ANNEX II
Post-Event Hurricane Damage Assessment

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II.1 SUMMARY OF PROJECTS

II.1.1 HURRICANE HINDCAST DATA

Two (2) TA&R projects have been conducted to develop a database of wind, seastate and current data of hurricanes in the Gulf of Mexico. These projects are TA&R Project No. 580, and TA&R Project No. 467, and are summarized below. Detailed summaries of these projects are provided in a later section of this Annex.

II.1.1.1 Hindcast Data on Winds, Waves and Currents during Hurricane Katrina and Rita

Previously an initial study responded to urgent industry needs for a preliminary assessment of the impact of Hurricanes Katrina and Rita by performing an "emergency response (ER)" wind and wave hindcast. The objective of this study was to develop a database of wind, sea state and currents resulting from Hurricanes Katrina and Rita meteorological data and application of advanced hindcast models.

The study utilized a large base of measured wind, wave, surge and current data, and included a more detailed analysis of the wind field. Particular attention was paid to provision of much higher resolution in shallow water and to the inclusion of the storm perturbed water level in the shallow water wave hindcast, and more robust current models were adopted. The report presents the data in a series of tables and figures illustrating the derived hindcast data.

Figure II.1 shows the track of Hurricane Katrina and Hurricane Rita through the Gulf of Mexico, also shown are the positions of the NDBC buoys against which the hindcast data was calibrated.

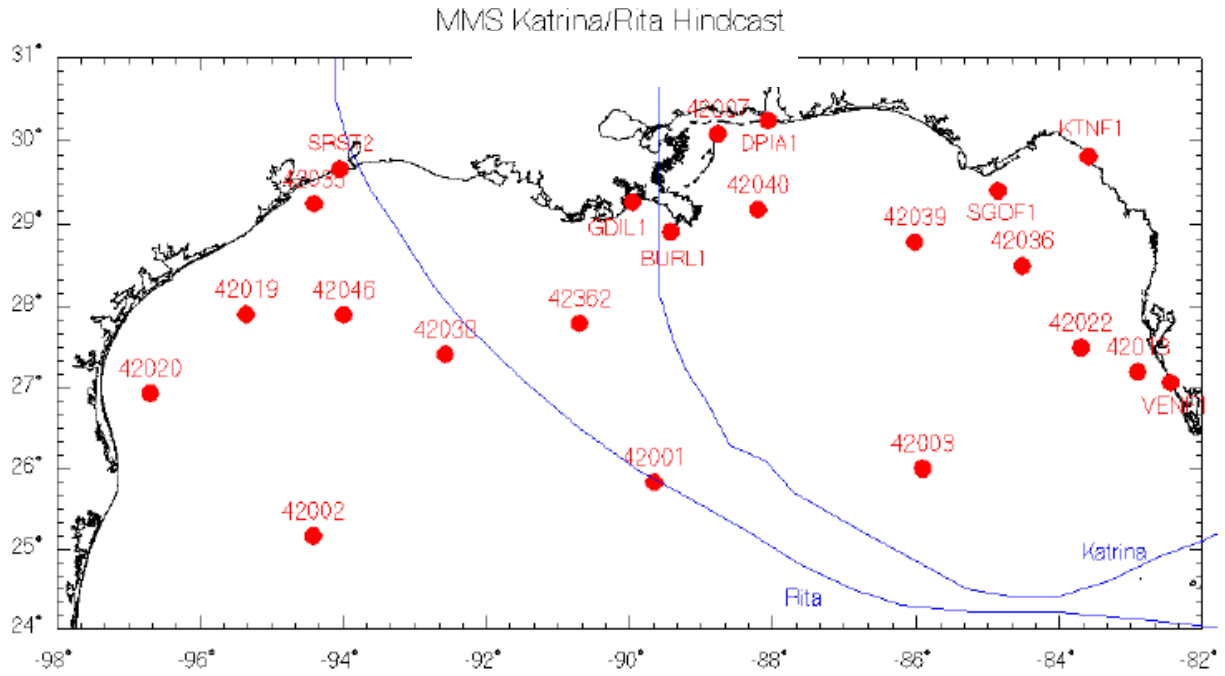


Figure II.1: Storm Track of Hurricane Katrina and Hurricane Rita through GOM with NDBC Buoys Shown

II.1.1.2 Hindcast Study of Winds, Waves and Currents in N. GOM in Hurricane Lili (2002)

This study developed a description of the evolution and distribution of the surface wind field, wave, salinity, sea surface temperature and current field in the northern GOM during the approach and passage of Hurricane Lili in 2002. The hindcast utilized all available public domain meteorological and oceanographic measured data, and Oceanweather's most accurate cyclone wind and wave hindcast methods. Hindcast results and accuracy were validated against available measured data. The narrative report includes a description of the data sources, storm evolution (track and intensity), wind and wave hindcast method and a summary of results.

II.1.2 HURRICANE EFFECTS ON MOORING CAPABILITIES

Four (4) TA&R projects have been conducted to examine the effects of damage to offshore platforms due to hurricanes. These projects are Projects No. 548, 466, 469 and 591, and are summarized below. Project No. 591 summarized the evaluation of subrope

damage following hurricanes and other events, and is also summarized below. Detailed summaries of these projects are also provided in a later section of this Annex.

II.1.2.1 Examination and Review of Mobile Offshore Drilling Unit (MODU) Loss of Station-keeping Ability during Hurricane Ivan and Assessment of Current Mooring Standards and Criteria to Prevent Similar Failures

The project examined the loss of Mobile Offshore Drilling Unit (MODU) station-keeping in the Gulf of Mexico during Hurricane Ivan, in September 2004, comparing those findings with that of recent Hurricanes Andrew (1992) and Lili (2002), and assessed the current mooring standards and criteria to prevent similar failures.

