BLOWOUT PREVENTER (BOP)
MAINTENANCE AND INSPECTION STUDY FINAL REPORT FOR THE BUREAU OF SAFETY AND ENVIRONMENTAL ENFORCEMENT

2650788-FRRecReg-FR-G	2	Final Report for Issue to BSEE	6/27/13
2650788-FRRecReg-FR-G	1	Issued as Draft to BSEE and for Industry Participant review	4/30/13
Report No.	**Revision**	**Purpose of Revision**	**Date**

June 2013

This work was performed by the American Bureau of Shipping and ABSG Consulting Inc. for the Bureau of Safety and Environmental Enforcement (BSEE) under the terms of BSEE contract number M11PC00027.

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SUMMARY

As part of the Blowout Preventer (BOP) Maintenance and Inspection for Deepwater Operations study (BSEE contract number M11PC00027), the American Bureau of Shipping (ABS) and ABSG Consulting Inc. (ABS Consulting) compiled and analyzed data and information related to BOP system failure events and maintenance, inspection, and test (MIT) activities. This report represents Deliverable G associated with Tasks 6.3.1, 6.3.2 and 6.3.3, as outlined in the contract.

The scope of this study included BOP systems, associated control systems, and components meeting the following criteria:

- Operation Location – Gulf of Mexico (GoM)
- Operating Depth – 5000 feet and deeper
- BOP Configurations:
    - **Class VI BOP**, five ram configuration and single annular or a four ram and dual annular*
    - **Class VII BOP**, five ram configuration and dual annular or a six ram and single annular*
    - **Class VIII BOP**, six ram configuration and dual annular*

      *Ram configurations can consist of a combination of blind/shear ram, non-sealing casing ram, and pipe ram preventers.

This document is the final report culminating from a number of deliverables developed during the study. The final report provides highlights derived from the other documents and seeks to summarize key findings and conclusions. If additional information is sought in any of the areas addressed in this document, the reader will find additional detail and supporting information in those documents. The final report contains the following sections:

Section 1 of this report provides the study objectives, scope, and describes the report organization in more detail.

Section 2 of the report provides an overview of the study phases and activities. In addition, this section summarizes various analyses. Specifically, this study included:

- ***Failure and Maintenance Data Analysis –*** This effort involved the collection and analysis of the failure event and maintenance task data from 23 rigs. Specifically, the data analysis included more than 430 failure events and 88,000 maintenance task activity records. This analysis results included failure and maintenance event trends and estimation of BOP and subsystem mean time to failure (MTTF) values.
- ***Failure Mode, Effect, and Critical Analyses (FMECAs) –*** Three teams including representatives from one of the BOP original equipment manufacturers (OEMs), drilling contractor, and operator performed a FMECA on a selected rig. The FMECAs associated equipment-level failure modes to BOP functions, aligned key MIT activities to the equipment-level failure modes, and assessed the risk of equipment-level failure modes. The

FMECA results help identify the more important equipment-level failures and maintenance activities.

- ***Reliability, Availability, and Maintainability (RAM) Studies*** **–** Two RAM studies were performed with each study being based on a typical configuration for one of the BOP OEM's design. These studies provide an estimate of the key reliability factor of merit, mean availability[1]. These results provide an estimation of the probability of BOP being operational to control a well kick. The results indicate the mean availability (while the BOP is latched on to a well) is between 98.7% and 99.0% depending on the BOP design and the assumed functions required to control the well. These studies also evaluated the impact of selected equipment improvements, as well as changes in test frequency.
- ***MIT Activities and MIT Management System Survey*** **–** This effort included a review and comparison of BOP MIT tasks (1) required by various regulation and industry standards/recommended practices and (2) contained in the MIT plans developed by drilling contractors. In addition, this effort included a survey of management systems and practices related to BOP maintenance activities. As expected, these results indicate API 53 is the key document in defining the minimum MIT tasks for BOP. In addition, the drilling contractor MIT plans and BOP OEM installation, operation, and maintenance (IOM) manuals include tasks addressing API 53 requirements and many other BOP maintenance activities. The management system survey results indicate many good practices are in place relative failure elimination, computerized maintenance management system (CMMS), overall maintenance management systems, preventive maintenance (PM) program, written instructions, and training.

Section 3 of this report provides a roadmap (by report) of key study results. In addition, each of the above-mentioned analyses generated findings, which identify potential improvement areas to be considered. In total, the analyses generated 21 findings and 8 observations. Some the key findings are as follows:

- Based on the failure event data, the top contributors to BOP failures were found to be:
    - Blue & Yellow Subsea Control System
    - MUX Control System
    - Pipe & Test Rams
    - Connectors*
    - Choke & Kill Valves and Lines

  *The "Connector" category contains all subsea connectors, including the wellhead and LMRP connectors, and other connectors such as stabs and wet mate connectors. If the connectors are subdivided, the wellhead, LMRP, and riser connectors account for 3% of the BOP system failures.

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[1] The mean availability is the proportion of time during a mission or time that the system is available for use. (source: http://www.weibull.com/hotwire/issue79/relbasics79.htm)

- Based on the failure event data, the estimated MTTFs are:
    - Overall BOP – 48.1 BOP days
    - Surface Control System – 177.5
    - Subsea Control System – 118.4
    - BOP Stack – 148.6

  (See Observation A in Table 3-3 regarding interpretation of these values)

- Based on the maintenance event data, BOP maintenance does not include the use of predictive maintenance technology to same degree as other industries.

- The FMECA results indicated the following are the highest risk equipment failures:
    - Blind Shear Rams (all three studies)
    - Casing Shear Rams (two of the three studies)
    - Connectors (two of the three studies)
    - Blue & Yellow Pod Hydraulics (two of the three studies)
    - Choke & Kill Lines and Valves (two of the three studies)
    - Pipe Rams (two of the three studies)
    - Hydraulic Supply Lines (two of the three studies)

- The FMECAs found the most frequent MIT activities related to detecting and preventing BOP equipment failures are:
    - Function Test (all three studies)
    - Pressure Test (all three studies)
    - Rebuilding/Replacing of Equipment (two of the three studies)
    - Dimensional/Ultrasonic Testing (two of the three studies)

- The RAM analyses estimated the mean availability while on the well for BOP 1 and BOP 2 for three operating scenarios as:
    - Operating Scenario Case A – Mean availability for failing of all redundancies so that the BOP is unavailable to control a well kick:
        - All BOP well control functions cases are 0.9991 for BOP 1 and 0.9991 for BOP 2
        - LMRP annular and pipe ram cases are 0.9946 for BOP 1 and 0.9943 for BOP 2
        - Annular only cases are 0.9931 for BOP 1 and 0.9928 for BOP 2
    - Operating Scenario Case B Mean availability of all BOP functions assuming pulling of the BOP is not required to perform corrective maintenance on subsea systems/components:
        - All BOP well control functions cases are 0.9902 for BOP 1 and 0.9875 for BOP2
        - LMRP annular and pipe ram cases are 0.9881 for BOP 1 and 0.9875 for BOP 2
        - Annular only cases are 0.9876 for BOP 1 and 0.9873 for BOP 2
    - Operating Scenario Case C – Mean availability of all BOP functions assuming pulling of the BOP is required to perform corrective maintenance on subsea systems/components
        - All BOP well control functions cases are 0.9835 for BOP 1and 0.9843 for BOP 2
        - LMRP annular and pipe ram cases are 0.9882 for BOP 1 and 0.9869 for BOP 2
        - Annular only cases are 0.9873 for BOP 1 and 0.9867 for BOP 2

- The management system survey indicated that PM intervals are primarily established based on OEM recommendations.
- The management system survey indicated that training of BOP maintainers after initial training (i.e., periodic or refresher training) is limited

Section 4 of this report contains recommendations for addressing the analyses findings and observations outlined in Section 3. These recommendations were developed in collaboration with industry participants (IPs). The study generated the following 7 recommendations. (Note: Recommendations have not been vetted with the IPs and therefore are subject to change, including the generation of additional recommendations.)

