for damage
  - Having spare parts and repairing plans

6.2.5 MOORING INTEGRITY MANAGEMENT GUIDELINES-DEEPSTAR CTR 11405

Based on the available information, Deepstar and API agreed that API will use Deepstar's *Mooring Integrity Management Guidelines* to develop API RP 2MIM. The MIG by Oil & Gas UK, 2008 was reviewed in Task 2 of this project. It describes an integrity management system from goal setting (expected performance standards) to each measurement for the goal achievement (such as design standards, deployment practices, day to day operation plan, damage operation plan, monitoring, inspection and continuous risk assessment). **Table 13** provides a brief summary of the guidelines. The objectives of the document include (1) promoting the practice of effectively managing the integrity of the mooring system and (2) providing a source of reference for those seeking to continue to improve the safe operation of all elements of their floating facility.

Table 13: Summary of Mooring Integrity Management Guidelines – DeepStar CTR 11405	
JIP run by:	AMOG Consulting
Start and end dates:	2012-2013
Number and type of participants:	Deepstar members
Approximate cost of project:	$580,000
Published public documents:	Report is available to Deepstar members; may be available to API
Published papers:	*OTC-25273 Industry Survey of Past Failures, Pre-emptive Replacements and Reported Degradations for Mooring Systems of Floating Production Units, E. Fontaine et. al., 2014*

Recently, a project for development of guidelines for risk-based mooring integrity management (funded by DeepStar and carried out by AMOG Consulting) produced the *Mooring Integrity Management Guidelines (MIMG)* document. Compared to MIG, MIMG is relatively more comprehensive. The document provides guidance that draws upon existing standards and guidelines for the inspection and integrity management of moorings, risers, marine hulls, and offshore facilities. It also presents a framework for the risk-based integrity management of permanent mooring systems. There has been discussion about releasing the MIMG to API for use in developing an API RP on Mooring Integrity Management. Currently, the MIMG document is still a DeepStar confidential document. The following is a brief overview:

A high level description of the mooring integrity management guideline provided in the document focuses on risk assessment and risk control process. They are described in four phases:

1. Design phase control
    - Technology
    - Design basis
    - Design methods
2. Fabrication phase control
    - Materials
    - Configuration
3. Installation phase control
    - Mishandling

- Accidental
- Out of tolerance

4. Operations phase control
   - Rate based (e.g., periodical inspection)
   - Event based (e.g., after a storm)
   - Procedural

The MIMG also provides two case studies to illustrate how to map a generic MIM process to a typical project life-cycle. One case is for a new mooring system of a GoM Semi-Submersible and the other is for an existing FPSO in North Sea.

6.3 Inspection Methods

6.3.1 Acoustic Emission Testing (AET) for Chain and Wire Rope

Acoustic emissions are the elastic energy waves that are spontaneously released by a material undergoing deformation. The acoustic emission signal reflects the dynamic internal stress redistribution within a material that occurs when an external stress is imposed on a component. As illustrated in Figure 12, an AET, in general, contains a sensor, preamplifier, filter, and amplifier, along with software analysis and storage equipment.

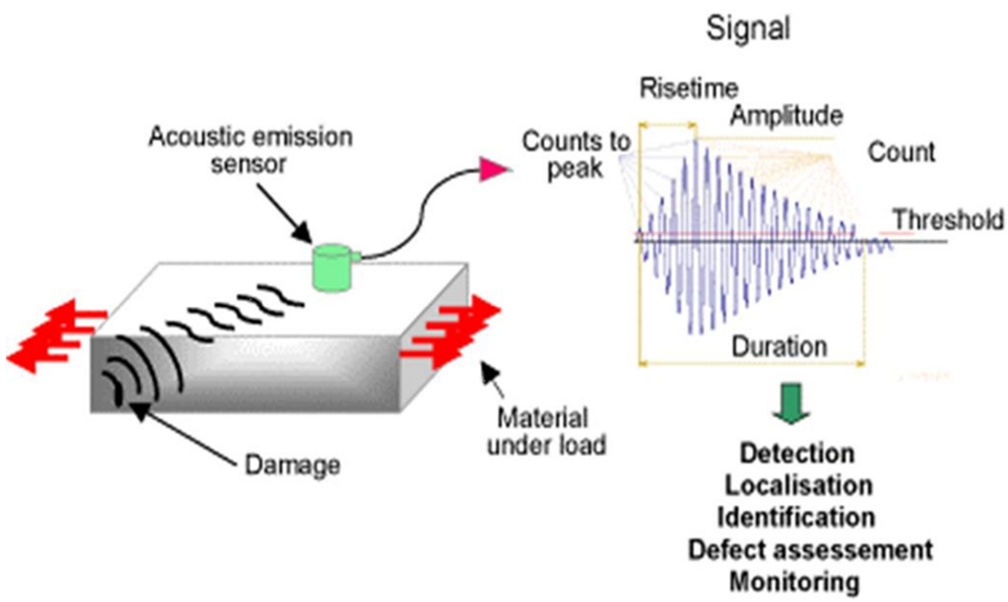

Figure 12 – Acoustic Emission Testing (*courtesy of FPS mooring integrity JIP*)

AET is a mature technology that finds applications in inspecting and monitoring of oil & gas pipelines, pressure vessels, storage tanks, aerospace structures, aircraft, railroads, bridges, gas trailer tubes, bucket trucks, etc. More recently, AET has been applied to marine industry for assessing structural integrity, detecting flaws, or monitoring weld quality.

Acoustic emission waves can be generated from a crack as well as other sources, including friction, cavitation, and impact. AET is affected by surrounding environmental noises, adding extraneous noise to the signals. For a successful application of AE, signal discrimination and noise reduction are crucial. In order to acquire a reliable level of structural flaw detection, an appropriate testing process and an analysis procedure for acoustic emission data are essential for the successful AET application.

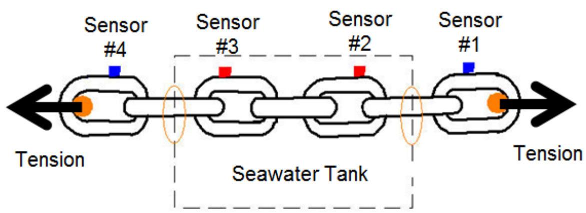

Figure 13 – Positions of the Acoustic Emission Sensors on the Chain Link (*courtesy of FPS mooring integrity JIP*)

A joint development project (JDP) was carried out to perform AET during a laboratory fatigue test of a full size mooring chain. In this test, an R4-grade studless mooring chain (5-inch diameter) was tested with three links submerged in a bath containing simulated seawater (Figure 13). During the fatigue test, the chain was loaded in tension cycles with the stress range of 13% to 38% of yield strength. The tension load was applied using pressure from hydraulic cylinders. The applied stresses as well as the deflection of the chain were continuously monitored.

The chain was instrumented with four R15I Physical Acoustics Corporation (PAC) acoustic emission sensors. This type of sensor has a 150 kHz resonant frequency with an operation range of 80 – 300 kHz. Two sensors (Sensors #2 and #3) were mounted on the chain links submerged inside the simulated seawater tank to detect the acoustic emission activities. The other two sensors (Sensors #1 and #4) were mounted outside the tank to serve as guard sensors to filter out the external noise from the test machine. The four acoustic emission sensors were connected to a MISTRAS Sensor Highway II System. This AET system was operated in a passive mode during the whole loading process to detect crack propagation. The acoustic emission signals were collected and analyzed to categorize the signature of the different stages of crack growth within the chain. If there was any damage caused by crack propagation, the characteristics of the propagating signal were acquired. By comparing the signals after damage has occurred with baseline data, the signature of acoustic emission was categorized and assessed.

Before the fatigue test, a series of Pencil Lead Break (PLB) tests were performed for attenuation measurements in accordance with ASTM E 976. These measurements were used to categorize the attenuation of the acoustic emissions across the contact regions of the chain links. From the attenuation test, the effective distance of acoustic emission is about 8 feet (2.44m) for a chain with a 5-inch (12.7cm) diameter. During the fatigue test, the three stages of crack growth (crack initiation, crack propagation, and fracture) were observed and the acoustic emission data collected from the test were displayed in three different formats: (1) Time history of acoustic emission cumulative energy, (2) Correlation plots of Energy vs. Amplitude vs. Duration, and (3) AE signal wave forms.

Many factors can generate acoustic emission signals during the process of chain fatigue damage (e.g., metal plastic deformation, crack formation, crack propagation, fracture). Each of these damage mechanisms could create different acoustic emission signal properties, even while producing similar wave form shapes. This JDP analyzed the signal properties for identified crack growth stages and characterized the acoustic emission signal properties for each stage, as listed in **Table 14**.

Table 14: Acoustic Emission (AE) Signal Properties During Crack Growth Stages			
AE Parameters	**Crack Initiation**	**Crack Propagation**	**Fracture**
Amplitude (dB)	59	71	85
Energy	36	292	2038
Count	213	654	849
Rise time (µs)	222	400	487
Duration (µs)	2379	5478	10090
Centroid freq. (kHz)	294	228	186

In the crack initiation stage, the acoustic emission signals were generated by the local plastic deformation and microcracks when the surface local stress is concentrated. Low-amplitude, low-energy, low-count, short rise time and high-centroid frequency were observed for the corresponding AE signal properties. In the crack propagation stage, the acoustic emission signals were generated by the new area of plastic deformation damage. Compared to the previous initiation stage, amplitude, energy and count were increased and centroid frequency was decreased for the crack propagation acoustic emission signal properties. When the chain entered the fracture stage (crack growth rapidly), the acoustic emission signal energy burst. Amplitude and count were increased and centroid frequency was decreased for the corresponding acoustic emission signal properties.

Using the acoustic emission signal properties shown below, the proposed warning criteria of acoustic emission parameters could be adopted for the structural health monitoring of mooring chain. The following is the list of criterion:

Acoustic Emissions	
• Amplitude: ≥ 55 dB • Energy: 30 – 3000 nJ • Counts: 200 – 1000	• Rise time: 2 – 500 µsec • Duration: 2 – 20000 µsec • Centroid frequency: 150 – 350 kHz
What will be determined through use:	Local crack growth, material yielding, and possibly corrosion on chain links
Technology:	Well established for components, but relatively new to mooring chain. Effective over a relatively small number of links
Application:	Currently proposed for proof loading monitoring of chain to determine how chain responds to proof load. Defect detection during proof loading will help prevent installation of poor quality product. (Note: chain can be subject to material yielding during a proof load. This can result in surface residual compressive stresses that beneficially affect fatigue life. Determination of yielding during proof loading can be important.) Potential use in monitoring and detecting of crack initiation and growth.
Air or water:	In-air only at present. Possible future use underwater, but would need to ascertain what can realistically be determined, and the value of the information collected. Any future underwater use would have to be baselined so that changes can be determined.
Advantages:	Determines if chain has defects *before* installation – one of the most valuable times to find problems. Gathers information on all parts of the links, not just those easily accessible. Permanent record of findings. Possible baseline for future application

Acoustic Emissions	
Disadvantages:	Applicable only over limited number of links, so would have to have multiple deployments to cover each section of chain during a proof loading, or re-proof load the chain as the equipment is moved. Significant slowing of proof loading process will incur additional manufacturer costs.
Possible future use:	Unlikely to be used for in-service chain monitoring in near future but could conceivably be used to monitor limited sections of chain is modified for underwater use. Also has potential use in monitoring and detecting of corrosion by identifying loss of material through single transmission analysis

Overall, AET is a promising technique for mooring chain and wire rope monitoring. However, to utilize it, several aspects of technology limitations need further investigation and breakthrough. First, it is possible for defects to go undetected altogether if the loading is not high enough to cause an acoustic event. Second, AET can only qualitatively measure risk of failure of a component; however, to obtain quantitative results such as size and depth of a defect (e.g., a crack), other inspection tools such as UT are necessary. Furthermore, for an effective measurement on a large object such as mooring chain and wire rope, a large amount of acoustic sensors are crucial, which makes it a challenge for data collection and signal transformation (e.g., cabling or underwater wireless communication). Last, unlike other inspection tools, AET is very sensitive to the background noise, and thus signal discrimination and noise reduction are essential to ensure an accurate measurement.