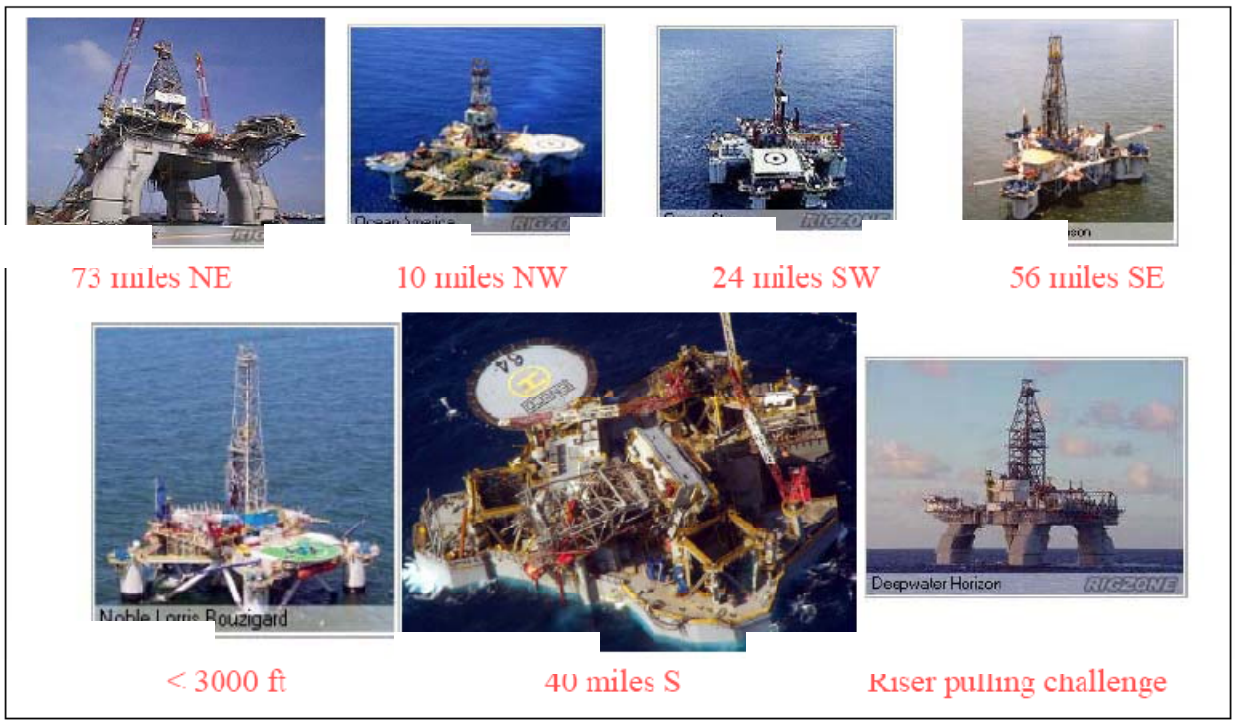


Figure II.2: Hurricane Ivan MODU Issues

The failures associated with the Mobile Drilling Units during Hurricane Ivan including gathering and reviewing information and determining cause available on the loss of station keeping of 5 Semisubmersible MODUs, the Collapse of a jackup MODU, along with the damage to 2 other jackup MODUs, which are shown in Figure II.2. It was found that unexpected failures resulted from possible non uniformities in equipment, with the need for greater quality control during manufacture. The airgap (distance between deck and

water level) was also shown to be a contributing factor in the failures, with recommendation made for the development of a new recommended practice.

II.1.2.2 Post Mortem Failure Assessment of Drilling Rigs During Hurricane Lili

In the aftermath of Hurricane Lili there was an opportunity to understand the effects of hurricanes in relation to the design standards that the offshore energy industry considers appropriate for maintaining an envelope of safety for MODUs. The aim of this project was to make the appropriate recommendations for the update of codes of practice for MODU design for the Gulf of Mexico based on this new understanding.