1. Consider developing an industry document defining guidelines for recording and collecting BOP component failure data. Consider addressing :
    - Component taxonomy
    - Component failure codes
    - Relevant operating parameters (e.g., BOP days, operating cycles) needed
2. Consider developing an industry guideline or recommended practice for performing BOP reliability analyses. Consider addressing the following issues:
    - Definition of BOP failure
    - Reliability factors of merit of interest for all key stakeholders (e.g., drilling contractors, operators, regulators)
    - Reliability modeling approaches to be used for the differing factors of merit
    - Consideration of common cause failures in the quantitative models
3. Consider conducting additional industry studies to investigate the application and expanded use of predictive maintenance techniques to BOP maintenance, including the evaluation of common predictive tools used by other industries for possible application to BOP systems and the identification of any new predictive maintenance technologies needed for BOP maintenance applications.
4. Consider piloting the use of reliability and/or risk-based analytical approaches, such as reliability-centered maintenance (RCM) and risk-based inspection (RBI), for evaluating and determining BOP MIT tasks.
5. Consider conducting a more extensive survey of reliability and maintenance management system practices used for BOP maintenance. The results of such a survey may be useful in identifying effective BOP management best practices.
6. Consider developing a guidance document related to key performance indicators, which could be used to monitor the performance and maintenance of BOPs. Consider including both leading and lagging indicators.

7. Consider conducting additional, more detailed studies to investigate the best means to improve failure management strategies for the higher risk components and harder to detect failure modes identified in the FMECAs.

In conclusion, BSEE's overall objective for this study was to generate and provide information related to the maintenance and inspection of BOPs operating in deepwater in the GoM. To this end, this study generated nine reports containing the following information:

- Estimation of BOP performance in terms of MTTF and mean availability
- Trending of actual BOP equipment failures and failure modes
- Review of planned and actual performed MIT tasks
- Alignment of MIT tasks with potential BOP equipment failures
- Identification of BOP equipment risks
- Comparison of MIT task requirements contained in regulations and industry standards/ recommended practices
- Survey of reliability and maintenance management systems related to BOP maintenance

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LIST OF ACRONYMS

ABS	—	American Bureau of Shipping
ABS Consulting	—	ABSG Consulting Inc.
API	—	American Petroleum Institute
BOP	—	Blowout Preventer
BSEE	—	Bureau of Safety and Environmental Enforcement
CMMS	—	Computerized Maintenance Management System
FMECA	—	Failure Mode, Effect, and Criticality Analysis
HPU	—	Hydraulic Power Unit
IOM	—	Installation, Operation, And Maintenance
IP	—	Industry Participant
LMRP	—	Lower Marine Riser Package
MIT	—	Maintenance, Inspection and Test
MTTF	—	Mean Time To Failure
MUX	—	Multiplex
OEM	—	Original Equipment Manufacturer
PM	—	Preventive Maintenance
RAM	—	Reliability, Availability, and Maintainability
RBD	—	Reliability Block Diagram
RBI	—	Risk-based Inspection
RCM	—	Reliability Centered Maintenance
RPN	—	Risk Priority Number

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1.0 INTRODUCTION

As part of the Blowout Preventer (BOP) Maintenance and Inspection for Deepwater Operations study (BSEE contract number M11PC00027), the American Bureau of Shipping (ABS) and ABSG Consulting Inc. (ABS Consulting) compiled and analyzed data and information related to BOP system failure events and maintenance, inspection, and test (MIT) activities and practices. This report represents Deliverable G associated with Tasks 6.3.1, 6.3.2 and 6.3.3, as outlined in the contract.

1.1 OBJECTIVES

As stated during the study kickoff meeting, BSEE's primary objective for the study was to generate information related to maintenance and inspection practices for deepwater BOPs.

1.2 SCOPE

The scope of this study effort included BOPs and associated control systems meeting the following criteria:

- Operation Location – Gulf of Mexico (GoM), i.e., BOP data related to operations and maintenance in the GoM
- Operating Depth – 5000 feet and deeper
- BOP Configurations:
  - **Class VI BOP**, five ram configuration and single annular or a four ram and dual annular*
  - **Class VII BOP**, five ram configuration and dual annular or a six ram and single annular*
  - **Class VIII BOP**, six ram configuration and dual annular*

  *Ram configurations can consist of a combination of blind/shear ram, non-sealing casing ram, and pipe ram preventers

Specifically, the following outlines a more detailed equipment-level scope covered by this study:

Surface Control System

- Hydraulic Power Unit (HPU)
- Electrical Power
- Multiplex (MUX) Control System
- Rigid Conduit & Hotline
- Surface Accumulators
- Control Panels

Subsea Control System

- Blue & Yellow Control Systems
- Lower Marine Riser Package (LMRP)-mounted Accumulators
- Emergency & Secondary Controls

BOP Stack

- Annulars
- Blind Shear Ram
- Casing Shear Ram
- Pipe & Test Rams*
- Choke & Kill Lines and Valves, Gas Bleed Valves
- Connectors**
- Stack-mounted Accumulators (Autoshear)

*This major component category includes a range of pipe ram types and the test ram.

**This major component category contains all subsea connectors including wellhead, LMRP, and riser connectors, as well as stabs, wet mate connectors, pod connectors, etc.

The functional scope of the study used for the Failure Mode, Effect, and Criticality Analyses (FMECAs) and Reliability, Availability, and Maintainability (RAM) studies included the following BOP functions:

1. Close and seal on the drill pipe and allow circulation on demand
2. Close and seal on open hole and allow volumetric well control operations on demand
3. Strip the drill string using the annular BOP(s)
4. Hang-off the drill pipe on a ram BOP and control the wellbore
5. Controlled operation – Shear the drill pipe and seal the wellbore
6. Emergency operation – Autoshear – Shear the drill pipe and seal the wellbore
7. Emergency operation – Emergency Disconnect System – Shear the drill pipe and seal the wellbore
8. Disconnect the LMRP/BOP
9. Circulate the well after drill pipe disconnect
10. Circulate across the BOP stack to remove trapped gas
11. Connect BOP and LMRP at landing (not included in API RP 53)

1.3 STUDY APPROACH

In executing this project, ABS and ABS Consulting teamed with industry participants (IPs) who included three drilling contractors, two BOP original equipment manufacturers (OEMs), and three operators. These IPs took part in this study by:

- Providing BOP failure data
- Providing maintenance and inspection information
- Participating in analyses as subject matter experts, relative to the design, engineering, operation, and maintenance of BOPs
- Assisting in developing improvement suggestions
- Providing information on management system practices and maintenance best practices
- Providing industry input on necessary and desired system improvement

This study involved the following three phases:

- Phase I: Data Collection, Compilation, and Analysis
- Phase II: Risk and Reliability Analyses and Management Systems and Technology Review
- Phase III: Final Report – Recommendations, Regulation Development

1.3.1 Phase I: Data Collection, Compilation, and Analysis

In order to generate the most relevant analyses and results, current performance and maintenance and inspection practices data and information were collected and compiled for use in the risk and reliability analyses. Specifically, this phase accomplished the following:

- Identified the failure and maintenance and inspection data needed to support the analyses
- Developed an approach for collecting the data
- Compiled the data for convenient use
- Analyzed the data for trends, such as failure trends and maintenance best practices

The details of this effort are provided in the data analysis report.

1.3.2 Phase II: Risk and Reliability Analyses and Management Systems and Technology Review

The study phase included the performance of FMECAs and RAM studies to:

- Assess the risk of BOP subsystem and component failures
- Evaluate current BOP maintenance and inspection practices on BOP reliability

In addition, this phase included a survey of MIT task activities and management systems to:

- Compare current MIT task activities used in the GoM to the task requirements included in regulations, and industry standards and recommended practices
- Identify maintenance and reliability management systems and practices used to maintain BOPs

Specifically, the FMECAs were performed to establish the relationships between specific subsystem/component failures and loss of system functionality. In addition, during the FMECAs the analysis teams (1) risk ranked the failures to help identify the most important failures and (2) aligned the current maintenance practices with specific equipment failures. The FMECA scopes included the physical equipment and functions outlined in Section 1.2 above, and analysis teams performed the FMECAs as follows:

- Overall functional-level FMECA to (1) evaluate the impact of the BOP functions and (2) associate the loss of BOP functions (i.e., BOP functional failures) to specific equipment-level failure modes
- Detailed FMECA of primary BOP equipment items to (1) identify specific causes of equipment failures, (2) link the equipment failure modes to BOP functional failures, (3) assess the risk of equipment-level failure modes, and (4) align proactive maintenance

tasks (which help prevent or detect the failure mode of interest) with specific equipment failure modes

The FMECA results are detailed in three FMECA reports. Result trends for the three FMECAs are provided in the FMECA summary report.