6.3.2 Fiber Optic for Synthetic Rope

The fiber optic was initially used exclusively for medical endoscopic applications. During the mid-1960s, optical fibers found new applications in the telecommunications industry for light wave communications. In the last 40 years, fiber optic monitoring became more popular thanks to the rapid technology development of a variety of optical monitoring techniques (including Fabry-Perot interferometers; FBG; and distributed sensors based on Rayleigh, Raman, and Brillouin optical scattering techniques). Its applications were expanded to industrial processing, bio-medical laser delivery system, structure health monitoring, the automotive industry, and marine applications (such as fiber optic hull stress monitoring systems). To apply for structural monitoring in marine, offshore, wind power, and civil infrastructure, FBG-based sensors are more favorable than any other types of fiber optic sensor configurations due to their (1) low cost, (2) ability to measure multitude of parameters such as temperature, pressure, strain, vibration, and (3) capability of being used for multi-points monitoring arrays.

Usage of fiber optic FBG sensors for marine application was not started until the late 1990s. One of the first projects in 1997 was the instrumentation of a 14-mile tie-back from the Troika wells in the GoM. The drilling risers of the vessels Ocean Clipper and Ocean 3 were instrumented with all fiber optic strain gauges to measure vortex-induced vibrations. These 24-inch diameter drilling risers extended to a depth of 7500 feet. This work was done during drilling operations on the Neptune well in the GoM and is the first known study for real-time vortex-induced vibrations measurements.

The fiber optic FBG sensor technology has also been applied to monitor synthetic rope. FBG technology may have the following advantages for mooring line monitoring:

- No electromagnetic interference results in very low signal noise, even in long length of signal loops of several kilometers.
- Glue-on fiber optic sensors have long life and are virtually maintenance free.
- Sensors may be multiplexed on a single optical fiber.

In addition, FBG sensor technology is well suited for measuring strain in synthetic rope where conventional strain gauges are difficult to install and the measurements are unreliable. Because of these advantages, and even though the cost of fiber optic sensors is much higher than that of conventional sensors, the fiber optic hull monitoring systems have attracted a lot of attention from researchers, ship owners and industries in recent years.

Fiber Optics	
What will be determined through use:	Measure strain, vibration, temperature, pressure
Technology:	Well established and has been applied in-air and underwater
Application:	Has been applied to subsea pipelines, production risers, and drilling risers to measure strain and vibration for fatigue life monitoring. Newly designed system, not retrofitting. Potential for retrofitting and for mooring line load monitoring
Air or water:	Has been used both in-air and water
Advantages:	Better quality of signal than conventional strain gauges
Disadvantages:	Relatively expensive; bonding techniques; long-term fatigue issue of fiber optic; sensor calibration; temperature compensation issue
Possible future use:	Mooring line load monitoring

6.3.4 3-D Laser Scanning for Mooring Chain

Photogrammetry is a fairly old technology that can be traced back to the mid-nineteenth century. It is the practice of determining the geometric properties of objects from photographic images. Photogrammetry is a passive monitoring technique. The technology development was mainly focused on the areas of image processing and image capturing techniques, such as imaging sensors and cameras. On the other hand, 3-D laser scanning technology can rapidly capture shapes of objects, buildings, and landscapes through controlled steering of laser beams followed by a distance measurement at every pointing direction.

Both photogrammetry and laser scanners can be applied for marine surveying, topological mapping, and mooring chain monitoring. However, there are some distinct differences between the two technologies. In general, photogrammetry is likely to be a better selection although a large quantity of images may be needed for a more detailed and accurate analysis of the object. However, 3-D laser scanning is well suited for monitoring any corrosion or crack on the chain. Disadvantages to using 3-D laser scanning typically include a longer time and a higher cost.

3-D Laser Scanning	
What will be determined through use:	Geometric properties of objects
Technology:	Well established
Application:	Survey and inspection
Air or water:	In-air and underwater
Advantages:	Produce accurate, detailed 3-D imagery of underwater structures
Disadvantages:	Time consuming and relatively high cost
Possible future use:	Underwater survey and inspection

6.3.5 Ultrasonic Guided Wave Testing (GWT)

Principles of GWT. Guided waves are acoustic, mechanical, or electromagnetic waves with propagation characteristics dictated by the properties and boundaries of the medium in which they travel. Ultrasonic guided waves, used for screening to detect changes in cross section, are elastic mechanical stress waves introduced into the pipe wall and constrained to propagate along the axis of the pipe segment within the pipe wall. The waves are of relatively low frequency (15-85 kHz) and are scattered and/or reflected by changes in the pipe cross section or acoustic impedance. Reflections can originate from corrosion, welds, supports, coating interfaces/ transitions, earth entrances, etc. One main difference between using guided waves for screening versus traditional ultrasonic testing or bulk waves is their ability to size and locate defects. For piping applications, the types of guided waves used for excitation are either longitudinal or torsional. Longitudinal waves are characterized by the compression motion they create along the axis of the pipe. A drawback to longitudinal waves is they are not ideal when inspecting liquid filled pipes because they can propagate into that medium, causing distortion of the data. A torsional wave is most commonly used for pipe inspection and results in the twisting of the pipe, preventing the energy from transferring into the pipe media. Upon impinging on a reflector, each of these excitation methods result in the reflection of symmetric and mode converted flexural waves. Flexural waves are generated from reflectors that are not symmetric about the pipe's circumference, such as an isolated corrosion patch. Therefore, the symmetric and flexural responses can be used to characterize a given reflector.

Each reflector along a pipe segment is characterized by its amplitude, flexural, and frequency responses. A symmetric amplitude response is present for all reflectors and is proportional to positive or negative cross-sectional change (CSC) when compared to the total surface area exposed by a transverse cut of the pipe. A non-symmetric amplitude response is created if the feature is non-symmetric and is used to estimate the feature's length around the circumference of the pipe, also known as circumferential extent (CE). For example, a weld has 100% CE; however, a defect with a given cross-sectional wall loss is more critical for a smaller CE as shown in Figure 14.

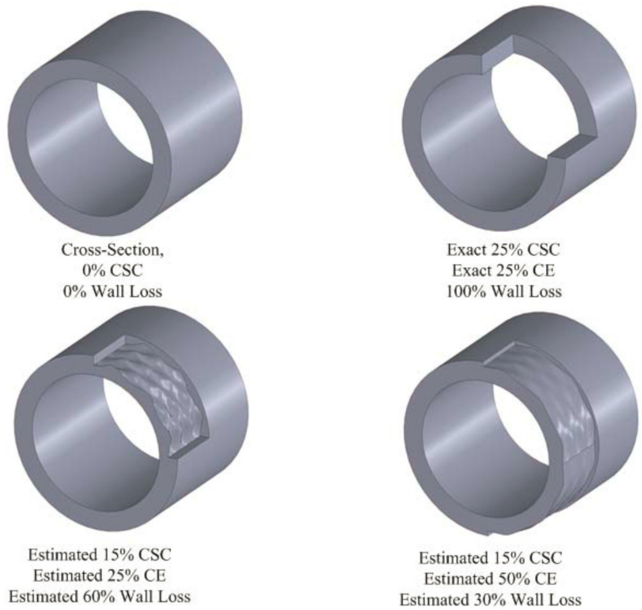

Figure 14 – Wall Loss as a Function of CSC and CE (*courtesy of FPS mooring integrity JIP*)

The attenuation or decay of the signal is logarithmic over the inspection distance down the pipe in either direction from the sensor location. The attenuation can be caused by pipe appurtenances, wrappings, linings, contents, soil loading, and/or general corrosion. Reflections from a series of defects and the associated energy loss are shown in Figure 15. Screening is generally conducted by comparing the known CSC of girth welds to unknown features such as corrosion. Welds are generally assumed as 22.5% CSC (positive) and vary from weld to weld; however, weld measurements can be taken to improve the accuracy of the screening. A flange or threaded coupling represents 100% CSC and therefore little or no energy is transmitted beyond this feature, marking the end of the diagnostic range for all examinations. A unique feature such as a 45-degree bend will, in most cases, distort the wave so that data may become unreliable for interpretation beyond the feature, which generally marks the end of the test.

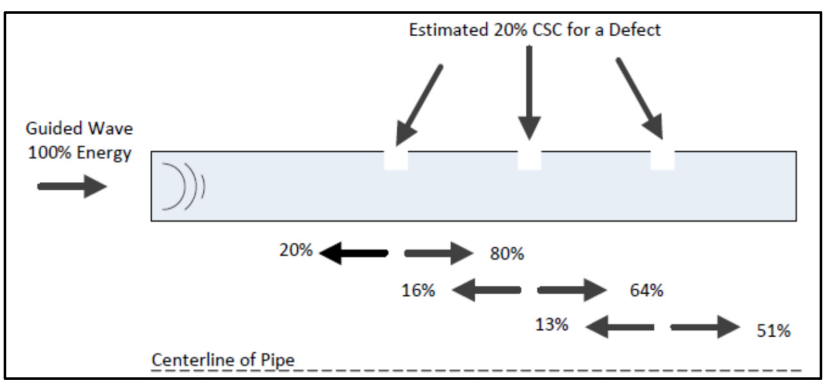

Figure 15 – Reflections from Guided Waves (*courtesy of FPS mooring integrity JIP*)

Competitive Guided Wave Technologies on the market. There are multiple manufacturers of competitive technologies on the market, including Guided Ultrasonics Limited™ (GUL), Plant Integrity Limited™ (Pi), FBS Incorporated™ (FBS), and Southwest Research Institute™ (SwRI). Depending on the manufacturer, either piezoelectric or magnetostrictive sensor technologies are used for generating and receiving the guided waves. Transducers are aligned in a module for either longitudinal waves (aligned with the pipe's central axis) or torsional (aligned with pipe circumference) and held in bracelets often referred to as collars. The collar is typically clamped around the pipe and coupled directly to the pipe, using an inflatable bladder to keep the transducers in contact with the pipe. A different collar or combination of collars is needed for each pipe diameter and the number of modules in each collar increases with pipe diameter.

Applications and challenges of GWT. There have been a broad range of applications, and more are being developed, but most of the actual industry experience in using GWT has been with pipe. Guided wave technology was originally developed for testing for corrosion under insulation but has since been applied in many other applications. One of its great advantages for pipeline inspection is the length of pipe that can be inspected from a distance (e.g., in pipeline road crossing, river crossings, vertical buried riser sections). See, for example, "*Guided Wave Testing – Maximizing Buried Pipe Corrosion Knowledge from each Excavation*" ASME 2012 Pressure vessel and piping conference, PVP2012-78561.

The application of GWT to the inspection of mooring chain is a more recent development, which has not yet achieved commercial application. A JIP was completed in 2013 under the name MoorInspect which looked at Guided Wave Ultrasonics (GWU), applied from a chain climbing robot (see Figure 16).