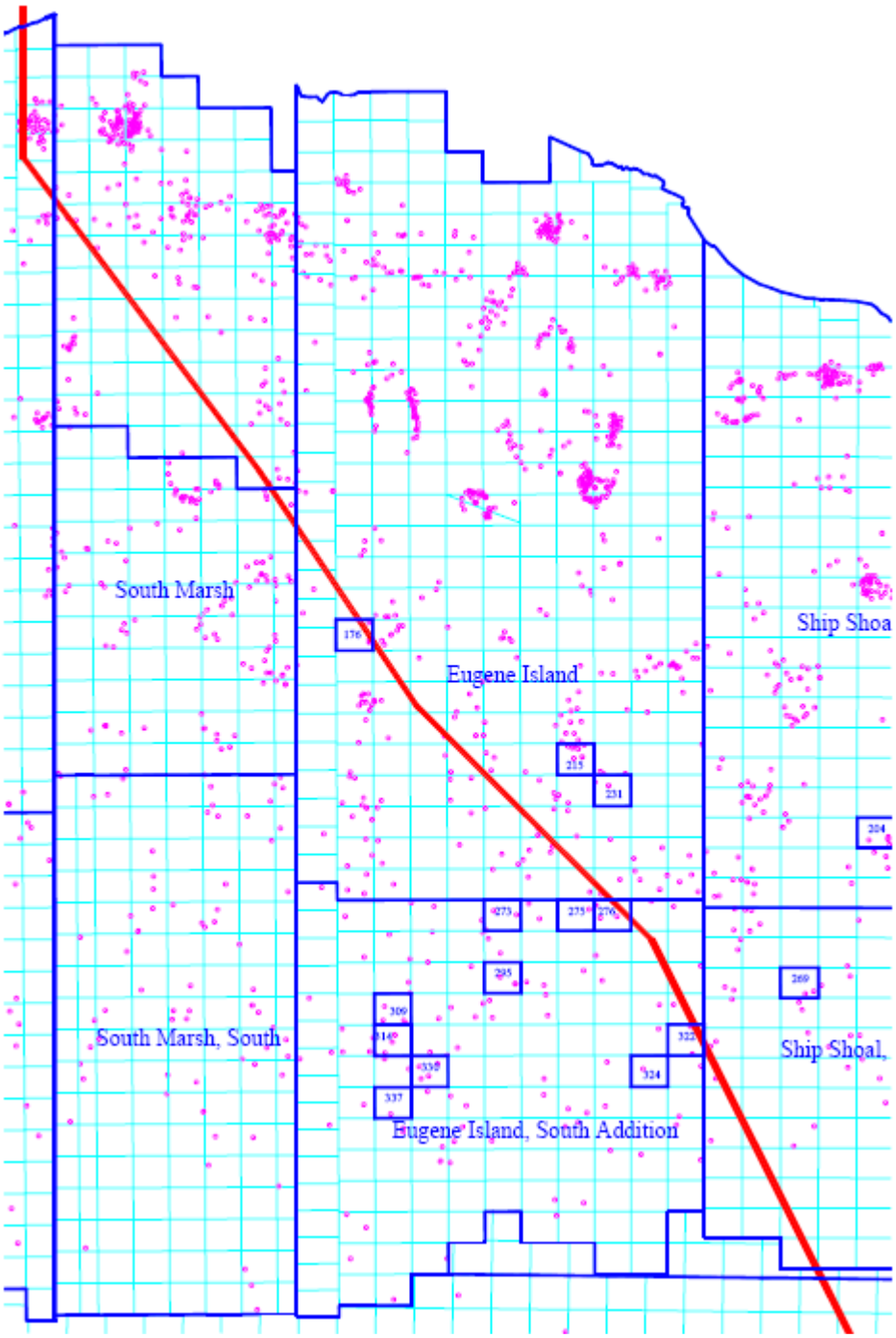
The main findings of this project showed that difference in hindcast metocean data, and the interpretation of those differences, lead to inconsistencies in the design approach for MODUs, which led in turn to failures during Hurricane Lili. It was recommended that MMS should consider sponsoring a workshop and/or a university research project to investigate and evaluate the difference in methods used by various metocean data suppliers, allowing for an assessment of the implication of these differences on the safety of existing MODUs.

Figure II.3 shows images before and after of the Nabors Dolphin 105 jackup rig. The rig was within 15 miles of the central path of the storm in the quadrant producing the worst waves and winds, which resulted in loading well beyond its design capacity.

Figure II.3: Nabors Dolphin 105 Pre and Post Hurricane Lili Event

II.1.2.3 Validation and Calibration of API-RP-2A Using Hurricane Lili to Update the Hurricane Andrew JIP Results

The aim of this project was to update the API-RP-2A design code section using Hurricane Lili data to validate and calibrate Hurricane Andrew's JIP results. Hurricane Lili did much damage to platforms, including the complete loss of some of the units. Figure II.4 shows the track of Hurricane Lili through the Gulf of Mexico outer continental shelf, highlighting the platforms affected.



Note: platforms shown as pink circles, blocks with damaged platforms outlined and labeled

Figure II.4: Storm Track of Hurricane Lili through GOM

The report consisted of two parts, namely a qualitative assessment and a quantitative assessment. The qualitative assessment examined the general nature of the platform survival, damage and failures; while the quantitative assessment used probabilistic

techniques to determine the performance of the platforms during Hurricane Lili and to compare against the predicted damages using analytical techniques as outlined in the API RP 2A standard.

The main conclusions of the report found that the critical factor determining platform performance was age, with platforms installed before 1980 experiencing significantly higher damage in comparison to those installed post-1980. It was also shown that multiple platforms of an operator's fleet can be put at significant risk from a single event, due to the close grouping of platforms. Overall, the usefulness of API RP 2A Section 17 was shown to provide for well designed platforms in terms of hurricane response.

II.1.2.4 Evaluate Accuracy of Polyester Subrope Damage Detection Performed by ROVs Following Hurricanes and Other Events

This project investigated the accuracy of non-invasive deepwater subsea inspections performed by common ROV-supported inspection tools and provided a comprehensive assessment of the knowledge gained from recent work on subrope behavior.

The main conclusions of the project found that the only major cause of rope structural loss over a 20 year period was thought to be through third party damage. Current detection methods of subrope damage were shown to be sufficient, however the use of ROV video inspection was recommended to be more utilized.

II.1.3 ASSESSMENT OF OFFSHORE PLATFORMS IN HURRICANES

Detailed assessment studies of fixed offshore platforms were conducted in order to assess the quality of their design and propose any recommendations to API RP 2A. The studies focused on the damages and destructions resulting from hurricanes Andrew, Lili, Ivan, Katrina and Rita. These studies are presented in the technical reports of TA&R Projects No. 549 and 578. Detailed summaries of these projects are provided in a later section of this Annex.