The study developed two RAM models to help quantified the BOP reliability and further assess the impact of the maintenance on BOP risk and reliability. To evaluate BOP performance, RAM models evaluated three operating scenarios: one scenario to estimate BOP performance relative to controlling a well kick if corrective maintenance is not performed to repair a BOP component failure and two scenarios to estimate the BOP performance relative to maintaining all BOP functions for controlling a well kick (i.e., corrective maintenance is performed when a component fails). The two scenarios involving corrective maintenance of BOP failures evaluated the regulatory requirement to perform corrective maintenance whenever a failure is detected for two differing corrective maintenance responses. The first of these scenarios provides results assuming the corrective maintenance of subsea systems/components can be performed without the pulling of the BOP stack. The second of these scenarios provide results assuming the corrective maintenance of subsea systems/components requires the securing of the well and the pulling of the stack.

Specifically, the RAM modeling for each operating scenario included:

- Developing a base case reliability block diagram (RBD) model for a typical configuration based on each BOP OEM's design
- Identifying and developing "What-If" case models to evaluate BOP performance relative to (1) extending test intervals and (2) improving the reliability of selected frequently failing components
- Quantifying the models with component-level reliability data compiled in Phase 1 of this study, to the extent the data were available
- Simulating the BOP performance using the Monte Carlo simulation approach
- Generating mean availability results for each model

The detailed RAM results are provided in the two RAM model reports and then compared in the RAM summary report.

The last part of Phase 2 involved a survey of MIT task activities and MIT management systems. Specifically, this part of the study included a comparative review of MIT task requirements contained in (1) prominent regulations (both US and International regulations) and (2) selected industry standards and recommended practices. This effort also involved a survey of MIT task activities contained in drilling contractors' MIT plans and BOP OEMs' installation, operation, and maintenance (IOM) manuals. These MIT plans were then compared to MIT requirements identified during the review of regulations, industry standards, and recommended practices. Finally, a survey was conducted of maintenance and reliability management systems and practices related to (1) failure elimination, (2) computerized maintenance management system (CMMS) use, (3) overall maintenance management processes, (4) preventive maintenance (PM) program, (5) written instructions, and (6) training.

The results of the MIT task activities and management system are detailed in the MIT Activities and MIT Management System report.

1.3.3 Phase III: Final Report

The final phase of this study involved summarizing the analyses results, identifying key findings and observations based on the analyses results, and generating recommendations to address some of the key issues. Section 3 of this report contains the findings and observations from the analyses. Section 4 provides recommendations related to some key issues identified during this study. (Note: At the time this draft final report is issued, the study team had not completed recommendation review and generation. The final revised version of this report may include additional recommendations.)

1.4 STUDY REPORTS

Table 1-1 lists the reports generated for this study.

Table 1-1: Study Reports

Report Title	Document Number
Blowout Preventer (BOP) Failure Event and Maintenance, Inspection and Test (MIT) Data Analysis for the Bureau of Safety and Environmental Enforcement	2650788-DAS-C1
Blowout Preventer (BOP) Failure Mode Effect Criticality Analysis (FMECA) – 1 for the Bureau of Safety and Environmental Enforcement	2650788-DFMECA-1-D2
Blowout Preventer (BOP) Failure Mode Effect Criticality Analysis (FMECA) – 2 for the Bureau of Safety and Environmental Enforcement	2650788-DFMECA-2-E1
Blowout Preventer (BOP) Failure Mode Effect Criticality Analysis (FMECA) – 3 for the Bureau of Safety and Environmental Enforcement	2650788-DFMECA-3-E2
Summary of Blowout Preventer (BOP) Failure Mode Effect Criticality Analyses (FMECAs) for the Bureau of Safety and Environmental Enforcement	2650788-FMECA-FS-E3
Blowout Preventer (BOP) Reliability, Availability, and Maintainability (RAM) Analysis - 1 for the Bureau of Safety and Environmental Enforcement	2650788-RAM-1-F1
Blowout Preventer (BOP) Reliability, Availability, and Maintainability (RAM) Analysis - 2 for the Bureau of Safety and Environmental Enforcement	2650788-RAM-1-F2
Summary of Blowout Preventer (BOP) Reliability, Availability, and Maintainability Analyses for the Bureau of Safety and Environmental Enforcement	2650788-RAM-SR-F3

Table 1-1: Study Reports

Report Title	Document Number
Survey of Blowout Preventer (BOP) Maintenance, Inspection, and Test (MIT) Activities and MIT Management Systems for the Bureau of Safety and Environmental Enforcement	2650788-MSPRR-F4

1.5 REPORT ORGANIZATION

Section 2 of this report provides an overview of the study analyses (including key results). Section 3 provides a roadmap of key study results and outlines the analyses findings. Section 4 provides recommendations for addressing the analyses findings and study conclusions.

2.0 STUDY ANALYSES OVERVIEW

This section of the report provides an overview of the analyses performed in concert with this study. Specifically, the following summaries of the four major analyses describe the objectives, scope and level of effort, approach, and the results. The four analyses are:

1. Data Analysis
2. FMECAs
3. RAM Studies
4. MIT Activities and MIT Management System Survey

2.1 DATA ANALYSIS

The data analysis effort involved the identification, compilation, characterization, and analysis of BOP failure event and maintenance event data maintained by the drilling contractors and BOP OEMs participating in this study. The data of interest focused on BOP failures and maintenance activities over a 5-year time period for drilling rigs operating in deepwater in the GoM. This effort involved the following activities:

- Identification of the data needed to support this study
- Collection of the needed data
- Compilation of IP-provided data
- Review and characterization of the data
- Analysis of the data for trends and estimation of the BOP MTTF

Vast amounts of data were made available by the study participants. The data analysis effort characterized, and assessed the data for use in the study. The objectives of the data analysis were to (1) provide as much up-to-date and relevant failure event and MIT activity data to support the FMECAs and RAM studies and (2) provide failure event and MIT activity data and trends to identify MIT improvements.

Specifically, both the failure event data and maintenance activity data were sorted and analyzed for trends. The data analysis reviewed the more than 430 failure events and 88,000 maintenance task activity records from 23 rigs. Various analytical techniques were used to identify trends: pie charting, Pareto analysis, and scatter plotting techniques. The final element of the failure event data analysis was the calculation of the MTTF for each of the three BOP systems (Surface Control System, Subsea Control System, and BOP Stack) and the entire BOP system.

One of the key findings from the data analysis indicates that the surface and subsea control system failures account for 61% of the BOP system failures (38% and 23% respectively). The BOP Stack accounts for the remaining 33% of the failures. (Note: Approximately 6% of the failure data were unspecified because the failed components could not be identified or the failure could not be assigned to a single BOP system because failure might have involved more than one system.) Further analysis of the failure events indicates that the following five major components account for 75% of the BOP system failures (excluding unspecified failures):

1. Blue & Yellow Subsea Control System (Subsea Control System) – 36%
2. MUX Control System (Surface Control Systems) – 15%
3. Pipe & Test Rams (BOP Stack) – 10%
4. Connectors* (BOP Stack) – 7%
5. Choke & Kill Valves and Lines (BOP Stack) – 7%

*The “Connector” category contains all subsea connectors, including the wellhead and LMRP connectors, and other connectors such as stabs and wet mate connectors. If the connectors are subdivided, the wellhead, LMRP, and riser connectors account for 3% of the BOP system failures (excluding unspecified failures).

In addition, the results show that seven failure modes account for 76% of the BOP system failures. The failure data analysis results include MTTF estimates for the entire BOP system and the three BOP systems separately (surface control, subsea control and BOP stack). The estimated MTTF for the entire BOP system was calculated to be 48.1 BOP operating days, 177.5 for the Surface Control System, 118.4 for the Subsea Control System, and 148.6 for the BOP Stack, all with units of BOP operating days. (Note: Because of level of BOP redundancy, these MTTF estimates are not reflective of MTTF for failures resulting in a BOP system failure, but rather the numbers are reflective MTTF for failures requiring a repair action.)