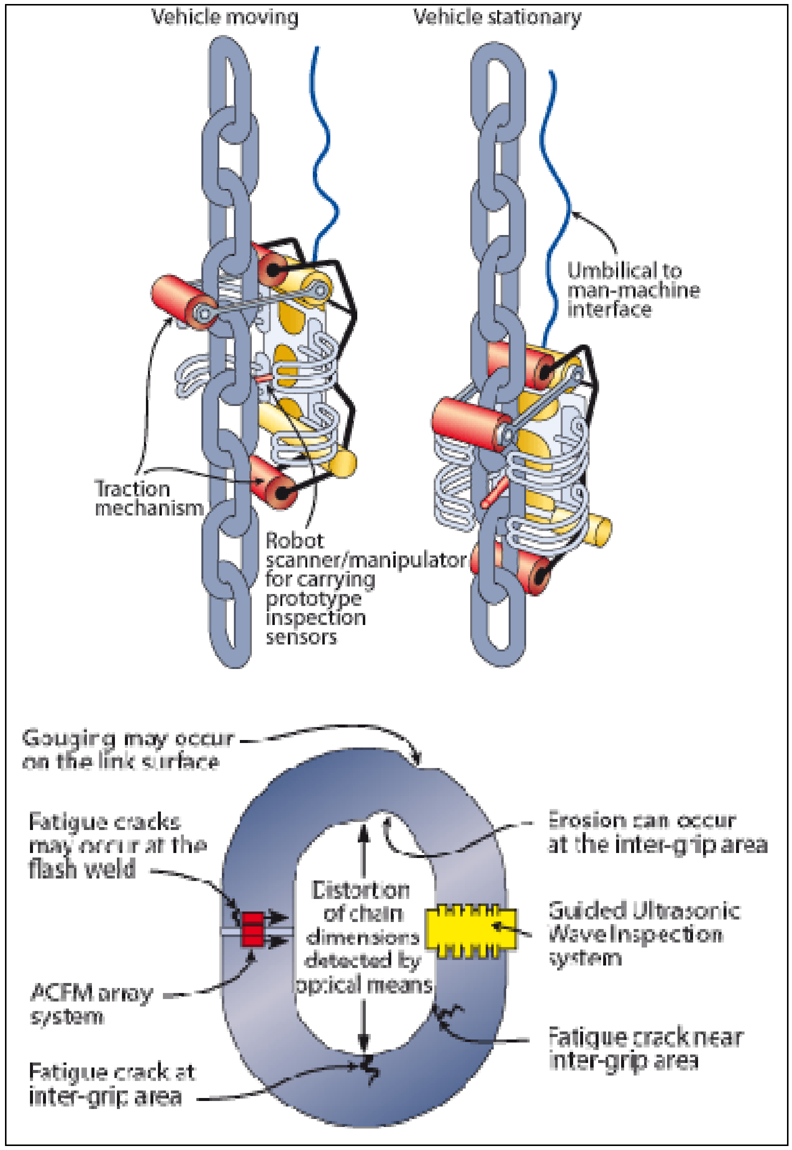

Figure 16 – GWT Chain Crawler (*courtesy of FPS mooring integrity JIP*)

The JIP demonstrated the underwater capabilities of a prototype system on a 4-link 160 mm mooring chain, supplied by Vicinay, in The Welding Institute's diver-training facility in Middlesbrough (NE UK). There are provisional plans for a follow-on JIP to take the prototype through to an operational system, deployed from an ROV. The intent will be to demonstrate the technology in a more realistic environment (e.g., the Underwater Centre at Loch Linnhe, Scotland).

Pipeline inspection GWT uses relatively low frequency waves (20 kHz to 60 kHz) since these have the penetration power to travel the distances needed (e.g., river crossings). The disadvantage of these low frequency waves is that the detectable defect size is relatively large. To inspect a chain link, the test range is shorter (between one and two meters) and the frequency higher, to achieve the needed resolution. The 2013 JIP found that intrados defects of approximately 10mm could be detected, but this is still a relatively large lower limit defect size.

Guided Wave Testing (GWT)	
What will be determined through use:	Locate (fatigue) cracks, corrosion, erosion, or other material loss on chain links
Technology:	Semi established for pipelines, but only experimental demonstration testing on mooring chain.
Application:	Guided wave technology was originally developed to test for corrosion under insulation and underground road crossings of pipelines. A JIP has experimentally demonstrated its application to 160 mm chain in a protected underwater environment. There has been no commercial application of the technology on chain.
Air or Water:	In-air and limited underwater at present. Possible future use for real underwater ROV deployed in-service inspection, but significant additional work required before that will be achieved.
Advantages:	Being an ultrasonic method makes the technology very reliable and accurate. The probability of detecting defects is high.
Disadvantages:	Currently only defects of 10 mm and above can be detected in chain; this is a significant fatigue crack. Every chain link has to be tested individually. Limited number of links can be tested each time and multiple deployment is necessary
Possible future use:	In-service chain monitoring could be achieved in the future, although not likely within next 5 years without significant industry interest and funding.

6.3.6 WIRELESS SENSOR NETWORKS

A sensor network includes a group of transducers with a communications infrastructure intended to monitor and record conditions at diverse locations. The basic function of a sensor network is for autonomous sensors to cooperatively pass data through the network to a main location, which is typically a computer. Most of the state-of-the-art networks are bi-directional, enabling the control of sensor activity. The basic component of a sensor network is a sensor node, consisting of sensor, microcomputer, transceiver, and power source. Depending upon how the transceiver communicates with the central computer, a sensor network can either be hardwired or wireless. Initially motivated by military usage, sensor networks are now widely applied to industrial and commercial areas for monitoring a variety of parameters, including temperature, humidity, pressure, illumination intensity, wind direction & speed, vibration intensity, sound intensity, voltage, pollutant levels, and vital body functions. The monitoring of mooring line can be put into the domain of structure health monitoring

(SHM), which is not a new concept. Generally SHM can be defined as a sensor network using many different types of sensors that are dispersed throughout a structure and take measurements of various parameters related to infrastructure health evaluation. These distributed sensors relay different signals depending upon location and measurements that, once combined, give a more detailed idea of the performance of materials and structural foundation.

In SHM, multiple sensors of strain gauges, accelerometers, and pressure transducers can form a network, and send measurement results to a computer in real-time for analysis of the structure integrity. Although this is only a one-directional sensor network, it can greatly reduce the structure failure of the mooring line. Current SHM systems consist of a sensor network wired to a local power supply with wireless communication to the computer. Wireless sensors work in a way similar to their wired counterparts; however, they have an added element of being linked by radio frequency/acoustic systems that are implemented into the circuitry. Recent development of less expensive hardware has enabled economically affordable implementation of sensor networks. The implementation of a wireless sensor network (WSN) can precisely identify damage that could lead to structural issues at an early stage and with more detail than other types of monitoring techniques. In addition, it generally costs much less for installation and maintenance of a WSN than a wired one. For these reasons, WSNs have attracted growing attention in recent years. They are more scalable and have demonstrated better reliability than wired networks. Additionally, WSNs have lower implementation costs since the installation is less time consuming and requires fewer materials. WSNs also need less maintenance. On the contrary, when wired systems are built, it takes more time to carefully place each sensor and wire in the monitored material without damage, which leads to a longer installation process and a potentially less aesthetically pleasing structure surface. When a WSN is activated, it is important to manage the synchronization between the signals in order to observe accurate monitoring. WSNs can have issues with timing since they are untethered. This is a minor drawback compared to the advantages of the wireless systems.

Wireless Sensor Network	
What will be determined through use:	Monitor and detect abnormal behavior through input of multi-parameters
Technology:	Well developed
Application:	Monitor and detect mooring system behaviors using multi inputs form each mooring legs and the platform
Air or Water:	Could be in-air and underwater
Advantages:	Reliable and less maintenance work in comparison with wired network
Disadvantages:	Signal interference, battery power

6.3.7 SUBSEA COMPUTED TOMOGRAPHY (CT) TECHNOLOGY

Subsea CT is based on the same principle as a medical CT scanner, which reconstructs a target from a series of projections. For subsea CT, the target is mostly steel and it uses gamma rays instead of X-rays. Currently, this system has been used for subsea pipeline measurement. It has been deployed via ROV in 4,150 feet water for a pipeline measurement (see Figure 17). For the subsea pipeline application, the system is able to:

- Measure defects to near mm resolution
- Provide a tomographic wall thickness and build up map of each scanning location (Figure 18)
- Inspect pipe-in-pipe lines to measure the wall thickness of both inner and outer pipes
- Provide accurate results unaffected by multiphase flow
- Inspect non intrusively by ROV deployment

This technology could be extended to mooring line inspection for defect, degradation (e.g., corrosion, pitting), marine growth, etc., where clearing of the mooring lines may be necessary.

Subsea CT Technology	
What will be determined through use:	Measure mooring line geometry details and corrosion detection of mooring lines
Technology:	Well developed
Application:	Applied to subsea pipeline; potential application to mooring lines
Air or Water:	In-air and underwater
Advantages:	Provides detailed line geometry; possibility that marine growth removal may not be necessary
Disadvantages:	Could be high cost
Possible future use:	Mooring line degradation detection

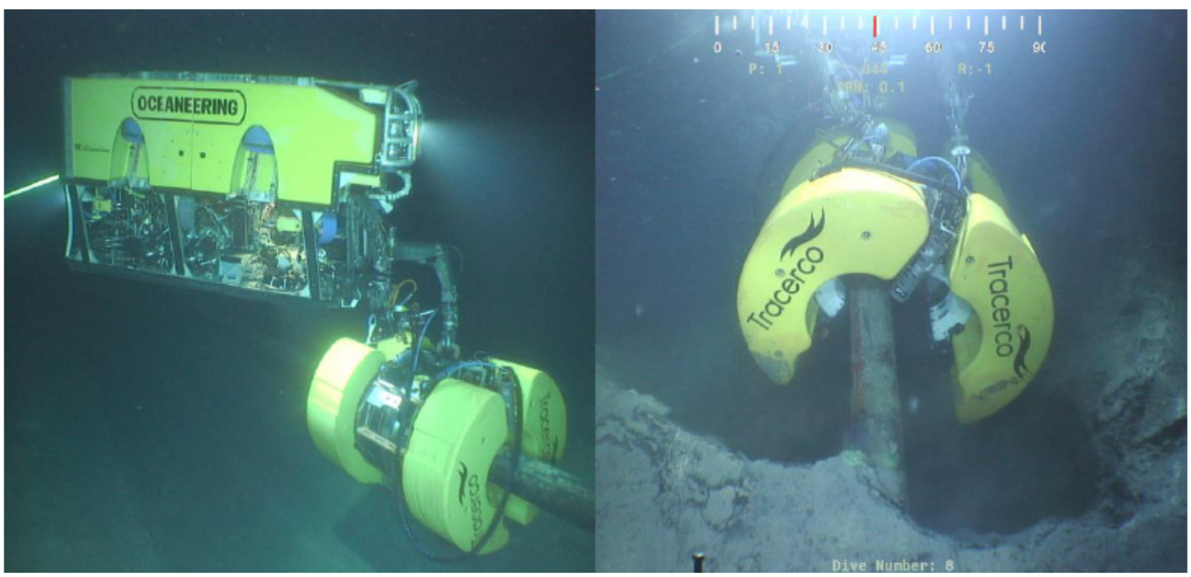

Figure 17 – Subsea CT Deployed via ROV (*courtesy of FPS mooring integrity JIP*)

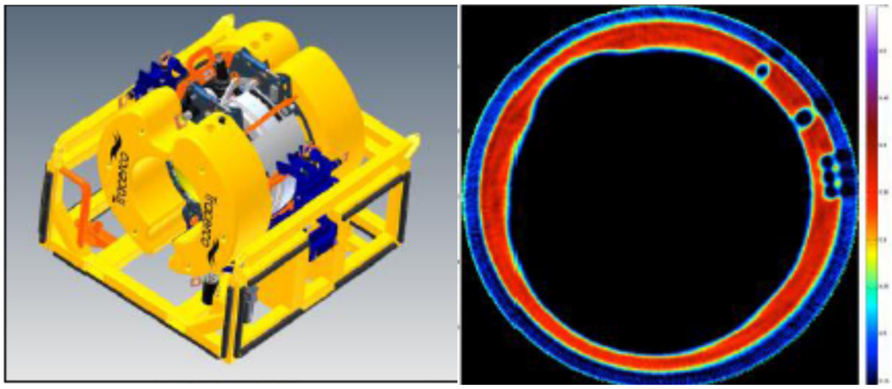

Figure 18 – Subsea CT Pipeline Measurement (*courtesy of FPS mooring integrity JIP*)