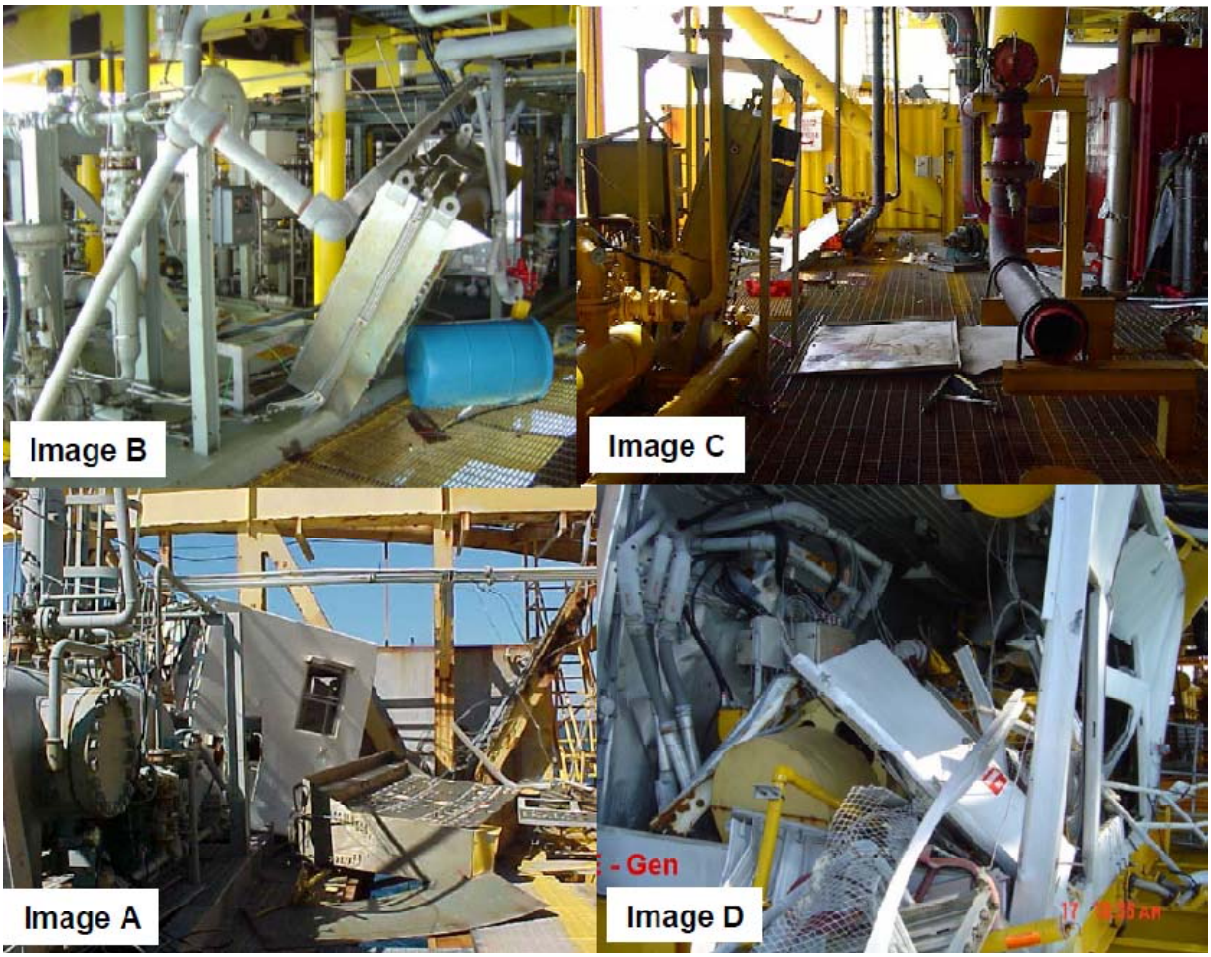


Figure II.5: Typical Non-Structural Topside Damage Caused by Wave-in Deck

II.1.3.1 Project No. 549 – Assessment of Fixed Offshore Platforms in Hurricane Ivan, Andrew and Lili

Hurricane Ivan (Ivan) was a major hurricane that passed through the Gulf of Mexico on September 14 and 15, 2004. It destroyed and damaged numerous offshore oil and gas platforms. This research project describes a method that used the results of Ivan to determine the current state of performance of API and MMS regulations in terms of the design of fixed offshore platforms. The project collected Ivan fixed platform damage information into a database and evaluated trends, performed a quantitative assessment that compared analytically predicted platform damage to actual observed damage, and made recommendations for suggested studies of key fixed platform design issues. The focus of the effort was on wave-induced damage to the structural systems (foundations, jacket and deck) and not on wind damage to topsides.

II.1.3.2 Project No. 551 – Assessment of Drilling and Workover Rig Storm Sea Fastenings on Offshore Floating Platforms during Hurricane Ivan

Drilling and workover rigs on Floating Production Systems (FPSs) are fastened to the decks of offshore structure sea fastenings to prevent movement during hurricanes. Sea fastenings include bolts, weldments, braces, or other means. During Hurricane Ivan, a number of drilling or workover rigs shifted. These movements were assessed along with the current design philosophy and criteria for storm sea fastenings, rig and storm sea fastening installation practices, and onboard storm operational practices to ready FPSs for a hurricane. Results provided information that can be used to assess any needs to revise tie-down criteria or practices to avoid future damage. Phase 1 was sponsored by MMS. The objectives were to collect information on FPSs that had drilling rig movements during Ivan and complete preliminary analyses to understand the observed movements relative to existing codes and practices. A Phase 2 study is envisioned as a JIP that would complete additional and more detailed analyses of rig tie-down failures and successes, and evaluate tie-down options for preventing observed movements.