The last part of this effort involved analysis of the maintenance task events, which include analysis of the corrective and proactive maintenance tasks performed, and an assessment of the effectiveness of maintenance tasks in detecting and preventing BOP system failures. The results indicate a high level of proactive maintenance being performed on BOP system. Specifically, 4.5% of the BOP system maintenance tasks performed are related to correcting failed or failing components (i.e., corrective maintenance) and more than 95% of the BOP system maintenance tasks performed are related to detecting or preventing failures. (Note: Corrective maintenance is used to indicate maintenance activities related to repairing/replacing BOP components which have failed or near failing. Proactive maintenance is used to indicate planned maintenance activities, predictive maintenance activities, scheduled inspections, and/or scheduled tests intended to detect or prevent BOP component failures before they fail and/or result in BOP system failure.) However, the percentage of predictive maintenance activities being performed is slightly more than 1% of the BOP maintenance. (Note: Predictive maintenance is used to indicate activties involving the application of traditional predictive techniques, such as vibration analysis, fluid analyses, thermograph, which are used to detect the onset of a BOP component failure.)

In addition, the maintenance task analyses indicate a potentially strong correlation between increased percentages of corrective maintenance and number of component failures with increased percentages of planned maintenance. Specifically, the yellow and blue subsea control system data indicated the highest percentage of planned maintenance, the largest number of failures, and the highest percentage of corrective maintenance. Similarly, annulars, connectors, control panels, and pipe rams indicated higher percentages of planned maintenance (equal to or greater than 5%) with a higher number of failures and a higher percentage of corrective maintenance. Similar correlations have been found in other industry maintenance studies. In addition, a significant percentage (more than 25%) of the most frequent failure modes are being detected during operation (versus during proactive maintenance). (Note: The terminology “failures detected during operations,” is used to indicate failures discovered while the BOP is latched on the well and not detected by test, inspection, or other type of proactive maintenance activity. This terminology is not meant to exclusively indicate failures detected during active operation of a BOP system function.)

2.2 FMECAS

Three FMECAs were performed by analysis teams, which included drilling contractor, BOP OEM, and operator representatives. Specifically, all three studies employed a functional-level FMECA followed by an equipment-level FMECA.

The objectives of each FMECA were to (1) establish the relationship between a specific subsystem/ equipment failure and a loss of system functionality, (2) identify the critical failures by using risk-ranking methods, and (3) align the current MIT practices and their associated frequencies with each functional failure and the associated subsystem and equipment failures. The FMECA results are documented in three separate reports and summarized in the FMECA summary report.

The functional-level FMECAs were used to establish the end effects of functional failures and to link these functional failures to specific equipment-level failure modes. The equipment-level FMECAs were conducted to identify the impact of major equipment and component failures on the BOP performance by evaluating equipment-level failure modes, identifying specific equipment-level causes, identifying the safeguards to prevent or detect the failure modes, and ranking the criticality of failure modes. In addition, the equipment-level FMECAs were used to align MIT activities with equipment-level failure modes and specific equipment failures. The individual FMECA reports outline the detail procedures for the FMECAs and include tables detailing the analysis results.

The FMECA summary report includes a comparison of the results from the three FMECAs, relative to the risk-ranking and maintenance task. Specifically, the comparisons of equipment-failure mode risk, frequency of occurrence, and detectability are provided in this report. Comparisons of the maintenance tasks associated with equipment/failure modes and frequency of being applied as a protection are included as a part of the maintenance task results. These results identified the following relative to most important failures, most frequently occurring failures, hardest to detect failures, and most frequently listed MIT task.

The most important equipment failures were:

- Blind shear rams (in all three FMECAs)
- Casing shear rams (in two of the three FMECAs)
- Connectors (in two of the three FMECAs)
- Blue & yellow POD hydraulics (in two of the three FMECAs)

- Choke & kill lines and valves (in two of the three FMECAs)
- Pipe rams (in two of the three FMECAs)
- Hydraulic supply lines (in two of the three FMECAs)
- Subsea Accumulators (in two of the three FMECAs)

The most frequently occurring equipment failures were found to be:

- Control systems (both the electric or hydraulic portions) (in all three FMECAs)
- Pipe rams (in two of the three FMECAs)
- Choke & kill lines and valves (in two of the three FMECAs)
- Blind Shear Rams (in two of three FMECAs)

The hardest to detect failures were related to the following equipment:

- Autoshear system (in all three FMECAs)
- Connector (in two of the three FMECAs)
- Rigid conduit (in two of the three FMECAs)

Finally, a sort and review of the MIT tasks listed as means to detect or prevent equipment failures found the following to be the most frequently listed MIT tasks:

- Function test (in all three FMECAs)
- Pressure test (in all three FMECAs)
- Dimensional/ultrasonic testing (in two of the three FMECAs)
- Rebuilding/replacing equipment (in two of the three FMECAs)

2.3 RELIABILITY, AVAILABILITY, AND MAINTAINABILITY (RAM) STUDIES

The RAM studies used RBDs with Monte Carlo simulation to estimate the mean availabilities for two typical BOP systems. (Availability, as used in these studies, is the probability that the BOP system properly functions on demand.) Specifically, these studies (1) developed RBDs to portray the various combinations of component/subsystems required for successful BOP operation, (2) identified and compiled failure data and MIT data for the BOP system components, and (3) simulated BOP system availability using the Monte Carlo simulation technique for a variety of operational and improvement cases.

The objective of RAM analyses was to determine the impact of MIT activities and other system improvements on the overall BOP system availability, based on two separate BOP OEM designs and configurations.

The analysis teams estimated BOP system availabilities for each of the BOP designs for the three operating scenarios:

- Operating Scenario A – Considers the on-well operation of the BOP until a system failure occurs and prevents the BOP from being capable of controlling a well kick via at least one well control measure (e.g., annular, pipe ram, shear ram) (i.e., all redundancies fail so that the BOP is no longer available to control a well kick). These scenario results represent the BOP system availability relative to controlling a well kick via at least one well control function, which provides a better measure of the safe operation of the BOP system. The estimated mean availability of BOP system during drilling operation (on well) ranged from 0.9937 to 0.9995.

- Operating Scenario B – Considers the on-well operation of the BOP relative to maintaining **all** BOP functions assuming the ability to perform corrective maintenance of surface and subsea components without the securing the well and the pulling of the BOP stack. This scenario models the regulatory requirement to perform corrective maintenance when a BOP failure is detected in order to help ensure all BOP well control functions. Specifically, this scenario models corrective maintenance using the mean-time-to-repair for the failed component without the pulling of the stack. These results represent the upper bound estimate of the BOP system availability for all functions. The estimated mean availability of BOP system during drilling operation (on well) ranged from 0.9871 to 0.9902.

- Operating Scenario C – Considers the on-well operation of the BOP relative to maintaining **all** BOP functions with the requirement that the well must be secured and the BOP stack pulled to the surface in order to perform corrective maintenance on all subsea system components. (Note: This scenario does not require securing of the well and pulling the BOP stack to perform corrective maintenance on surface BOP system components). As with operating scenario B, this scenario models the regulatory requirement to perform corrective maintenance when a BOP failure is detected in order to help ensure all BOP well control functions. Specifically, this scenario models corrective maintenance with the BOP unavailable time being based on (1) the average time to secure the well when a subsea component fails and (2) the mean-time-to-repair for a failed surface component. (Note: Based on input from the industry participants, the average time to secure well was set at 96 hours.) These scenario results provide the BOP availability for all functions operating assuming all subsea component repairs require the securing of the well and the pulling of the subsea systems. These results represent the lower bound estimate of the BOP system availability for all functions. The estimated mean availability of BOP system during drilling operation (on well) ranged from 0.9871 to 0.9902.

For each operating scenario, the mean availability for each operating scenario was estimated for the operation of all BOP well control functions (base case). In addition, the studies estimated system availabilities for alternative operating configurations (i.e., annular and pipe ram operation and annular-only operation) and What-If models involving changes to the testing interval and improvements to selected component reliabilities. Table 2-1 presents the comparison of the availability results for the two BOP designs. These results include the surface controls, the subsea controls and the BOP stack equipment. In addition, the RAM studies assumed that subsea control and BOP stack failures result in (1) the BOP being pulled and (2) the surface failures repaired without having to pull the BOP stack.