6.3.8 X-Ray Micro Tomography for Inspection of Synthetic Fiber Ropes

A 3-D NDT inspection technique, based on the acquisition of multiple X-ray attenuation images using X-ray micro-tomography has been well developed for inspection of pipelines. The technique can be used on samples ranging in size from a few mm to about 1000 mm. The resolution is around 1/2000 of the sample size. It could be used to inspection synthetic rope splices and damaged areas. There has been a promotion toward the extension of the technology for real time inspection of critical rope zones such as the following:

- Splices and terminations (quality control in Manufacturing plant and on site)
- Damaged zones (decision to repair or replace)
- Repairs (checking internal construction)

A rope inspection project was proposed with the following four tasks:

1. Evaluate defect detection requirements
2. Define resolution, geometry and data analysis requirements
3. Propose a detailed specification and costing
4. Prototype development

X-Ray Micro-Tomography for Inspection of Synthetic Fiber Ropes	
What will be determined through use:	Provide 3-D quantitative images of external and internal shape of samples
Technology:	Well developed
Application:	Applied in pipeline inspection. Current technology could possibly inspect rope samples with sizes between a few mm and 1m.
Air or Water:	Both in-air and underwater
Advantages:	Provide 3-D quantitative images of external and internal shape of samples and hence for quality control, and damage detection
Disadvantages:	The application to real project needs further research.
Possible future use:	Rope inspection in-air and underwater

6.4 POTENTIAL MONITORING METHODS

Potential monitoring methods include (1) new methods being developed or tested for the application of mooring line damage (failure, degradation) detection and (2) real time monitoring for verification and checking tension and fatigue life.

6.4.1 DIRECT IN-LINE TENSION MONITORING (INTER-M PULSE)

Inter-M-Pulse is an in-line mooring monitoring device that takes direct measurements of mooring line tension and angle. It was jointly developed by InterMoor and Pulse. It utilizes individual fully-qualified technology and is a self-contained chain link (no exposed connectors/cables). The measured data is transmitted acoustically to the top side control room interface (see Figure 19). Figure 20 shows the key parameters of the device. The key functionalities of the Inter-M-Pulse include the following:

- Detect if mooring line is outside normal tension loads
- Detect and report complete failure immediately
- Provides full history of mooring line tension
- Detect line creep and aid in re-tensioning efforts
- May obsolete fiber rope coupon testing

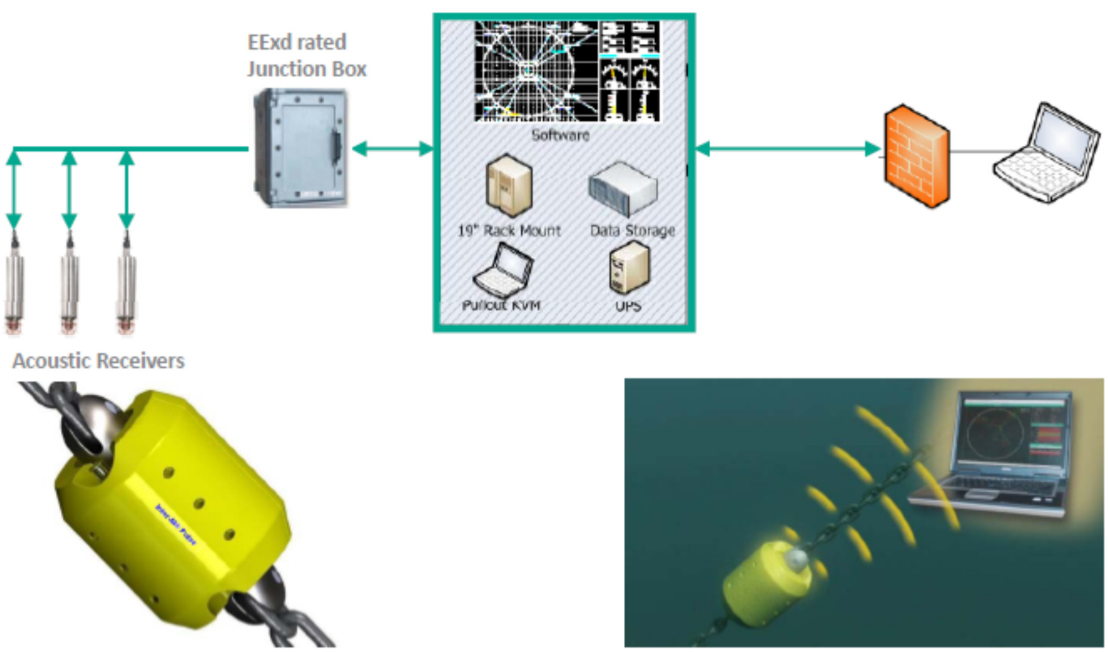

Figure 19 – In-line Mooring Monitoring Device (*Inter-M-Pulse, courtesy of InterMoor*)

Inter-M Pulse			
Parameter	**Value**	**Logging Programme**	**Battery Life**
Measuring range	10 tonnes to Breaking Load	Continuous logging @ 1hz	0.55 years
Accuracy	+/- 5 tonnes	20 mins @ 1hz every 3h	3.7 years
Resolution	2 tonnes	20 mins @ 1hz every 6h	5.7 years
Communication	Once per day / Statistical		

Figure 20 – Inter-M-Pulse Parameters (*courtesy of InterMoor*)

The first sea trail was conducted from December 2011 to June 2012 for BP Ocean Nomad Semisubmersible in North Sea UK Sector. The mooring line is made up of chain of 76mm (800T MBL) and fiber rope. The data was sent back to the topside system via the acoustic data link once per minute for several hours a day. The sea trial proved that the system will communicate in a range of sea states from calm to a maximum wave height of 7.8 m, with a significant wave height of 5.1m. The full scale calibration test was conducted with the results given in Figure 21, which also illustrates the monitoring screen. This product is still in its infancy and at present has not been used on many projects. The product has mostly been used on short-term drilling campaigns where the operator has been checking line tension and winch accuracy.

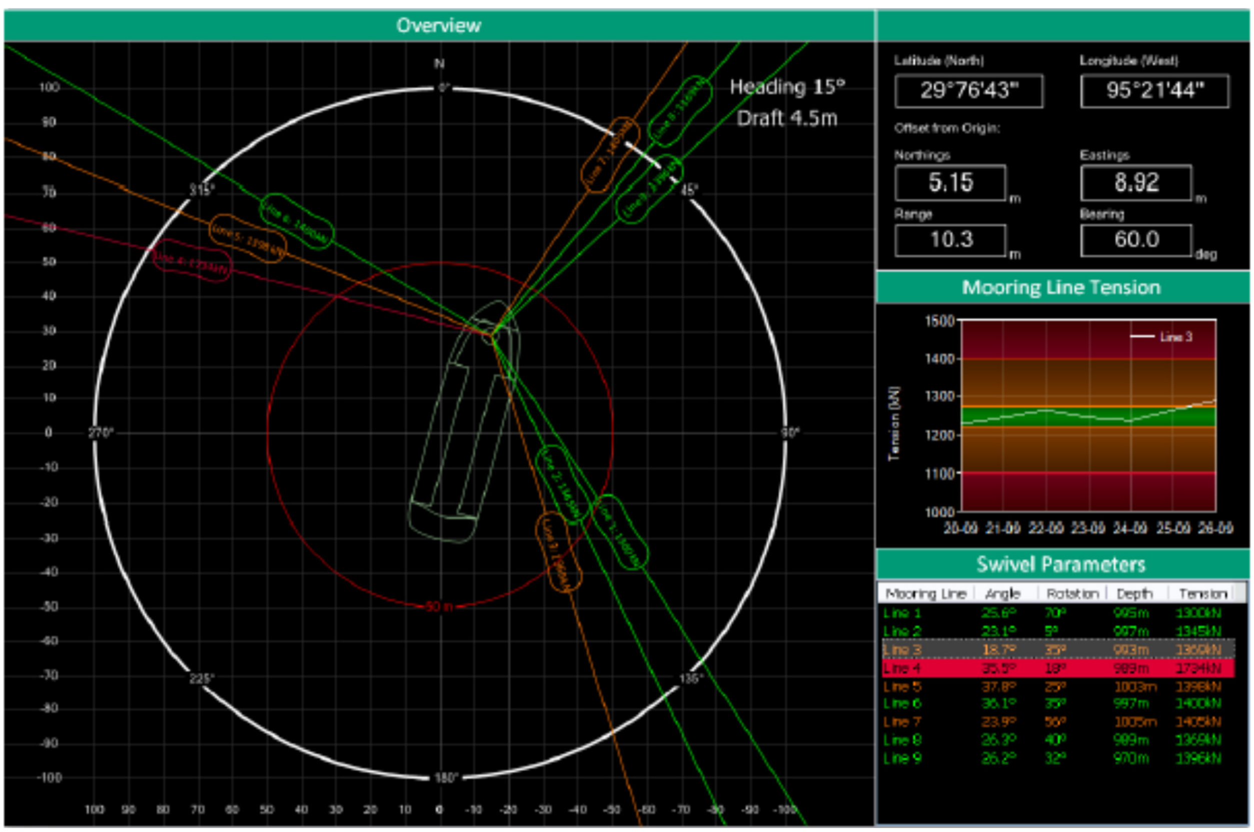

Figure 21 – Inter-M-Pulse Monitoring Screen and Full-scale Calibration Test Results

InterMoor has also been working on the application of the product to deepwater FPSO moorings. One of the challenges is that, for those projects that are a long way off, it is difficult to insert an "in-line" monitoring system into a pre-designed system. The best way is to work with design engineers is at the outset of new systems to ensure that the Inter-M-Pulse can be suitably specified at an appropriate location mid-line.

Inter-M-Pulse	
Maturity:	Under development. In small scale trials. Likely available for full scale commercial use in near future
Intent:	Direct monitoring of mooring line tension and retention of tension history for possible use in retrospective fatigue analysis (e.g., for future “life extension”)
Application:	Can be used on most types of installation
Deployment:	Continuous from original installation to decommissioning
Advantages:	Direct mooring line tension measurement; integral part of mooring system; data stored locally and transmitted to surface continually; real time mooring line loss reporting; gathered data can be used to validate fatigue calculations.
Disadvantages:	Limited experience; only small scale so far; change out of batteries relies on ROV (and hence potential collision); difficult to retrofit – really only for new designs when designed into the mooring line

6.4.2 Sonar-based System for Real Time Feedback on the Status of Mooring Lines

The primary aim of the sonar technology is to measure the relative position of each of the targets and calculate the offset of the measured point to the expected position. This provides the ability to detect the change in catenary profile, which is likely to be associated with a line failure. The sonar technology transmits acoustic energy and the received echoes are processed to obtain the target locations. Two sonar-based systems are illustrated in Figure 22 and Figure 23. The sonar-based monitoring system has been deployed on Teekay Petrojarl Foinaven FPSO with an internal fixed turret. The application of this technology is still at the early stage.