II.1.3.3 Project No. 578 – Assessment of Fixed Offshore Platform Performance in Hurricanes Katrina and Rita

Hurricanes Katrina and Rita passed through over approximately 3,000 platforms in the Gulf of Mexico during the fall of 2005. This research project addressed the reasons of why some platforms performed satisfactorily while some others failed during the hurricanes. This research sheds light on the usefulness and recommendations into API RP 2A, which is an industry-wide and accepted offshore platform structural design code.

II.1.3.4 Project No. 593 – Jackup MODUs- Assessment Checksheet for Hurricane Season

The driver for this research was to investigate the safety of the Jack-up mobile offshore drilling units (MODUs). The research was driven by the need to find out the adequacy of the current jack up structures, the statistics of failures in the past hurricanes such as Ivan, Katrina and Rita (in years 2004 and 2005), interpret the modes of failures and suggest design recommendations for future jack-up rigs.

II.1.4 GEOTECHNICAL POST-EVENT DAMAGE ASSESSMENT

II.1.4.1 Offshore Hurricane Readiness & Recovery Conference

The main goal of this project aimed to assess the performance of the Gulf of Mexico oil and gas infrastructure (MODUs, fixed and floating production systems, and pipelines) during Hurricane Ivan and to evaluate the present design and operational standards, practices, and technology to identify needs and opportunities for improvement. Wave conditions in Hurricane Ivan significantly exceeded those specified in API RP 2A design code. Four MODUs went adrift due to broken mooring systems and one MODU was damaged. For deepwater floating production systems (FPSs), drilling rigs were moved or lost on 4 FPSs and facilities on decks were damaged on 10 FPSs. A total of 7 shallow water fixed platforms were destroyed, including one toppled by a mudslide and six damaged by the environmental loads exceeding the design criteria. More than 150 pipelines were damaged due to mudslides, anchor dragging from drifting MODU, and bottom currents.

However, no significant damage on the floating production systems (such as hulls, moorings, and risers) and newer fixed platform with present-day designs indicated that the present design technology on offshore floating and fixed production system were understood and validated.

II.1.4.2 Mudslides during Hurricane Ivan and an Assessment of the Potential for Future Mudslides in the Gulf of Mexico

Hurricanes Ivan and Katrina have caused a number of reported mudslides triggered by significant wave-induced pressures on the ocean floor in the Mississippi Delta region. A simple limit equilibrium model used in this study was verified to work well on the prediction of factor of safety against mudslide initiation. The bathymetric data, soil strength data, and metocean data associated with the reported wave-induced mudslides were analyzed by using the limit equilibrium model. The analysis results from the limit equilibrium model were incorporated into the framework of probabilistic analyses to estimate the risks of future mudslide occurring in a particular area (See Figure II.6).

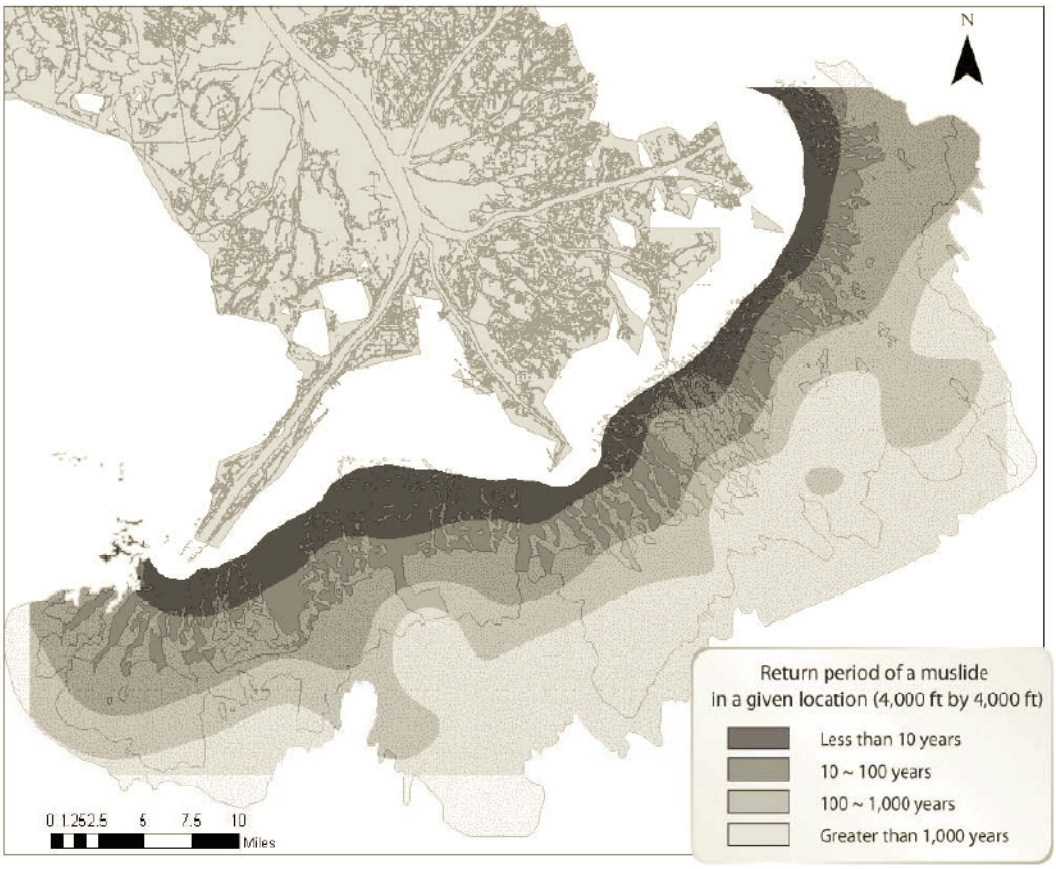


Figure II.6: Return periods of a mudslide occurring (4000 ft by 4000 ft area)

II.1.5 PIPELINES POST-EVENT DAMAGE ASSESSMENT

The Offshore Federal Oil & Gas infrastructure includes over 33, 000 miles of pipeline that provides the means to service and transport approximately 30% of US domestically produced oil and gas from offshore wells to onshore refineries. As the U.S. grows increasingly dependent on the steady supply of energy from offshore oil and gas reserves, MMS remains attentive to the destructive forces of hurricanes and the extensive challenges to protect pipelines in advance of and to re-start pipeline production following these catastrophic natural events.