Table 2.1: Comparison of BOP Availability Results Summary

BOP Analysis Cases	**Operating Scenario A**		**Operating Scenario B**		**Operating Scenario C**	
	Mean Availability For Drilling Operation Period (On Well) With At Least One Well Control Function Remaining To Control A Well Kick		Mean Availability For Drilling Operation Period (On Well) While Maintaining **All** BOP Well Control Functions Assuming CM Performed Without Pulling Of The Stack		Mean Availability For Drilling Operation Period (On Well) While Maintaining **All** BOP Well Control Functions Assuming Any SubeaCM Performed Requires Securing Of The Well And Pulling Of The Stack	
	BOP 1	**BOP 2**	**BOP 1**	**BOP 2**	**BOP 1**	**BOP 2**
Base Case: All Well Control Functions	.9991	.9991	.9902	.9875	.9835	.9843
Design Change 1 (LMRP Annular (s) & Pipe Rams Only)	.9946	.9943	.9881	.9875	.9882	.9869
Design Change 2 (LMRP Annular (s) Only)	.9937	.9928	.9876	.9873	.9878	.9867
What-If Case 1 (4 week test interval)	.9995	.9991	.9871	.9863	.984	.9822
What If Case 2 (Improved reliability of select components)	.9993	.9994	.9912	.9913	.99	.9882

From a safety perspective, Operating Scenario A - All Well Control Functions results provide the estimated availability for BOP to control a well kick via at least one BOP well control function. The estimated availability for BOP 1 and BOP 2 were same at 0.9991%. The estimated availability of the BOP systems for operating scenario A ranges from 0.9928 to 0.9995 for the various operating configurations and What-if cases.

From a regulatory requirement related to maintaining **all** BOP functions based on two different corrective maintenance responses for detected component failures, operating scenarios B and C provide these results. These results show, as expected, the availability is lower for maintaining all BOP functions. The results indicated a slightly lower availability for BOP 2 (than BOP 1), which results because of (1) the higher failure frequency of selected BOP 2 system components (relative to the BOP 1 system counterparts), (2) the additional subsystems/components associated with the second annular ring in the BOP 2 design, and (3) the associated corrective maintenance time to address these failures.

Table 2-1 contains availability results for the two What-If scenarios: (1) increase in pressure test interval from every two weeks to every four weeks and (2) reliability improvements of selected components. What-If Case 1 analysis indicates the system availability is not significantly changed by the extending of the test interval for all operating scenarios with an average availability reduction of 0.2% for operating scenarios B and C. Specifically, no change in the operating scenario A was the expected result since this scenario is based on allowing the BOP functionality to degrade until the BOP can't sufficiently function to control a kick (i.e., this scenario does not include the performance of 2-week test). As for operating scenarios B and C, the BOP availability for all operating configurations drops for three of the four cases. (Note: The fourth case may indicate no change or drop in availability, but due to model rounding of the results, it is not possible to determine the significance between the results, 0.9835 and 0.984.)

The second What-If scenario postulated reliability improvements (i.e., lower failure rates) for a selected number of higher frequency failing BOP components (e.g., SPM valves, solenoids, choke & kill valves). These What-If analyses show that improving the reliability performance of a few selected components in the BOP 1 and 2 system caused a slight improvement in the estimated BOP availability in all three operating scenarios.

In addition to the availability results, the following observations resulted from the RAM studies.

- While the BOP system is constructed with many subsystems that internally have multiple layers of redundancy, the BOP also has several single component failure points in its design. These single failures are the dominant contributors to the estimated BOP probability of failure on demand. The dominant contributors to the estimated BOP failure on demand probability are provided in Table 2-2.

Table 2-2: Comparison of BOP Single Point of Failure

BOP 1	BOP 2
LMRP Connector Failure	LMRP Connector Failure
Well Head Connector Failure	Well Head Connector Failure

(Note: These dominant contributors were identified based on the total failure rate data for these devices for all failure modes without any differentiation to unsafe and safe failure fraction of the respective failure rate.)

- To demonstrate the contribution of the component failures associated with non-shearing control measures (i.e., pipe rams and annulars), BOP system system availability considering pipe rams and annular(s), and annular(s) only operating were evaluated (i.e., design changes 1 and 2). While these results indicate that the removal of the shear rams and pipe rams (design change 2) had little impact on BOP system availability, this results because the remaining component failures, especially the two single point of failure items, have a more significant impact on the BOP system availability (than the impact of the removed items on the system availability). However, readers are cautioned not to draw the conclusion that these results indicate the redundancy provided by the removed well control items are not important. The shear and pipe rams are considered important part of the BOP system and provide the required redundancy and essential functions for controlling the well

- Improving the reliability of, or gaining a better understanding of unsafe and safe failure fractions for, the single point of failure components and other components, which were the major contributors to the BOP estimated unavailability, should cause a significant improvement in BOP availability. Improvements might be achieved through better construction/quality assurance of these items, better item design, and/or reducing detection/ repair time of the items.

2.4 MIT ACTIVITIES AND MIT MANAGEMENT SYSTEM SURVEY

The MIT activities and MIT management survey involved the review of the MIT activities (i.e., proactive maintenance tasks) that were (1) required by various regulations, industry standards, and recommended practices and (2) included in drilling contractor MIT plans and BOP OEM IOM manuals. In addition, a survey of the reliability and maintenance management systems employed by the drilling contractors and BOP OEMs was conducted.

The objectives of the MIT activities and MIT management system survey were to identify (1) key MIT activities and (2) some of the key maintenance and reliability management system practices affecting BOP reliability performance.

This effort summarized the MIT activities and their associated frequencies (1) contained in applicable, worldwide regulations, industry standards, and recommended practices and (2) included in IP MIT plans for BOPs operating in the GoM. In addition, it provided the results from (1) a survey of reliability and maintenance management system and (2) a comparison of the MIT activities and practices.

This study effort outlined and compared the MIT activities identified in applicable BOP regulations and industry standards and recommended practices. Specifically, this effort included a review of the following regulations and industry standards and recommended practices:

- *Blowout Prevention in California: Equipment Selection and Testing, Tenth Edition*, California Department of Conservation, Division of Oil, Gas, and Geothermal Resources
- *Consolidated Newfoundland and Labrador Regulation 1150/96*, Petroleum Drilling Regulations under the Petroleum and Natural Gas Act, St. John’s, Newfoundland; and Labrador, Canada
- *Drilling Blowout Prevention Requirements and Procedures, Directive 36*, Alberta Energy and Utilities Board

- *Guideline for Certification of Blow-Out Preventers, Edition 2011*, GL Noble Denton
- *Guidelines Regarding the Facilities Regulation*, Petroleum Safety Authority Norway, 20.12.2007
- *Oil and Gas and Sulfur Operations in the Outer Continental Shelf, Code of Federal Regulations (CFR), Part 250, Recommended Practices for Blowout Prevention Equipment Systems for Drilling Wells, Third Edition*, American Petroleum Institute (API) Recommended Practice (RP) 53. Recommended Practices for Blowout Prevention Equipment Systems for Drilling Wells, Fourth Edition, API RP 53
- *Recommended Practice for Well Control Operations, Second Edition*, API RP 59
- *Well Integrity in Drilling and Well Operations, Rev.3*, Norsok Standard D-10
- *Specification for Choke and Kill Systems, First Edition*, API Specification 16C
- *Specification for Drilling Well Control Equipment and Control Systems for Diverter Equipment*, API Specification 16D
- *Specification for Drill-through Equipment, Third Edition*, API Specification 16A
- *Specification for Wellhead and Christmas Tree Equipment, Nineteenth Edition*, ANSI/API Specification 6A

In addition, a survey of the current MIT activities included in drilling contractors' MIT plans and OEMs' IOM manuals was performed. This effort resulted in the compilation of typical MIT activities and associated frequencies employed to maintenance BOPs operating in the GoM. This survey lists more than 300 BOP MIT activities. Appendix B of the MIT Activities and MIT Management System Survey report contains the complete results.