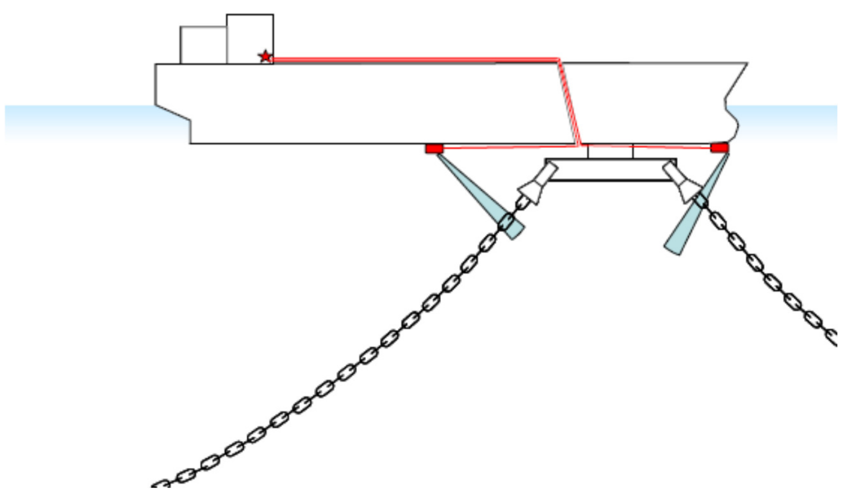

Figure 22 – Sonar-based Monitoring System Attached to Hull (*courtesy of FPS mooring integrity JIP*)

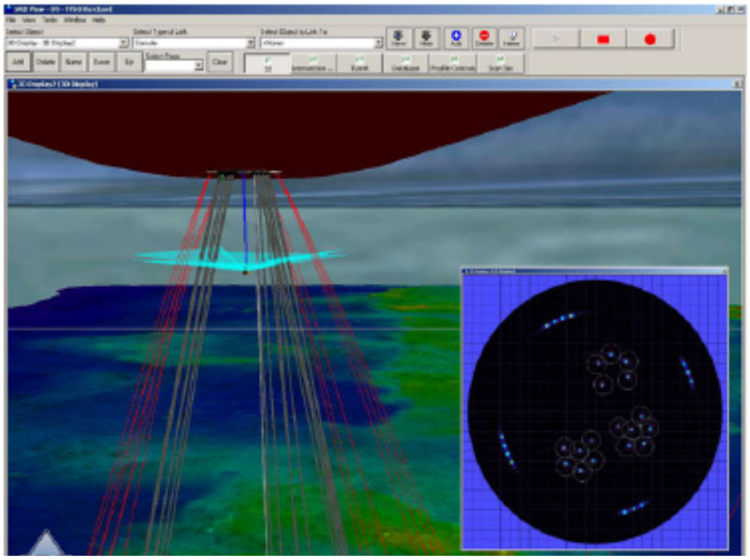

Figure 23 – Sonar-based Monitoring System Under Turret (*courtesy of FPS mooring integrity JIP*)

The sonar-based system should be able to monitor the presence and position of all mooring lines, risers, and umbilicals with up to 360-degree coverage beneath the FPSO, and be able to detect their failure. The systems can be installed on new or existing FPSOs with fixed or disconnectable and internal or external turrets. All measurements are made directly by the sonar head(s) deployed beneath the vessel. The simultaneous real-time feedback on the status of all lines is displayed on a central radar type. It can provide alarms that are user-configurable to detect the absence of expected targets, movement outside the expected position, or behavior different to that of other lines.

Sonar	
Maturity:	Under development
Intent:	Real time information on mooring line failure
Application:	Can be used on most types of installation but best suited to turret moored system. Spread moored semi-submersible would require more complex installation with more sensors
Deployment:	Any time from original installation forward
Advantages:	Real time mooring line loss reporting; recoverable for relatively easy maintenance; completely independent of mooring lines (no contact required); can be retrofitted
Disadvantages:	Limited experience; limited ability to infer mooring line tensions

6.5 Recommendation Discussion for Mooring System Life Extension

6.5.1 Objectives/Purposes for Developing a Mooring Integrity Management (MIM) Plan

The original design lives of many mooring systems are approaching maturity. Over time the mooring systems are subject to ageing mechanisms, leading to deterioration of their condition, with potential impact on fitness-for-service, functionality and safety.

The key issue for ageing mooring system is the increased uncertainty associated with its performance in the later stages, characterized by the life extension phase and the assessment of the associated mooring integrity. One of the objectives of the development of MIM plan is to understand the current condition of the mooring system. In addition, it can provide a link between the assessment process and the inspection strategy for the mooring system.

In general, the dutyholder needs to provide evidence that foreseeable damage such as wear and corrosion to the mooring system, escalation potentials, and all likely scenarios have been considered. Thus, it is of utmost importance that deterioration and degradation are incorporated into a well-formed MIM plan.

6.5.2 Mooring System As-Designed and As-installed

The mooring integrity management of an existing mooring system requires accurate knowledge of both the condition of the mooring system with respect to fatigue and corrosion and the response of the mooring system in the aged condition. These, in turn, require appropriate inspection techniques and numerical analysis methods. It is important to achieve the correct balance between numerical analysis and inspection for the effective mooring integrity management in general.

6.5.3 List of Mooring System Components

Wire rope is usually not allowed to be life extended once its designed life is expired. However, the following main components may be considered for life extension:

- Chain
- Subsea connectors
- Polyester ropes
- Chain jack
- Windlass
- Fairlead
- Chainstopper
- Anchor system

6.5.4 Data Collection

Assessment of the existing mooring system requires consideration of many factors and the collection of data that may affect the mooring performance, including the following:

- Drawings for mooring system and all components, including ropes, chains, connectors and anchoring system (piles or anchors)
- Design basis
- Existing mooring analyses, including for individual components
- Existing ISIP/IMRR and results/findings (also revision history)
- Reviewing survey reports
- Owners/operators reports/ replacement history

- Record of modifications, including updated drawings
- Records of installation (e.g., piles orientation, inclination)
- Metocean history (normal & extreme events), preferably 5 years, from monitoring system or Hindcast Analysis
- Measured load history

6.5.5 Existing Condition Assessment

The baseline condition assessment should address the technical, operational and organizational aspects of the integrity of the mooring system. The assessment should provide a clear description of the system configuration and the boundaries of the assessment. The various threats and associated degradation mechanisms applicable to the mooring system should be identified and their nature should be specified. The degree to which these threats have been prevented and/or mitigated should be summarized. The key components/locations that present elevated risk to the ongoing integrity of the mooring system should be identified and future monitoring/inspection activities specified.

The baseline condition assessment should also address the organizational processes of knowledge transfer and system understanding. This includes the status of as-built documentation, as-installed documentation, inspection strategies and plans, system monitoring and system numerical modeling. The completeness of immediate and short-term incident response planning should be evaluated, along with any equipment sparing/emergency repair equipment availability and condition. The existing condition should be compared to the original baseline survey. The existing condition survey should include the following:

- Inspection for corrosion, dimensional checks, and wear, as accessible
- Inspection wire ropes and synthetic ropes for mechanical damage and sheathing conditions, including anodes on wire sockets (if installed)
- General visual inspection of mooring components and connectors, and top of piles
- Verification of change in length of synthetic fiber rope (if applicable)
- General visual inspection of fairleads and mooring equipment (e.g., windlasses, chain jacks, chainstoppers)
- General visual inspection of turret bearings, boogies, and wears pads. If accessible, ball bearings and races are to be inspected
- Un-inspectable areas to be discussed on a case-by-case basis

The minimum inspected chain diameter, together with the corrosion rate projected based on the past corrosion rate, is to be used in the mooring strength assessment. For mooring fatigue assessment, the past fatigues are to be calculated based on the measured load history/metocean data. If those measured data are not available, the hindcast data can be used.

6.5.6 Risk Assessment

A risk of mooring failure should be assessed, based on the existing mooring system condition, to determine the future inspection internal and monitoring items and intervals as well. The behavior of mooring systems can be quite complex. Accordingly, when assessing the consequence of particular component failures to a mooring system, numerical simulation can be very effective. Where available, inspection reports should be analyzed to:

- Identify the type, magnitude and possible cause of deterioration present in each component and compare against those identified through the risk assessment
- Trend or track deterioration from the as-built condition against the predicted rates of deterioration in the original design
- Investigate any anomalies and defects to determine their impact on continuing operations in terms of the operating environment
- Gather information on unknown or unidentified material properties

In considering the current risk of failure of a mooring system, the confidence in the mooring system design and implementation should be assessed from design approaches, the management of non-conformances during construction and installation, etc.

6.5.7 Recommended Actions: Monitoring Items and Intervals, Inspection Items and Interval, Spare Items

For existing mooring system without any monitoring equipment installed, it is recommended that a monitoring system should be added to the unit to detect any possible failure of mooring line. Also the inspection intervals for the life-extended mooring system should be increased, as compared to the newly designed mooring system. The increased interval should be based on the latest inspection results and its risk assessment. Risk-based procedures can be used to improve inspection planning and the scheduling at the mooring component level. Inspection items should include the following as a minimum:

- Mooring line profile
- Chain diameter measurement in various directions
- Chain/wire rope corrosion/wear condition
- Chain/wire rope/polyester rope twisting condition
- Polyester rope length change due to creep
- Pretension

APPENDIX A – SUMMARY TABLES OF CODES/STANDARDS REVIEWED

Table 15: Subject Matter Table Gap Analysis

Item	USA				International		UK Organizations				Norway	
	API Standards				ISO Standards		UK HSE Documents			Oil & Gas UK		
	API RP 2SK	API RP 2FPS	API RP 2SM	API RP 2I	19901-7	19904-1	SN-3/2005	RP 444	IS 4/2013	MIG	NORSOK N-005	NORSOK N-001
General Description	Mainly stationkeeping guidelines and very limited on mooring inspection/ maintenance requirements and synthetic fiber rope mooring	The in-service inspection and maintenance of floating installation adopts the SIM methodology and applies RBI procedure	Refer to API 2I for inspection, maintenance, and condition assessment	Covers the inspection of mooring lines and mooring jewelry as well as discard criteria	Includes in-service inspection, monitoring and maintenance by introducing SIM	Generally identical to API RP 2FPS	Specifically for chain wear in the trumpet bell mouth for FPSOs	More of an informative document than providing specific recommendations	Guidance in design, installation, inspection, and monitoring of mooring system	Provides the guidance of development of MIM	Present high-level requirements regarding in-service inspection program, which is applicable to all types of offshore structures, including. mooring system	Contains little on Monitoring or Inspection for Moored Units. NMD No. 998 is referenced.
Type of Floating Facility covered												
All permanent	x	x	x	x	x	x			x	X (but leans heavily towards FPSO)	x	x
Shipshaped only							x	x				
MODU	x		x	x	x				x		x	x
Installation Inspection												
Compare installed to design		18.3.2		4.5.2	12.3.2.2 (implied)	18.3.2				3.2 (d) Section 8		
Pre-stretch all polyester			Annex B.2 (not clearly specify)		14 & A.14 (implied, but suggests continues to stretch)					3.2 (c)		
Look for installation damage				4.5.2.1/5.5.1.1	12.3.2.2 (implied)					3.2	4.3 for inclusion in MIM	
Detailed 3-D Location of points on mooring system				Mentioned, but not required								
Detailed measurement of "as-installed" component lengths					A14.2.2.1 (for fiber, but very limited)					3.2 (installed lengths can be significantly different from "contract" or "certified" lengths)		