Over the past decade, the U.S. Gulf of Mexico (GOM) has experienced a heightened level of major hurricane activity (Category 4+) crossing the central and western portion of the GOM's offshore Oil and Gas developed region. Many of hurricanes, including Lili (2002), Ivan (2004), Katrina and Rita (2005), and Gustav and Ike (2008) resulted in significant damage and/or destruction to offshore Oil and Gas facilities and pipelines. The following are the already complete studies that were launched to analyze damage assessment reports

from operators in order to determine the type, cause and extent of pipeline damage incurred during Hurricanes Ivan, Lili, Katrina and Rita, and to provide guidance for improving pipeline integrity/design to reduce potential damage from future GOM hurricanes:

- Project No. 503 - Evaluate and Compare Hurricane-Induced Damage to Offshore Pipelines for Hurricane Lili;
- Project No. 553 - Pipeline Damage Assessment from Hurricane Ivan;
- Project No. 581 - Pipeline Damage Assessment from Hurricane Katrina/Rita.

According to the studies, at that time, in general, the offshore pipe design approaches in GOM and the industry practices related to human and environmental safety were satisfactory. Major negative impact of hurricanes events had been the disruption in oil and gas production due to pipelines and infrastructure damage. In almost all the hurricane events the majority of pipeline failures were near platforms and in mudflow areas. While increased number of instances where pipeline damage resulted by drill rings that lost station-keeping had been a characteristic of Hurricanes Rita and Katrina, hurricane events crossing the Mississippi Delta region, for example Hurricanes Andrew and Ivan, resulted in a high number of pipeline failures due to soil movement and mudflows. Localized failures at pipe crossings and excessive pipe movement in shallow waters had been identified as a concern after Hurricane Ivan. During Hurricane Lili small diameter risers in shallow waters were mostly damaged due to bending fatigue as they were not able to span longer distances.

Careful evaluation of shallow water pipelines in mudflow areas, development of specific criteria for pipeline damage surveys to focus on the most likely undetected damage, definition of a formal process to identify and prioritize critical energy infrastructure repairs, permitting and approvals, utilization of an efficient web-based visual data management tool to support post-hurricane rehabilitation activities, and knowledge sharing and further specialized studies related to the identified dominant causes of failure were recommended by the studies. To address small-diameter riser failure issue, clamp spacings were recommended to address both cyclic wave force fatigue as well as oscillatory Vortex Induced Vibration (VIV) considerations. Redundant diver-installed back-up clamps were recommended to be added in addition to the original clamp to provide a secondary defense to clamp failure.

The detailed review reports for these projects are presented in a later section of this Annex.

Figure II.7: Kinked Pipeline Hurricane Damage

II.2 HURRICANE HINDCAST DATA

II.2.1 PROJECT NO. 580 – HINDCAST DATA ON WINDS, WAVES, AND CURRENTS IN NORTHERN GULF OF MEXICO IN HURRICANES KATRINA AND RITA

II.2.1.1 Introduction

II.2.1.1.1 Background

Oceanweather Inc. responded to urgent industry needs for a preliminary assessment of the impact of Hurricanes Katrina and Rita by performing and distributing to several offshore operators an “emergency response (ER)" wind and wave hindcast. As part of this funded study, MMS contracted researchers providing Hurricane Katrina/Rita research data to deliver a second and more in-depth hindcast data analysis (referred to as "fast response (FR)") that resulted in this new study.

II.2.1.1.2 Technical Scope

The purpose of this study is to develop a comprehensive, validated and reliable database of wind, sea state, and currents (vertically averaged in shallow water, mixed layer profile in deep water) associated with Hurricanes Katrina (2005) and Rita (2005) in the Northern Gulf of Mexico (GOM) through the implementation and application of advanced hindcast models.

II.2.1.1.3 Study Limitations

With regard to modeling of ocean currents, unlike in its previous studies of Andrew and Lili, this study does not apply state-of-art 3D ocean models such as the Princeton Model (POM) and HYCOM. To date such efforts have met with very limited success and resulting current hindcasts have not been nearly as reliable as wave hindcasts in a quantitative sense. Rather in this study the focus is on the two regimes that succumb to relatively simple 2D and 1D approaches.

II.2.1.2 Project Conclusions

II.2.1.2.1 Key Conclusions and Results

The hindcast results are given in the report in a series of tables and figures, showing the wind speeds and significant wave heights during Hurricane Katrina and Rita.

In the report the winds are referred to as the effective over water 30 minute average winds at a height of 10m above sea level. "Gust" factors, based on the 30 minute average data, are used to derive wind speeds for shorter averaging intervals.

At the time of Category 5 strength, Katrina generated higher peak winds than Rita. Peak wind speeds at maximum intensity in Katrina were in the range of 55 m/s to 60 m/s while Rita's wind speeds peaked between 45 m/s and 50 m/s.

The peak wave heights (Hs) were found to be between 16m to 17m range for Hurricane Katrina over most of its history, and between 14m to 15m for Hurricane Rita.