Finally, the effort included a survey of drilling contractor and BOP personnel to identify reliability and maintenance management system and practices in use by the IPs participating in this study. Specifically, the survey respondents consisted of 21 individuals – 16 from drilling contracting companies and 5 from BOP OEM companies.

The survey inquired about MIT management system practices in the following six key areas:

1. Failure Elimination
2. CMMS
3. Maintenance Management Practices
4. PM Program
5. Written Instructions
6. Training

The results indicated many good practices currently in and noted some improvements for each area reviewed. The detailed results are provided in Section 4 of the MIT Activities and MIT Management System Survey report.

The MIT requirements in the various regulations were compared. In general, this review and comparison indicated the MIT requirements contained in API 53 are referenced or incorporated in most all regulations and industry standards related to BOPs. Also, the MIT activities required by regulations, and industry practices/recommended practices were compared the MIT activities currently implemented for BOPs operating in the GoM. Because the above-mentioned review of regulations and other industry standards/recommended practices indicated the inclusion of API 53 requirements, the IPs MIT plans were compared to API 53 MIT requirements. The comparison of the API 53 activities to the drilling contractors' MIT plans indicated that the API-required tasks comprise about 10% of the maintenance activities performed, indicating the IP's MIT plans include significantly more maintenance activities than required by API 53 and regulations.

3.0 STUDY RESULTS

This section summarizes the overall study results. Specifically, Section 3.1 provides a roadmap to help identify key results associated with the eight analysis reports included in this study. Sections 3.2 and 3.3 summarize the findings and observations from the analysis results. The findings represent factual results from one or more of the analyses. The observations represent other items of note identified during analyses.

3.1 KEY RESULTS ROADMAP

Table 3-1 identifies key analysis results and references the reports or reports containing the relevant information. The analysis results are grouped by the following informational areas:

- BOP Equipment Criticality
- BOP Equipment Failure & Performance
- BOP MIT Activities
- BOP MIT Management Systems

Table 3-1: Key Analysis Result Roadmap

Analysis Result	Report	
	Document	**Document Section**
BOP Equipment Criticality		
Equipment Failure Mode Criticality	FMECA Reports 1, 2, and 3[1]	Section 2.2.3 and Appendices B, C and D
Highest Criticality Equipment Failure Modes	FMECA Reports 1, 2, and 3 FMECA Summary Report[2]	Section 2.2.3 and Appendices B, C and D Section 3.2
Most Difficult to Detect Equipment Failure Modes	FMECA Reports 1, 2, and 3 FMECA Summary Report	Section 2.2.3 and Appendices B, C and D Section 3.2
Equipment Failure Mode Occurrence Rankings	FMECA Reports 1, 2, and 3 FMECA Summary Report	Section 2.2.3 and Appendices B, C and D Section 3.2
BOP Equipment Failures and Performance		
Equipment Failure Trends Most common subsystem and component failures Most common failure modes	Data Analysis Report [3]	Sections 3.1.1, 3.1.2, 3.1.3, 3.1.4, and 3.1.5

Table 3-1: Key Analysis Result Roadmap

Analysis Result	Report	
	Document	**Document Section**
Estimated BOP MTTF Overall BOP system BOP subsystems	Data Analysis Report	Section 3.1.6
Estimated BOP Mean Availabilities	RAM Reports 1 and 2[4] RAM Summary Report[5]	Section 2.4.1 Section 5
BOP MIT Activities		
MIT Activities Required by Regulations, and Industry Standards and Recommended Practices	BOP MIT Activities and MIT Management System Report[6]	Section 2.2
Common MIT Activities Included in IP MIT Plans	BOP MIT Activities and MIT Management System Report	Section 3.3 and Appendix B
Maintenance Trends (for completed MIT Tasks) Percentage by Maintenance Task Type Percentage of Corrective Maintenance	Data Analysis Report	Section 3.2
MIT Tasks Associated with Specific Equipment Failure Mode	FMECA Reports 1, 2, and 3	Appendix B
MIT Tasks Most Frequently Aligned with Equipment Failure Modes	FMECA Summary Report	Section 3.3
BOP Management Systems		
Failure Elimination Practices	BOP MIT Activities and MIT Management System Report	Section 4.3
CMMS, Maintenance Management Practice, and PM Programs	BOP MIT Activities and MIT Management System Report	Section 4.3
Training and Written Instructions	BOP MIT Activities and MIT Management System Report	Section 4.3

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[1] Blowout Preventer (BOP) Failure Mode Effect Criticality Analysis (FMECA)-1 for the Bureau of Safety and Environmental Enforcement, 2650788-DFMECA-1-D2; Blowout Preventer (BOP) Failure Mode Effect Criticality Analysis (FMECA)-2 for the Bureau of Safety and Environmental Enforcement, 2650788-DFMECA-2-E1; and Blowout Preventer (BOP) Failure Mode Effect Criticality Analysis (FMECA)-3 for the Bureau of Safety and Environmental Enforcement, 2650788-DFMECA-3-E2

[2] Summary of Blowout Preventer (BOP) Failure Mode Effect Criticality Analyses (FMECAs) for the Bureau of Safety and Environmental Enforcement 2650788-FMECA-FS-E3

[3] Blowout Preventer (BOP) Failure Event and Maintenance, Inspection and Test (MIT) Data Analysis for the Bureau of Safety and Environmental Enforcement, 2650788-DAS-C1

[4] Blowout Preventer (BOP) Reliability, Availability, and Maintainability (RAM) Analysis-1 for the Bureau of Safety and Environmental Enforcement, 2650788-RAM-1-F1; and Blowout Preventer (BOP) Reliability, Availability, and Maintainability (RAM) Analysis-2 for the Bureau of Safety and Environmental Enforcement, 2650788-RAM-1-F2

[5] Summary of Blowout Preventer (BOP) Reliability, Availability, and Maintainability Analyses for the Bureau of Safety and Environmental Enforcement 2650788-RAM-SR-F3

[6] Survey of Blowout Preventer (BOP) Maintenance, Inspection, and Test (MIT) Activities and MIT Management Systems for the Bureau of Safety and Environmental Enforcement, 2650788-MSPRR-F4

3.2 ANALYSES FINDINGS

This section summarizes the findings from the study analyses. These findings represent factual analytical results from the analyses. Table 3-2 contains a tracking number, finding, analysis reference, and basis for the finding.

Table 3-2: Analyses Findings

No.	Finding	Analysis Document	Finding Basis
1	Based on the failure event data, the top contributors to BOP failures were found to be: • Blue & Yellow Subsea Control System • MUX Control System • Pipe & Test Rams • Connectors* • Choke & Kill Valves and Lines *The ”Connector” category contains all subsea connectors including the wellhead and LMRP connectors, as well as other connectors such as stabs and wet mate connectors. If the connectors are subdivided, the wellhead, LMRP, and riser connectors account for 3% of the BOP system failures.	Data Analysis Report	Pareto analysis of the failure events indicated these five primary BOP systems accounted for 75% of the BOP failures

Table 3-2: Analyses Findings

No.	Finding	Analysis Document	Finding Basis
2	Based on the failure event data, the estimated MTTFs are: • Overall BOP – 48.1 BOP days • Surface Control System – 177.5 • Subsea Control System – 118.4 • BOP Stack – 148.6 (See Observation A in Table 3-3 regarding interpretation of these values)	Data Analysis Report	These values are calculated on the failure data and BOP operating day information provided. The values were calculated using a simple estimation approach (vs. statistical analyses).
3	Based on the maintenance event data, corrective maintenance activities comprise about 4.5% of all the BOP maintenance tasks.	Data Analysis Report	A Pareto analysis of the corrective maintenance tanks and proactive maintenance tasks indicated corrective maintenance makes up 4.5% of the tasks and proactive maintenance make ups 95.5% of the tasks
4	Based on the maintenance event data, BOP maintenance does not include the use of predictive maintenance technology to same degree as other industries.	Data Analysis Report	MIT task classification revealed predictive maintenance activities comprise less than 1% of all proactive maintenance tasks

Table 3-2: Analyses Findings

No.	Finding	Analysis Document	Finding Basis
5	The FMECA results indicated the following are the highest risk equipment failures: • Blind shear rams (all three studies) • Casing shear rams (two of the three studies) • Connectors (two of the three studies) • Blue & yellow pod hydraulics (two of the three studies) • Choke & kill lines and valves (two of the three studies) • Pipe rams (two of the three studies) • Hydraulic supply lines (two of the three studies)	FMECA Summary Report	The risk priority number (RPN) rankings for all three (or two of the three) of the FMECAs confirmed these as the highest risk items.
6	The FMECA results indicated the following are the equipment highest occurrence rankings: • Control systems (all three studies) • Pipe rams (two of the three studies) • Choke & kill lines and valves (two of the three studies)	FMECA Summary Report	The RPN rankings for all three (or two of the three) of the FMECAs confirmed these as the highest occurrence frequency items.
7	The FMECA results indicated, the following lists the equipment with highest detectability ranking : • Autoshear system (all three studies) • Connectors (two of the three studies) • Rigid conduit (two of the three studies)	FMECA Summary Report	The RPN rankings for all three (or two of the three) of the FMECAs confirmed these as the highest detectability items.