Table 15: Subject Matter Table Gap Analysis

Item	USA				International		UK Organizations				Norway	
	API Standards				ISO Standards		UK HSE Documents			Oil & Gas UK		
	API RP 2SK	API RP 2FPS	API RP 2SM	API RP 2I	19901-7	19904-1	SN-3/2005	RP 444	IS 4/2013	MIG	NORSOK N-005	NORSOK N-001
Track metocean conditions, draft, etc., during survey				4.5.2.1						General for all surveys		
Seabed sections pulled straight	7.4.3		9.4.4 (generally follow API 2SK)	N	10.4.6							7.11
Component Twist	Mentioned, but no specific criteria		9.3.4	4.5.2.1/5.5.1.1	Mentioned but no specific criteria			6.2.2		Discussed but no specific criteria		
Monitoring									Appendix7 discusses different monitoring methods			
Line Load	8.4 (very limited)	17.2.3			11.3	17.2.3		Chapter 17 discusses methods	Appendices 2, 13 where possible			
Position or Vessel Offset	8.4 (very limited)				11.3				Appendices 2, 13 if tensions not monitored. Continuously	4.2		
Maintenance of records for defined period (normally 30 days)									Appendices 2, 18 (30 days)			
Failed Component Detection	N	17.2.3				17.2.3			Appendices 2, 14	Chapter 7		
Time to detect failed component									Appendices 2, 14 “Earliest practicable opportunity”	4.2 & Chapter 7 (based on risk/ criticality, probably less than 24 hrs.)		
Failure Response Procedures and Response Plan									Appendices 2, 17	Chapter 5 (detailed description)	5.1	
Failed mooring lines/components to be reported									Appendices 2, 21 to 23			
Specific operating limits on line failure									Paragraph 7			

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Table 15: Subject Matter Table Gap Analysis

Item	USA				International		UK Organizations				Norway	
	API Standards				ISO Standards		UK HSE Documents			Oil & Gas UK		
	API RP 2SK	API RP 2FPS	API RP 2SM	API RP 2I	19901-7	19904-1	SN-3/2005	RP 444	IS 4/2013	MIG	NORSOK N-005	NORSOK N-001
Design Verification: Compare vessel Offset (under known metocean) to Calculated	N									4.2 & 4.3		
Behavior	N									Executive Summary		
Compare behavior to design expectations	N								Appendices 2, 19 (confirm behavior at intervals set by dutyholder)		E.3.3.2 (Keep record of mooring system behavior to determine if anything is going wrong.)	
Mooring Integrity Management (MIM) Plans												
MIM Required		18.2 (Structural Integrity Management [SIM])			12.3.1	18.2 SIM			Para 8 "…take into account Oil & Gas UK. 2I & 2SM give guidance on … frequency"	Throughout	4.3 (plan is not explicitly required)	
Detailed description of MIM										Throughout	Some details given in Sections 4 & 5	
MIM based in part on Mooring Integrity Risk Review (or similar)					12.3.2.3				Appendices 2, 10	Chapter 6 and Appendix 6		
Require "Consequence-based" MIM												
Performance Standard and Verification Scheme for Mooring									Para 9	4.2 and extensively in Appendix 4		
MIM should be continually updated based on past experience										Not specifically mentioned, but inherently part of SCE requirements	4.3	
Acceptance/ Rejection Criteria				Throughout					Appendices 2, 12 (to be developed by dutyholder)	Limited guidance	4.4 (acceptance criteria shall be documented)	

Table 15: Subject Matter Table Gap Analysis

Item	USA				International		UK Organizations				Norway	
	API Standards				ISO Standards		UK HSE Documents			Oil & Gas UK		
	API RP 2SK	API RP 2FPS	API RP 2SM	API RP 2I	19901-7	19904-1	SN-3/2005	RP 444	IS 4/2013	MIG	NORSOK N-005	NORSOK N-001
Inspection Schedule				Detailed prescriptive				18.7			5.3	
Inspection Interval		18.3.2 (generally requires scheduled and unscheduled inspection)		4.5.3	12.3.1 (general)	18.3.2 (generally requires scheduled and unscheduled inspection)	Para 8 (bell mouth only; based on findings of initial inspection)					
Annual Inspection required					12.3.2.5							
Detailed Inspection every approximately 5 years				4.5.2.2								
Inspection after severe event		18.3.2.3		4.5.2.3	12.3.2.2	18.3.2					5.4	
Frequency of inspection increases with age				2.6/3.5					Appendices 2, 11			
Identify specific components for monitoring				Not specific 4.5.2.2						Chapter 8. Suggests can be used for monitoring component degradation, but also to help identify mooring system shape if 3-D location measured		
Track finding to compare with previous survey										Executive Summary	5.3 (interval should be based on previous findings)	
Inspection Type								Chapter 18 discusses different inspection methods		Appendix 8 discusses different inspection methods		
Visual	All codes based on visual inspection for underwater components											
Change out mooring leg											Chapter 3, Section 4, L (may rotate out a leg for inspection) in DNV OS E301, which is referenced by Norway codes	

Table 15: Subject Matter Table Gap Analysis												
Item	USA				International		UK Organizations				Norway	
	API Standards				ISO Standards		UK HSE Documents			Oil & Gas UK		
	API RP 2SK	API RP 2FPS	API RP 2SM	API RP 2I	19901-7	19904-1	SN-3/2005	RP 444	IS 4/2013	MIG	NORSOK N-005	NORSOK N-001
Inspection – Components Covered – Mooring Line												
Chain				4.6.2 In Detail (including discard criteria)	A.12							
Steel Wire Rope				4.6.3 In Detail (including discard criteria)	A.12							
Polyester			Throughout	5.0 In Detail (including discard criteria)								
Other synthetic				5.0 In Detail								
Clump weights				N								
Buoys				4.6.4.2	A.12.3.1.6							
Standard manufactured connectors (e.g., Kenter)	No codes/standards allow use of standard connectors for permanent moorings											
Purpose built connectors				4.6.4.1	A.12.3.1.5							
Wire rope terminations				4.6.3	A.12.3.1.5							
Fiber rope splices				5.0								
Inspection – Components Covered – Facility												
Winches				4.5.3.2								
Fairleads				4.5.3.2	A.12.3.1.3							
Anchors				4.6.2.1.5								
Chainstoppers, Trumpet, bell mouth				4.5.3.2	A.12.3.1.3							

Table 15: Subject Matter Table Gap Analysis

Item	USA				International		UK Organizations				Norway	
	API Standards				ISO Standards		UK HSE Documents			Oil & Gas UK		
	API RP 2SK	API RP 2FPS	API RP 2SM	API RP 2I	19901-7	19904-1	SN-3/2005	RP 444	IS 4/2013	MIG	NORSOK N-005	NORSOK N-001
Inspection – Areas of particular interest												
Fairlead, Trumpet Bell Mouth	6.2.2			4.6.2.1.2	12.3.2.2		Para 6		Appendices 2, 9			
Splash zone				4.6.2.1.3	12.3.2.2							
Touchdown point/Thrash zone				4.6.2.1.4	12.3.2.2				Appendices 2, 9			
Below Seabed				Not explicitly								
Trenching				N								
Thruster-assisted Moorings										4.4 Some consideration		
Thruster-Assisted monitoring of mooring line tension, position, etc.	8.4											
Mainly based on Class for survey												
Extent of Thruster Failure from FMEA	5.9.3				8.9.3				Appendices 2, 3			
Failure the same as a mooring line	5.9.2				8.9.2				Appendices 2, 7 (extent to be defined by dutyholder)			
Capability in complete blackout									Appendices 2, 4 (10 year)			
Thrusters considered SCE									Appendices 2, 8			

Table 16: API RP 2SK Design and Analysis of Stationkeeping Systems for Floating Structures (3rd Edition, 2005)			
Section#	**Item#**	**Item Title/Description**	**Comments**
	General	This RP is principally on the design analysis methodology and makes some limited mention of ongoing inspections. The mooring system inspection for MODU presented in Appendix K is in compliance with API RP 2I.	
Section 2	2.3.6	"To inspect a permanent mooring, divers or Remotely Operated Vehicles (ROVs) are often used."	
	2.5.6	"A regular inspection program is essential to monitor the integrity of the moorings."	
Section 6	6.2.2	"The portion of mooring line in direct contact with a fairlead should be regularly inspected."	
Section 7	7.4.3	"After installation, the mooring should be test loaded to ensure adequate holding capacity of the anchoring system, eliminate slack in the grounded portion of the mooring lines, detect damage to the mooring components during installation, and ensure that the mooring line's inverse catenary is sufficiently formed to prevent unacceptable mooring line slacking due to additional inverse catenary cut-in during storm conditions."	
Section 8	8.2.3	"Connecting links such as shackles and detachable links should be fully inspected by non-destructive testing (magnetic particle, die penetrant, eddy current, etc.) according to recognized standards. Cast connecting links should also be examined by x-ray or ultrasonic testing to detect internal casting defects. Inspection, mechanical, proof and break testing of other types of connecting links should meet similar requirements or other recognized standards."	
	8.2.4	"Mid-line buoys subject to high motions should be inspected on a regular basis to ensure the integrity of the buoy connections to the mooring lines."	
	8.4	Moored floating units should be equipped with a calibrated system for measuring mooring line tensions and a system for measuring mooring line payout if the operation requires mooring line adjustment, and line tensions should be continuously displayed at each winch. For units that do not require a tension measurement device, a device for detecting mooring failure should be considered. "Moored floating units should be equipped with a system for monitoring the position of the vessel if the operation requires restraining the vessel offset. For units with automatic thruster-assist system, the measurement of position should be by at least two different means. For units with manual thruster assist system, the measurement of position should be by at least one means." "Floating units with a single point mooring should be equipped with a device for measuring heading. If the headings are to be controlled, at least two different heading measurements are required. If the heading control is automatic, the accuracy and frequency of both measurements should be adequate to meet automatic control requirements."	

Table 16: API RP 2SK Design and Analysis of Stationkeeping Systems for Floating Structures (3rd Edition, 2005)			
Section#	**Item#**	**Item Title/Description**	**Comments**
Appendix E	6.2.2	For drag embedded plate anchors, the following is to be monitored and verified: - Line load in drag installation line; - Catenary shape of installation line based on line tension and line length to verify that uplift at the seabed during embedment is within allowable ranges and to verify anchor position; - Direction of anchor embedment; - Anchor penetration.	

Table 17: API RP 2SM Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring(2nd Edition, 2014)			
Section#	**Item#**	**Item Title/Description**	**Comments**
	General	This RP specifically applies to synthetic fiber ropes used for both permanent and temporary offshore installation.	
Section 4	4.3.3	Evaluation of offsets requires detailed information on the permanent elongation (bedding-in) and load-elongation properties, which need to be representative of the planned mooring operation including installation tension, pretension and mooring line length management. The length of the mooring lines in the field may be required to be adjusted due to permanent elongation which may due to creep or construction stretch or other mechanisms.	
Section 9	9.3.4	The maximum twist in-place shall not exceed the manufacturer's limits based on torque tests.	
	9.4.3	Fiber rope may be pre-deployed prior to hook-up with the moored unit. A dropped rope cannot be used until it is demonstrated that 90% of the design strength is retained as per API RP 2I.	
	9.4.4	Anchor test load requirements for permanent and temporary moorings are in API 2SK. The mooring test load for fiber ropes in mooring systems should also satisfy the need to achieve an acceptable post-installation stiffness value for the fiber ropes.	
Section 10	10.1	A plan for the fiber rope inspection, maintenance, and condition assessment shall be developed as per API RP 2I.	
	10.2	As outlined in API RP 2I, the use of fiber rope test inserts for subsequent rope inspection is not generally recommended for permanent or temporary moorings.	
	10.3	During operations, mooring line tensions or geometry should be monitored regularly, and the mooring lines should be adjusted, if needed, to maintain stationkeeping performance.	
Annex B	B.2	The typical installation tension is given as 40% RBS as an example.	This practice is followed by industry. However, this RP did not explicit specify the installation tension in order to remove the permanent installation due to creep, construction stretch or other mechanism.