The storm surge was found to peak between 8 and 9 meters during Hurricane Katrina, and between 5 and 6 meters for Hurricane Rita.

Validation of the results against the NDBC buoys shows that all buoys during Katrina exhibited bias in HS and TP average of -0.70 cm and -0.63 sec respectively and the correlation coefficient in HS is 0.96. During Rita the HS bias is -0.02 cm and the TP bias is - 0.68 sec. with correlation coefficient in HS of 0.98. Validation of the current modeling showed that the predicted wave velocities were slightly lower than the measured to a depth of 40m.

II.2.1.2.2 OSER Goals

This study developed a description of the evolution and distribution of the surface wind field, wave, and current field in the northern GOM during the approach and passage of Hurricanes Katrina (2005) and Rita (2005). This is inline with the OSER program goals part of which is to best assess, retain or restore the integrity of offshore energy assets.

II.2.1.2.3 Recommendations

This report outlines the results of the hindcast analysis only, and so no recommendations are made.

II.2.1.3 Current State of Knowledge

While much of the JIP work on hindcast modeling to date has been proprietary to the industry sponsors, the underlying modeling and analysis methods have been documented and exposed to the scientific and engineering communities in the peer reviewed literature and major conference proceedings, allowing for integration into API updates.

II.2.2 PROJECT NO.467 – HINDCAST STUDY OF WINDS, WAVES, AND CURRENTS IN N. GOM IN HURRICANE LILI

II.2.2.1 Introduction

II.2.2.1.1 Background

The purpose of this study is to develop a description of the evolution and distribution of the surface wind field, wave, salinity, sea surface temperature and current field in the northern Gulf of Mexico during the approach and passage of Hurricane Lili.

II.2.2.1.2 Technical Scope

The main objective of the report was to present hindcast results in tabular, graphical and computer readable form.

II.2.2.1.3 Study Limitations

The hindcast of a historical storm consists of three basic steps. Firstly, the wind field is specified in a process that requires considerable work by a meteorologist to develop required input parameters for a tropical boundary layer model. Second step is to produce kinematic analysis for use in areas in which the numerical model solution is not sufficiently accurate. Third, the resulting wind fields are applied in proven ocean wave and hydrodynamical models. Therefore, this methodology is dependent on interpretation from the meteorologist, the accuracy of the modeling and assumptions made.

II.2.2.2 Project Conclusions

II.2.2.2.1 Key Conclusions and Results

The hindcast results are given in the report in a series of tables and figures, showing the wind speeds and significant waves heights during Hurricane Lili.

In the report the winds are referred to as the effective over water 30 minute average winds at a height of 10m above sea level. "Gust" factors, based on the 30 minute average data, are used to derive wind speeds for shorter averaging intervals.

Two dimensional wave spectrum at 15 minute intervals were developed using the UNIWAVE hindcast model, with integrated properties of the spectrum calculated from the 2D spectrum at all Northern Gulf grid points.

Validation of the hindcast was performed against all available NDBC buoys in the Gulf of Mexico, and showed good correlation against the modeled results.

II.2.2.2.1 OSER Goals

This study developed a description of the evolution and distribution of the surface wind field, wave, salinity, sea surface temperature and current field in the northern GOM during the approach and passage of Hurricanes Lili (2002). This is inline with the OSER program goals part of which is to best assess, retain or restore the integrity of offshore energy assets.

II.2.2.2.2 Recommendations

The report outlines the results of the hindcast analysis only, and so no recommendations are made.

II.2.2.3 Current State of Knowledge

This report outlines the hindcast data obtained from Hurricane Lili only, which will provide useful information for hurricane validation analysis, and enable greater accuracy in the design of structures for hurricane loadings.

II.3 HURRICANE EFFECTS OF MOORING CAPABILITIES

II.3.1 PROJECT NO. 548 – POST MORTEM FAILURE ASSESSMENT OF MODUS DURING HURRICANE IVAN

II.3.1.1 Introduction

II.3.1.1.1 Background

Appropriate verification of standards for Mobile Offshore Drilling Unit's (MODUs) in the Gulf of Mexico is an ongoing issue given that the events, against which they are calibrated, such as hurricanes, are rare. In the aftermath of a hurricane there is a unique opportunity to reflect on the events that took place, to chronicle them, and give the industry an understanding of their impact on the standards that the industry considers appropriate in maintaining an envelope of safety for MODUs. Hurricane Ivan tracked through a high density corridor of MODUs in the Gulf of Mexico in September 2004, and provided such an opportunity for standards validation.

II.3.1.1.2 Technical Scope

The main objectives of the report were to:

- Study the failures associated with the Mobile Drilling Units during Hurricane Ivan including gathering and reviewing information and determining cause available on:
  - Loss of station keeping of 5 Semisubmersible MODUs
  - Collapse of a jackup MODU
  - Damage to 2 other jackup MODUs
  - Settlement on the legs of one or more other MODUS which could have resulted in casualties;
- Develop any recommended update on criteria and perform analysis determining if the updated criteria would have caused these units to avoid the resulting effect during the hurricane;

- Re-visit the Recommendations from the Hurricane Andrew and Hurricane Lili Studies on station keeping, and update any recommendations for future mitigation action;
- Make Recommendations to the criteria for sitting jackups and make any recommendations for future mitigation action.

II.3.1.1.3 Study Limitations

Since Hurricane Ivan two further hurricanes have occurred, Hurricane Katrina in August 2005 and Hurricane Rita in September 2005, which are not part of that study. At the time of writing that report neither of these events had been subject to a complete investigation in a publically available document (Katrina/Rita assessments reports, however; had been completed at the time of writing this report and they are included in this report; Projects No. 578, 580, and 581).