Table 3-2: Analyses Findings

No.	Finding	Analysis Document	Finding Basis
8	The FMECAs found the most frequent MIT activities related to detecting and preventing BOP equipment failures are: • Function test (all three studies) • Pressure test (all three studies) • Rebuilding/replacing of equipment (two of the three studies) • Dimensional/ultrasonic testing (two of the three studies)	FMECA Summary Report	The three (or two of the three of the FMECAs) included these MIT activities as the frequent MIT activities associated with BOP equipment failures
9	The RAM analyses estimated the mean availability while on the well for providing at least one BOP function to control a well kick (i.e., Operating Case A - BOP operated without performing corrective maintenance while on the well) for BOP 1 and BOP 2 as: • All BOP functions cases are 0.9991 for BOP 1 and 0.9991 for BOP 2 • LMRP annular and pipe ram cases are 0.9946 for BOP 1 and 0.9943 for BOP 2 • Annular only cases are 0.9937 for BOP 1 and 0.9928 for BOP 2	RAM Reports 1 and 2	The Monte Carlo simulation results for the three operating configurations for the two BOP designs using available project failure data .

Table 3-2: Analyses Findings

No.	Finding	Analysis Document	Finding Basis
10	The RAM analyses estimated the mean availability while on the well for maintaining all BOP functions for differing corrective maintenance responses forBOP 1 and BOP 2 as: Operating Case B (Corrective maintenance without the pulling of the stack) • All BOP functions cases are 0.9902 for BOP 1 and 0.9875 for BOP 2 • LMRP annular and pipe ram cases are 0.9881 for BOP 1 and 0.9875 for BOP 2 • Annular only cases are 0.9876 for BOP 1 and 0.9873 for BOP 2 Operating Case C (Corrective maintenance requires securing of the well and pulling of the stack) • All BOP functions cases are 0.9835 for BOP 1 and 0.9843 for BOP 2 • LMRP annular and pipe ram cases are 0.9882 for BOP 1 and 0.9869 for BOP 2 Annular only cases are 0.9878 for BOP 1 and 0.9867 for BOP 2	RAM Reports 1 and 2	The Monte Carlo simulation results for the three operating configurations for the two BOP designs using available project failure data

Table 3-2: Analyses Findings

No.	Finding	Analysis Document	Finding Basis
11	The RAM models for operating scenario A indicate that extending the test interval from 2 to 4 weeks does not change the mean availability.	RAM Reports 1 and 2	The Monte Carlo simulation results for operating scenario A What-if case 1 for the two BOP designs using available project failure data
12	The RAM models indicate that extending the test interval from 2 to 4 weeks reduces the mean availability (for all functions while on the well) for both Operating Cases B and C: For Operating Case B • BOP 1 mean availability reduced from 0.9902 to 0.9871 • BOP 2 mean availability reduced from 0.9875 to 0.9863 For Operating Case C: • BOP 1 did not significantly change the mean availability • BOP 2 the mean availability reduced from 0.9843 to 0.9822	RAM Reports 1 and 2	The Monte Carlo simulation results for operating scenarios B and C What-if Case 1 for the two BOP designs using available project failure data
13	Both RAM model availability results are dominated the following single point of failures (1) wellhead connector and (2) LMRP connector	RAM Reports 1 and 2	Based on contribution to system unavailability, the identified items are the dominant contributors
14	BOP MIT plans include significantly more tasks than required by API 53.	MIT Activities and MIT Management System Report	The comparison of the API 53-required tasks to the planned MIT tasks indicated that API 53-required tasks comprise less than 20% of the total number of task items and about 10% of total number of performed tasks.

Table 3-2: Analyses Findings

No.	Finding	Analysis Document	Finding Basis
15	The management system survey indicated identified that BOP failures are being documented	MIT Activities and MIT Management System Report	More than ninety percent of the survey respondents indicated BOP failures are documented. The most common documentation approach is work orders.
16	The management system survey indicated that CMMS (or other similar computer systems) are being used for the management of BOP maintenance	MIT Activities and MIT Management System Report	Seventy five percent of the survey respondents indicated CMMS systems were being used to manage BOP maintenance
17	The management system survey indicated that BOP maintenance activities are frequently or always managed via work orders	MIT Activities and MIT Management System Report	Seventy percent of the survey respondents indicated BOP maintenance is always (>95%) or frequently (75% to 95%) managed via work orders
18	The management system survey indicated that PM intervals are primarily established based on OEM recommendations.	MIT Activities and MIT Management System Report	Eighty percent of the survey respondents indicated OEM recommendations played a part in establishing PM intervals
19	The management system survey indicated that PM intervals are mostly calendar based (versus equipment condition or operational time).	MIT Activities and MIT Management System Report	Seventy percent of the survey respondents indicated a calendar-based approach is used for setting PM intervals.
20	The management system survey indicated that surface and subsea parts are replaced on scheduled intervals.	MIT Activities and MIT Management System Report	Eighty percent of the survey respondents indicated the subsea part replacement philosophy is based on a scheduled interval approach. A little more than fifty percent of the survey respondents indicated this same approach was used for surface equipment.
21	The management system survey indicated that training of BOP maintainers after initial training (i.e., periodic or refresher training) is limited	MIT Activities and MIT Management System Report	Less than twenty five percent of the survey respondents indicated refresher or periodic training is provided.

3.3 ANALYSES OBSERVATIONS

This section summarizes the observations from the study analyses. These observations represent notable items identified from the analyses. Table 3-3 contains a tracking letter, observation, analysis reference, and basis for the observation.

Table 3-3: Analyses Observations

No.	Observation	Analysis Document	Observation Basis
A	The calculated MTTF values are not representative of the MTTF for the BOP system (in terms failure of system functionality). Rather, these values represent a mean time to a repair action.	Data Analysis Report	Because of the level of redundancy designed into the BOP, most single failures do not result in a loss of BOP system function. However, the BOP regulatory requirements consider these failures requiring repair (or other suitable corrective action). Therefore, some failures, which do not result in system failure, are counted as failure when calculating the “apparent” BOP system MTTF.
B	There is a possible correlation between increasing percent of planned maintenance (i.e., intrusive, interval-based maintenance) and increasing BOP failures and increasing corrective maintenance.	Data Analysis Report	The scatter diagram plots of (1) planned maintenance percentage and BOP failures and (2) planned maintenance percentage and corrective maintenance indicate a possible correlation. However, there are some potential outlying data points whose removal would lower the strength of the correlation.
C	The availability and quality limitations of component-level failure event data impacted the accuracy and level of detail for the RAM modeling.	Data Analysis Report and RAM Reports 1 and 2	Specifically, failure data were often missing/ lacking the following: • Identification of failed component(s) • Estimation of the cumulative BOP operating days
D	Reliability and risk analyses do not appear to be commonly used to determine and evaluate BOP MIT tasks.	MIT Activities and MIT Management System Report	As seen during the compilation of IP planned MIT activities and the management system survey results, reliability and risks analyses, such reliability–centered maintenance (RCM) and risk-based inspection (RBI), are not commonly used by

Table 3-3: Analyses Observations

No.	Observation	Analysis Document	Observation Basis
			drilling contractors and BOP OEM when defining BOP MIT tasks.
E	It does not appear to be a common practice to use trending of repeat BOP failures a tool for determining when formal failure investigations are needed.	MIT Activities and MIT Management System Report	Only about 10% of the survey respondents indicated criteria related to trending of repeat failures were used to determine when a formal investigation is needed.
F	The generation and monitoring of key performance maintenance indicators does not appear a common BOP maintenance practice.	MIT Activities and MIT Management System Report	The survey questions related to key performance indicators did not indicate a strong presence of systems to generate key performance maintenance indicators, or the use of these indicators to monitor BOP maintenance.