Table 18: API RP 2I In-service Inspection of Mooring Hardware for Floating Structures (3rd Edition, 2008)			
Section#	**Item#**	**Item Title/Description**	**Comments**
	General	This RP provides guidelines for in-service inspection of mooring components of MODUs and permanent floating installations with prescriptive approach. The retirement criteria for chain, wire and fiber ropes are given. However, this RP is not explicit on RBI, which ties in with the MIM.	
	1.3.1	Inspection Philosophy: A retirement criteria of limiting the strength reduction to 10% minimum breaking strength (MBS) is applied to this RP.	
Section 1	1.3.2	Discusses the relationship between design check and inspection. Addresses the potential for changing the discard criteria (10% MBS). With the sound design check, a component may be accepted for continued service even though it was found to have already exceeded the discard criteria of 10% MBS.	
	1.3.3	Safety of inspection personnel is discussed.	
	1.4	Component traceability and the service history of all components shall be tracked.	
Section 2	-	Guidelines for in-service inspection of MODU mooring chain and anchor jewelry. Dockside and offshore inspection are discussed for MODU mooring and MPI is recommended. Offshore inspection can measure five-link length and two diameters. Dockside inspection should measure the length of individual links. It is recommended that 100% of chain should be inspected visually and the measurement should be taken once at every 100 feet of chain and both sides of each connecting link. Detailed guidelines for chain reject, repair, removal, replacement are given in Section 2.4. Chain inspection intervals are given as a minimum requirement and may be modified based on the condition and previous inspection history of the chain. Special event inspection is detailed in Annex B.	For MODU mooring system – Chain
Section 3	-	Guidelines for in-service inspection of MODU mooring wire ropes. The types of defect and their relative significance are discussed. In addition to visual inspection, the measurement of the distance of three lay length and rope diameters in three directions at the beginning, middle, and the end of the portion are to be taken as a minimum. In addition, internal inspection should be performed on the oldest rope or the ropes with the most severe external corrosion. Similar to Section2, the rejecting criteria and wire rope inspection interval are given for wire rope in Sections 3.4 and 3.5 respectively.	For MODU mooring system – wire rope (mainly for six-strand wire rope and dry inspection)

Table 18: API RP 2I In-service Inspection of Mooring Hardware for Floating Structures (3rd Edition, 2008)			
Section#	**Item#**	**Item Title/Description**	**Comments**
Section 4	4.5.1	Inspection objectives are given for permanent mooring system; confirm that the wear and corrosion is within the design values as well as monitor the integrity of the connections of individual components. The inspection is mainly visual conducted by divers or ROV under water.	
	4.5.2	Inspection types: - As-built survey conducted from anchors to fairleads to verify the installed as designed, to check & monitor damage during installation, and permanent twist - Periodic survey to check against the original survey - Special event survey based on the purpose of the survey	The as-built survey also serves as the baseline for comparison for all subsequent scheduled inspections over the service life of the installation. Detailed 3-D location of connectors or buoys can provide feedback in mooring system performance.
	4.5.3	Inspection Schedules: - As-built survey should be conducted within 3 months or ASAP after initial hookup of the mooring system. Additional survey is required after subsequent installation. - Periodic survey should be conducted < once every 5 years. Visual inspection should be done annually for the above water parts. - Special survey should be considered after severe storms or other events that warrant inspection.	
	4.6	Detailed component inspection and discard criteria on chain, wire rope, connecters, and buoys are discussed.	
Section 5	5.1	Typical in-service inspection and maintenance of fiber rope mooring for both MODU and permanent moorings	
	5.2	Inspection and Testing Techniques: Visual inspection and destructive inspection and testing are mentioned.	Industry's experience with fiber rope inserts indicates the information gained from the testing of test inserts has been of limited benefit, which is not recommended.
	5.3	Discard criteria for fiber rope is the similar to steel components. Guidelines for damage assessment, rope discard, repair, and replacement are given. Soil ingress, marine growth, and twisting in synthetic rope are discussed in details.	It should be noted that the allowable fiber area reduction depends on rope construction, subrope splicing method, and other factors. Annex C suggests that allowable fiber area reduction could be small.
	5.5	Inspection and maintenance: The inspection objective, type, and schedule established for steel moorings in Section 4.5 are generally applicable to fiber rope moorings. This section addresses only additional issues unique to fiber ropes. - As-built inspection should verify the twist, the fiber rope near surface termination position and installation tension. - Periodic inspection should be done to verify that the system is operating as designed by recording anchor leg re-tensioning caused by non-recoverable elongation and the pretensions of mooring lines, and	

Table 18: API RP 2I In-service Inspection of Mooring Hardware for Floating Structures (3rd Edition, 2008)			
Section#	**Item#**	**Item Title/Description**	**Comments**
		removing foreign particles and marine growth if possible without damaging the rope.	
Annex A		Contains a detailed list of what should be maintained within the component history record: - Manufacturing record (a reference baseline for future component inspections) - Inspection record (trace changes in the mooring component throughout its service life) - Usage record (Identify and track components that subject to extreme loads) - Retirement record	

Table 19: ISO 19901-7 Stationkeeping Systems for Floating Offshore Structures and Mobile Offshore Units (2nd Edition, 2013)			
Section#	**Item#**	**Item Title/Description**	**Comments**
	General	This ISO document generally deals with mooring design analysis. However, it does state issues related to mooring integrity such as "Structural Integrity Management (SIM) System" and that a means of either tension measurement or failure detection should be in place.	
Section 10	10.4.6	After installation, the mooring should be test loaded is required.	Same to API RP 2SK
Section 11	11.3	"Moored floating structures shall be equipped with a calibrated system for measuring mooring line tensions and a system for measuring line payout if the operation requires mooring line adjustment, and line tensions shall be continuously displayed at each winch. For permanent floating structures that do not require a tension measurement device, a means of detecting mooring failure shall be installed. " "For structures with thrusters that are intended for mooring line tension reduction, a means of indicating line tension and/or floating structure offset shall be provided. This means should be suitably redundant to cover the single-line failure condition." "If serviceability requirements impose constraints on the floating structure offset, the structure shall be equipped with a system to monitor its position." "Floating structures with a single point mooring and MODUs shall be equipped with instrumentation to monitor heading. If the heading is to be controlled, at least two different heading references shall be provided. If heading control is automatic, the accuracy and update rate of both devices shall be adequate to meet automatic control requirements. If heading control is critical, three independent heading references shall be provided so that a drifting reference can be rejected without a heading excursion."	Similar to API RP 2SK
Section 12		Mooring integrity is discussed. SIM system philosophies are detailed in this section. Stages in the development and implementation of a SIM system are: - database development and data acquisition - evaluation - planning - implementation - verification	

Table 19: ISO 19901-7 Stationkeeping Systems for Floating Offshore Structures and Mobile Offshore Units (2nd Edition, 2013)			
Section#	**Item#**	**Item Title/Description**	**Comments**
Annex A	A.1.6.4	"The inspection of these mooring systems involves the use of divers or ROVs."	Same to API RP 2SK
	A5.2.2	"A regular inspection program is essential to monitor the integrity of the moorings."	Same to API RP 2SK
	A9.2.4	"The portion of mooring line in direct contact with a fairlead should be regularly inspected."	Same to API RP 2SK
	A12.3	For above-surface mooring line, API RP 2I is referenced. For the submerged mooring lines, ROVs are recommended to be used for inspection. Connecting links can be visually inspected by ROV. Additional inspections by MPI or UT should also be considered.	

Table 20: API RP 2FPS Recommended Practice for Planning, Designing, and Constructing Floating Production Systems (2nd Edition 2011) and ISO 19904-1 Floating Offshore Structures – Part 1: Monohulls, Semi-submersibles and Spars (1st Edition, 2006)			
Section#	**Item#**	**Item Title/Description**	**Comments**
	General	This API RP 2FPS document, which is almost identical to ISO 19904-1, provides requirements and guidance for the structural design and/or assessment of floating offshore platforms. Stationkeeping system is covered generally. The inspection programs are introduced mainly for structural inspection instead of mooring system.	
Section 17	17.2.3	"Monitoring of mooring line tension or line angle should be performed to detect line failure, for example, by instrumentation, ROV inspection or underwater cameras. Local winch and chainstopper control shall be specified, and can involve remote control and monitoring of winch, chainstopper and line parameters."	
Section 18	18.2	This section introduces the SIM of floating structures. The owner shall ensure that suitable arrangements are in place for monitoring and maintaining the integrity of a floating structure throughout its life cycle. Stages in the development of a SIM system include database development and data acquisition, evaluation, planning, and implementation.	
	18.3.2	Two categories of inspections are introduced: - Scheduled inspections: A baseline inspection shall be carried out and recorded before the structure leaves the fabrication yard or before the structure is put into service. Scheduled inspections shall be performed on a regular basis to monitor the condition of the structure and are normally performed during the implementation stage of the SIM system. - Unscheduled inspections: Unscheduled inspections occur as a result of an unexpected event (e.g., an accident), exposure to a near-design-level event (e.g., a hurricane), or a change in ownership or platform location.	
	18.4.3	Some types of inspections are introduced, including GVI, CVI, TM, WI, etc. The minimum inspection requirements for main structure are given in 18.5.2.	
	18.5.3	ISO 19904-1, Table 8, specifies minimum requirements for the type of inspection and the frequency with which they are to be performed for the various structural and non-structural attachments.	

Table 20: API RP 2FPS Recommended Practice for Planning, Designing, and Constructing Floating Production Systems (2nd Edition 2011) and ISO 19904-1 Floating Offshore Structures – Part 1: Monohulls, Semi-submersibles and Spars (1st Edition, 2006)			
Section#	**Item#**	**Item Title/Description**	**Comments**
Annex A	18.4.3	Different types of inspection programs are detailed in this section: GVI should be performed in accordance with ISO 17637. CVI should be performed in accordance with ISO 17637. WI (Weld inspection): For surface breaking defects, these include MPI (magnetic particle inspection), EC (eddy current), ACPD (alternating current potential drop) and ACFM. NDT should be performed in accordance with the general rules specified in ISO 17635. For embedded defects, use is normally made of volumetric NDT techniques such as ultrasonics (see ISO 17640), radiography (see ISO 17636), and x-rays.	
	18.4.7	Some typical monitoring programs that have been implemented for different structural configurations are presented. a) Monohull: - forces in critical mooring hardware and angle of departure of mooring lines; - motion response monitors to support helicopter operations; - ballast level monitors in the control room; - motion monitoring in waves and swell (measurement can be a requirement of helicopter operation support). b) Semi-submersible: - forces in critical mooring hardware and angle of departure of mooring lines; - crack growth and development in a critical structural member or brace; - leak detection in non-flooded members; - weight growth, weight distribution and stability; - ballast-level monitors in the control room; - motion monitoring in waves and swell (measurement can be a requirement of helicopter operation support). c) Spar: - humidity detectors where leak-before-break strategy has been adopted, as appropriate; - tension in mooring lines.	

Table 21: HSE Offshore Information Sheet (IS) No. 4/2013 (HSE IS 4/2014)			
Section#	**Item#**	**Item Title/Description**	**Comments**
	General	This IS applies to offshore installation moorings including design, installation, inspection, and monitoring of mooring system. This IS replaces OTO 2001/50 on stationkeeping and SPEC/ENF/50 on the reporting of mooring failures.	
Action required	Safety cases	New safety cases should comply with ISO 19901-7 Annex B.2	
	Operating limits	Dutyholders should establish appropriate operating limits after a line failure.	
	Inspection and maintenance system	All installations require an inspection and maintenance system by following Oil & Gas Mooring Integrity Guidance. API RP 2I and API RP 2SM are also referenced.	
	Verification scheme	Dutyholders should define suitable performance standards for thrusters and the heading control system where they are required for stationkeeping.	
	TAM	The personnel for the Thruster-Assisted Mooring (TAM) must be adequately trained in the response to loss of moorings, and manual control of thrusters	
Appendix 1 Codes and Standards	ISO 19901-7	Annex B.2 is more stringent than the main text. The particular differences to the main text and to the other mooring design codes in Annex B.2 are listed.	Annex B.2 reflects NMD998. A Canadian section is included in Annex B, which states the same technical requirements for Norway.
Appendix 2 General Mooring Guidance	TAM	The extent of thruster system failure in the accidental limit state case should be determined from a failure mode and effect analysis (FMEA). A complete failure of the thruster system (e.g., through a blackout) should be considered under, as a minimum, a 10-year storm. Dutyholders should define suitable performance standards for thrusters and heading control systems where these components are required for stationkeeping.	ISO 19901-7 and DNV-OS-E301 or LR rules are referenced for FMEA requirement and power management.
	Mooring Inspection	Areas of likely wear should be included in any inspection program. Dutyholders are expected to identify critical areas of their mooring systems and to have mooring inspection regimes in place in line with the Oil & Gas UK Mooring Integrity Guidance and in addition to Classification Society requirements where these are applicable. In addition, dutyholders should establish clear acceptance and rejection criteria for inspection of all mooring components. The frequency of inspection should increase with age of the mooring.	API RP 2I and DNV-RP-E304 are referenced in terms of the frequency of inspection.

Table 21: HSE Offshore Information Sheet (IS) No. 4/2013 (HSE IS 4/2014)			
Section#	**Item#**	**Item Title/Description**	**Comments**
	Mooring tension and position monitoring	The dutyholder should measure and record mooring line tensions. Where this is not practical, suitable arrangements should be in place to verify the integrity of the mooring system and detect a line breakage. These arrangements should be appropriate for the detection and confirmation of a mooring line break at the earliest practicable opportunity.	DNV-OS-E301 is referenced for appropriate arrangements for position and mooring tension monitoring.
	Response to line break detection	Control room operators should have reliable equipment with an alarm that indicates a line breakage. Appropriate response procedures should be documented and included in the emergency response manual.	Oil & Gas UK Mooring Integrity Guidance is referenced.
	Data logging and operational performance	NMD regulation 998 requires mooring tension measurements to be retained for 30 days. Vessel positions, motion responses, and environmental conditions should also be similarly recorded. This data should be used to confirm that the behavior of the vessel and mooring systems in various conditions is as predicted in the mooring analysis.	
	Adverse weather policy	The adverse weather policy should be guided by the tension and excursion limits of the mooring system.	

Table 22: Oil & Gas UK Mooring Integrity Guideline (MIG) (November 2008)			
Section#	**Item#**	**Item Title/Description**	**Comments**
	General	This is not a formal code/standard but is referenced in HSE IS No. 4/2013. This document provides guidance of development of Mooring Integrity Management (MIM) system.	
Section 2		The key parts of a MIM include system description, performance standard, operational procedure, verification scheme, failure philosophy and contingency plan.	
Section 3	3.1	**Design/manufacture** stage impact on MIM is discussed, such as the following: - The level of potential robustness and redundancy should be considered; principles of ALARP are mentioned to determine the risks - Tension-torsion fatigue between fiber rope and six-strand wire rope - Clearance of polyester rope to seabed - Chain wear in some trumpet - Longer return period such as 10,000year condition for robustness check - Poor choice of load cases, environment condition, etc. - Proof load duration for holding the proof load	
	3.2	**Deployment** stage impact on MIM is discussed, such as the following: - Torsional compatibility issue for some components in series - Expert knowledge or awareness of the deck personnel - Installation tolerance - Handing requirements of fiber ropes compared to wire ropes and chain	
Section 4	4.1	Mooring system is an SCE, which requires that the mooring system must be subject to verification scheme. The normal practice is to create a Performance Standard (PS) for the SCE to include operational functionality, and how this level of functionality is assured or verified.	
	4.2	The following subjects should be considered in PS, the detailed example of PS is given in Appendix 4: - Vessel offset(typically assured by DGPS with design verification) - Time to detect mooring failure - Minimum required strength of the mooring system - Fatigue life - Turret Friction - Metocean Condition - Maximum depth of seabed trenching at the touchdown	
Section 5		Issues on how to develop failure response procedures and contingency planning are discussed in details, such as how to identify a failure, what action to take when a failure is suspected or confirmed, and emergency response analysis service.	

Table 22: Oil & Gas UK Mooring Integrity Guideline (MIG) (November 2008)

Section#	Item#	Item Title/Description	Comments
Section 6		This section as well as Appendix 6 provides guidance and examples for carrying out a risk review specifically for a mooring system. General stages of risk assessment process should include: - Level of risk review (quantitative, semi-quantitative or qualitative) - Choice of component level - HAZID - Risk estimation- Consequence and likelihood - Risk rating to determine if the risk is acceptable, intolerable, or between these two extremes - Risk reduction	
Section 7		Mooring Monitoring is discussed. Appendix 7 provides the following potential monitoring methods: - Hull mounted sonar - Seabed sonar - Hull mounted cameras - Pressure sensors - Tension monitoring by turret strain - Tension measurement in line - strain measurement - Alternating current stress measurement (ACSM) - Tension monitoring near touchdown - Seismic detection - Tension monitoring at stopper - Hydro-acoustic - Distance hydro-acoustic - Strain wire	Note that some of the monitoring methods are not suitable to all mooring components (chain, wire rope, fiber rope).
Section 8		Mooring Inspection methods is discussed. Appendix 8 provides the following potential monitoring methods: - GVI - CVI - 3-D imaging - Chain link measurement - Rope measurement - Sound - "Ultrasonics (conventional or phased array ultrasonics; low frequency resonance or guided waves)" - ACFM - Interlink resistance	Note that some of the inspection methods may not be commercial available.

Table 23: NORSOK N-001 Integrity of Offshore Structures (September 2012)			
Section#	**Item#**	**Item Title/Description**	**Comments**
	General	This standard covers all types of offshore structures, including bottom founded and floating. It is mainly about the design and to make sure that the integrity of the facility is ensured through the correct use of load and resistance factors. As such, the document has little to do with monitoring or inspection, but does give some general guidance, particularly on what should be done if defects are found.	
Section 4		General Provisions and Design Principles	
	4.4	Analysis of Existing Facilities: While there is no specific discussion of mooring systems, the requirements of this section would apply if, for example, the design life had been exceeded, some defect is found during inspection, or if the mooring system is otherwise impaired.	
	4.7	Robustness Assessment: General requirement that a single failure does not have unacceptable consequences	
	4.8	Interface Assessment: Requires that there be good communications between the different disciplines. For a moored unit this would require communications between the mooring design and hull-in-way-of-fairlead designer, etc.	
Section 5		Documentation and Verification: Information on requirements for documentation and verification during the various life phases of a facility. General useful guidance, but little that is of specific value for moorings.	
Section 6		Actions and Action Effects: Design only	
Section 7		General Structural Design: Has limited discussion on corrosion and condition monitoring, generally pointing to other NORSOK standards. If fatigue analysis is not performed, chains above 20 years should be inspected annually using MPI or similar test methods, on all available parts. Loose studs should be MPI tested before cold pressing.	
Section 8		Design of Various Types of Structures	

Table 24: NORSOK N-005 Condition Monitoring of Loadbearing Structures (December 1997)			
Section#	**Item#**	**Item Title/Description**	**Comments**
	General	This standard covers all types of offshore structures, including bottom founded and floating. It uses the terminology of IMR for "In-Service Inspection, Maintenance, and Repair." The scope is intended to be broad.	
Section 4		General	
	4.2	Class Certificate can be used as verification of the condition provided the Class Rules meet the basic NORSOK requirements.	
	4.3	The intent of the IMR plan is to ensure that the structure is suitable for its intended purpose. To that end, the IMR should be developed as part of an overall strategy and philosophy that includes monitoring, inspection, repair, data logging etc. Installation damage is explicitly mentioned as an item the consequences of which need to be considered. The condition monitoring program should be continually updated to account for any changes in the facility.	
	4.4	The acceptance criteria need to be documented. The condition monitoring philosophy (see Section 4.3) needs to be supplied to the designer so that it can be incorporated into the design, and to show how the design meets the philosophy. Damage caused during construction needs to be considered in the IMR. The results of inspections and monitoring need to be reported, and any trends accounted for.	
Section 5		Program for Condition Monitoring	
	5.1	Condition Monitoring Philosophy: More detail is given on the requirements within the philosophy, including emphasis on SCE. Monitoring should include the structural response and environment if there is large uncertainty. Emergency preparedness procedures are part of the philosophy.	
	5.2	Requirements to a Program for Condition Monitoring: The condition monitoring program needs to comply with regulations. It should account for damage or defects and should be fitness for purpose. A stability monitoring system is required on floating installations.	

Table 24: NORSOK N-005 Condition Monitoring of Loadbearing Structures (December 1997)			
Section#	**Item#**	**Item Title/Description**	**Comments**
	5.3	Intervals for Condition Monitoring: The interval should be fluid, depending on the results of previous surveys and monitoring. There should be an initial installation survey (but this is aimed at looking for defects, not explicitly to ensure that the installed condition is as designed, as could be the case for a mooring system - although unlikely for a fixed structure). Survey required after extreme event of damage.	
Section 6		Implementation of Condition Monitoring Requires safety of personnel be assured, qualified personnel be used, proper planning of inspections, gives some additional advice on some of the different factors affecting the different environments (in-air, splash zone, under water), keeping records of the inspection, and actually using the results of the inspection to ensure that the structure is safe and changes in the inspection program are not required.	
Annex A		Inspection Methods (Informative) This gives general guidelines, but is of little value for inspection of mooring systems - more aimed at detecting crack or measuring thicknesses.	
Annex B		Safety Procedures for In-Service Inspection (In formative) - Self explanatory	
Annex C		Jacket Structures (Normative)	
Annex D		Column Stabilized Units (Normative) Mainly aimed at the structure of the CSU. Integrity of the mooring system is “…normally secured by a redundant design…” “For mooring systems a separate document describing inspection, maintenance and replacement philosophy shall be established…” which should include methods, frequency, acceptance, etc.	

Table 24: NORSOK N-005 Condition Monitoring of Loadbearing Structures (December 1997)			
Section#	**Item#**	**Item Title/Description**	**Comments**
Annex E		Ship-Shaped Units (Normative)	
	E.3.3.2	Mooring Lines: Inspection and testing is to be planned based on design analyses, including the reliability of the DP system, if applicable. Guidance is very general A record of the mooring system behavior is to be maintained and if anchor drag is suspected /detected, the situation is to be evaluated. Survey results need to be evaluated against acceptance criteria, predictions and accumulated experience. Anomalies to be acted upon and remedial measures taken.	
Annex F		Concrete Structures (Normative)	

APPENDIX B – FAILURES CASES OF MOORING SYSTEMS

	96/97	97/98	98/99	99/00	00/01	01/02	Total
Moorings/DP	0	0	1	2	1	3	7
FPSO/FSU Total Incidents	11	10	15	22	10	11	79
Mooring/DP percentage of FPSO/FSU incidents	0%	0%	6.7%	9.1%	10%	27.3%	8.9%

UK Sector of the North Sea Data

Period 1980 to 2001 (ORION database)								
	Drilling Semis		**Production Semis**		**Accommodation Semis**		**FPSO's**	
	N	**F**	**N**	**F**	**N**	**F**	**N**	**F**
Anchor Failure	170	0.211	8	0.111	23		8	0.113

UK Sector of the North Sea Data

Where N = number of events and F = occurrences per unit year. Anchor failure defined as "Problems with anchor/anchor lines, mooring devices, winching equipment or fairleads (e.g., anchor dragging, breaking of mooring lines, loss of anchor(s), winch failures."

Incident Description	Mobile Drilling Units	Production
Single Failure	9	3
Multiple Failures	3	-

Number of Anchor Incidents in the Period of 1990-2003 in the Norwegian Sector

Figure 24 – Mooring Incidents Statistics (*courtesy of Mooring Integrity JIP*)