Table 3-3: Analyses Observations

No.	Observation	Analysis Document	Observation Basis
G	Industry practices on expected use of, and training on, written instructions is not consistent.	MIT Activities and MIT Management System Report	The survey questions related to the expected use of written instruction had mixed results, with about half the respondents indicating written instructions are intended to be guidelines for performing tasks. The other half of respondents indicated written instructions provided the step-by-step instructions for performing the tasks. In addition, there was not a strong indication BOP maintainers receive training on written PM and repair instructions.
H	The BOP MIT practices and management systems investigated in this study represent one aspect (i.e., BOP maintenance) of a life-cycle approach asset management approach relative to BOP performance. This study did not investigate many of the life-cycle phases needed for BOP performance (e.g., design, fabrication, procurement, installation, operation)	Compilation of All Study Documents	This observation is provided for perspective on the study relative to a holistic life-cycle approach to BOP performance.

4.0 RECOMMENDATIONS AND CONCLUDING REMARKS

This report section provides study recommendations and conclusions. Table 4-1 lists the study recommendations developed at the time of the report issue. As this study was performed in collaboration with IPs, further review and implementation of the following recommendations should involve a high level of industry participation.

Table 4-1: Study Recommendations

No.	Recommendation
1	Consider developing an industry document defining guidelines for recording and collecting BOP component failure data. Consider addressing : • Component taxonomy • Component failure codes • Relevant operating parameters (e.g., BOP days, operating cycles) needed • Data collection approaches, so that the data needed to determine failure distributions and to establish safe and unsafe failure fractions for the most critical BOP components are collected One major project challenge was the availability of high quality component failure data. Specifically, this study observed several issues relative to the collection and analysis of the raw failure data. Two significant issues were that the industry (1) does not employ a common component taxonomy structure for recording of component-level failures, which resulted in a good deal of subjectivity to identify the failed subsystem/component and (2) does not track relevant component operating parameters (e.g., BOP days, operating cycles) in detail. In addition, failure events often did not include sufficient information to determine the specific failed subsystem/component and/or the subsystem/component's failure mode. Also, it would likely be helpful to discuss and define requirements related to the electronic capture and transfer of component reliability data.
2	Consider developing an industry guideline or recommended practice for performing BOP reliability analyses. Consider addressing these issues: • Definition of BOP failure • Reliability factors of merit of interest for all key stakeholders (e.g., IPs, drilling contractors, operators, OEMs, regulators) • Reliability modeling approaches to be used for the differing factors of merit • Application of safe and unsafe failure fractions to failure rate data (so that BOP models can differentiate between spurious trip and failure of safety related operations.) • Consideration of common cause/dependent failures in the RAM models During the data analysis and RAM studies, many discussions and opinions were held regarding the proper approach for assessing BOP reliability. Some issues were basic reliability issues, such as 'When has the BOP failed?' (e.g., when the BOP system loses functionality, when a single component fails) and 'What is the proper reliability factor of

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	merit for measuring BOP performance?' (Note: This study team concluded that there are several factors of merit important to BOP performance and that the importance of those factors somewhat vary by stakeholder.) Some of the more complex issues discussed related to the identification of the best modeling technique and how to address common cause/ dependent failures.
3	Consider adopting a collaborative strategy with industry to address the application and expanded use of predictive maintenance techniques to BOP maintenance, including the evaluation of common predictive tools used by other industries for possible application to BOP systems and the identification of any new predictive maintenance technologies needed for BOP maintenance applications. The analysis of MIT events and planned MIT activities indicated a small percentage of proactive maintenance task are predictive maintenance tasks. The use of predictive maintenance techniques have proven successful in many industries, and have resulted in improved component and system reliability with less intrusive proactive maintenance (e.g., replacement or disassembly and rebuilding of components based on time). There are definitely some unique issues related to BOP MIT activities (mostly due to much of the equipment being subsea), which make the application of predictive maintenance challenging. However, an industry study may identify potential applications of currently available predictive maintenance technologies to surface equipment and may create suggestions for developing new predictive maintenance technologies for subsea equipment.
4	Consider piloting the use of reliability and/or risk-based analytical approaches, such as RCM and RBI, for evaluating and determining BOP MIT tasks. This study found that many MIT tasks are time-based, requiring performance of intrusive tasks based on OEM recommendations. While OEM recommendations are often a good starting point for a proactive maintenance program, other industries have proven that the application of analytical tools, such as RCM and RBI, can result in better failure management strategies than prescriptive, time-based approaches. The application of reliability and risk analysis tools to maintenance decisions has resulted in a better balance and alignment of MIT resources to potential failures.
5	Consider conducting a more extensive survey of reliability and maintenance management system practices used for BOP maintenance. The results of such a survey may be useful in identifying effective BOP management best practices. The survey conducted as part of this study included a limited number of responses from a small cross-section of the participating organizations. While the responses appear to indicate trends on some key issues, drawing any firm conclusions on reliability and maintenance practices is difficult because the response population is small. In addition, the survey was not designed to correlate the responses to BOP performance (e.g., correlating reliability factors of merit, such as BOP system availability to management system practices). When designing

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	this survey, it is recommended these study results be used to design a survey to investigate potential correlations between some of the study observations (e.g., any correlation between refresher training and BOP performance, any significant impact on BOP performance related to the high reliance on OEM recommendations.) In addition, the scope of survey to include additional BOP organizations involved in maintaining BOP should be considered.
6	Consider developing a guidance document related to key performance indicators, which could be used to monitor the performance and maintenance of BOPs. Consider including both leading and lagging indicators. The MIT management survey appeared to indicate there was limited use of key performance indicators. Other industries have proven that reliability and maintenance key performance indicators are useful and vital to monitoring and driving continuous improvement of asset reliability performance. Other industries have used a combination of lagging and leading indicators to drive and monitor asset reliability performance. Some example of KPIs used in other industries for asset management include but are not limited to: (1) overall equipment performance/asset availability (lagging), (2) unplanned downtime (lagging), (3) number of asset incidences (lagging), (4) percent of preventive maintenance, predictive maintenance, inspections, and test completed on schedule (leading), (5) work order backlogs (leading), (6) percent of emergency maintenance work (leading), (7) ratio of corrective maintenance work to proactive maintenance work or total maintenance work (leading), and (8) percent of corrective maintenance work resulting from preventive maintenance and from predictive maintenance work (leading).
7	Consider conducting additional, more detailed studies to investigate the best means to improve failure management strategies for the higher risk components and harder to detect failure modes identified in the FMECAs. The FMECA results identified seven higher risk equipment items and three items in which the equipment failures are harder to detect. Additional detailed reliability analyses may identify means to improve MIT activities and thus reduce the failure risk and/or improve detectability of unannounced failures. Specifically, these study results suggest further analysis of the following BOP components may be warranted: • Blind shear rams • Casing shear rams • Connectors • Blue & yellow POD hydraulics • Choke & kill lines and valves • Pipe rams • Hydraulic supply lines • Subsea accumulators • Control systems (both the electric or hydraulic portions)

In conclusion, BSEE’s overall objective for this study was to generate and provide information related to the maintenance and inspection of BOPs operating in deepwater in the GoM. To this end, this study has generated the following information:

- Estimation of BOP performance in terms of MTTF and mean availability
- Trending of actual BOP equipment failures and failure modes
- Review of planned and actual performed MIT tasks
- Alignment of MIT tasks with potential BOP equipment failures
- Identification of BOP equipment risks
- Comparison of MIT task requirements contained in regulations and industry standards/ recommended practices
- Survey of reliability and maintenance management systems related to BOP maintenance