II.3.1.2 Project Conclusions

II.3.1.2.1 Key Conclusions and Results

In summary the report found:

- A number of unexpected wire failures were reported, in this study, on five semi-submersibles, leading to the possible requirement of studies into equipment uniformity;
- Higher airgaps are required, with a new recommended practice RP95J [1] to be developed. Part of the practice will consider an enhanced quality system as applied to pre-laid and rig moorings (which may indeed already be practiced); since any analysis assumes that the equipment will hold the design loads of each component;
- The enormous lengths of the mooring lines (2-3 miles) each means it is very difficult to assure that every single component will be of robust quality without an extra-ordinary quality system backing up the equipment;
- Greater quality control is required in the manufacture and installation of components, due to the expense of mooring lines. There is a need for the offshore energy industry to develop standards that allow for greater traceability of components;
- Jackups with a sufficient airgap have proved to be robust during hurricane loading. However, the new configurations of jackups are more prone to floating off and creating a hazard;

- Comparison of rig hindcast data to the 10 year criteria shows that, in general, jackups perform better than their defined criteria.

II.3.1.2.2 OSER Goals

MODUs in the Gulf of Mexico are a critical part of the infrastructure that brings oil and gas production to the marketplace. This study is similar to studies that were previously undertaken in the aftermath of Hurricane Andrew, and Hurricane Lili –sponsored by the MMS to chronicle failures and to seek recommendations from the lessons learned from the failures. This is inline with the OSER program goals part of which is to best assess, retain or restore the integrity of offshore energy assets.

II.3.1.2.3 Recommendations

The following recommendations are made:

- Operators should maintain a high level of quality control on mooring components;
- There is a research need to instrument some semi-submersibles in order to benchmark the mooring analysis assumptions and methodology. Operators should be encouraged to add instrumentation to gather this information;
- IADC and API committees working on new guidance for jackup rigs should consider a section to identify critical infrastructure, as well as considering a higher return period storm for rigs in close proximity to critical structures.

II.3.1.3 Current State of Knowledge

Since Hurricanes Ivan, Katrina and Rita a Joint Industry Study has been formed [2] and has resulted in quick action to outstanding issues within the specifications, with interim guidelines issued with appropriate criteria for mooring and semi-submersibles.

A search for improvements in safety and performance of jackup rigs is currently underway. It is understood there are initiatives underway to bring these issues before the IADC jackup committee that has already had discussions concerning the need to address the question of an upgraded criteria when in proximity to critical infrastructure.

II.3.2 PROJECT NO. 469 – POST MORTEM FAILURE ASSESSMENT OF DRILLING RIGS DURING HURRICANE LILI

II.3.2.1 Introduction

II.3.2.1.1 Background

Mobile Offshore Drilling Units (MODUs) in the Gulf of Mexico are a critical part of the infrastructure that brings oil and gas prospects to development. Industry standards that allow safe and economic operations are important both to the community and regulatory interests. Appropriate calibration of those standards is an on-going issue particularly because the events by which they can be calibrated such as hurricanes are rare events. In the aftermath of Hurricane Lili there was a unique opportunity to reflect on the events that took place, to chronicle them, and give the industry an understanding of their impact on the standards that the industry considers appropriate in maintaining an envelope of safety for MODUs.

II.3.2.1.2 Technical Scope

The aim of this project is to make recommendations for the update of codes of practice for MODU design for the Gulf of Mexico.

II.3.2.1.3 Study Limitations

This study is an historical review of the impact of Hurricane Lili on MODUs. The review is descriptive in nature, and as such is dependent on the interpretation of the author.

II.3.2.2 Project Conclusions

II.3.2.2.1 Key Conclusions and Results

The main conclusions of the report are:

- Significant variations were found between the results of the hindcast companies regularly supplying metocean information. Variation in metocean data leads to variations in the loading regimes designed for, and thus probabilities of failure;

- Users incorrectly interpret the metocean data of one metocean consulting company to the other;
- Investigation into semi-submersible incidents showed that the design criteria had been exceeded, due to a combination of wind speeds, wave height, and current which were found to be considerably higher than the standard API criteria;
- Potential damage caused from rigs that are adrift is extremely high, and damage which is acceptable to an individual owner may not be acceptable to a regulator;
- Anchor drag can be beneficial in preventing mooring line breakage by allowing some redistribution of loads, but can be difficult to accurately predict given the variety of soil conditions experienced in the GOM;
- Investigation of jackup failures show failure occurred due to the severe weather conditions, and that age had no effect.

II.3.2.2.2 OSER Goals

MODUs in the Gulf of Mexico are a critical part of the infrastructure that brings oil and gas production to the marketplace. This is similar to a study that was previously undertaken in the aftermath of Hurricane Andrew –sponsored by the MMS to seek recommendations from the lessons learned from the failures. This study on Hurricane Lili takes into account the information in the report on Hurricane Andrew in coming to its conclusions and recommendations. This is inline with the OSER program goals part of which is to best assess, retain or restore the integrity of offshore energy assets.

II.3.2.2.3 Recommendations

The following recommendations were made:

- All MODU incidents should be reported and the information made generally available. Ideally reports should go to the regulator through a standards organization;
- The MMS should consider sponsoring a workshop and/or a university research project to investigate and evaluate the difference in methods used by various metocean data suppliers. This would allow for an assessment of the implication of these differences on the safety of existing MODUs;
- If maximum loads are exceeded, there is a need to develop a methods to limit movement should the primary mooring system fail;
- Further research is needed to predict the ultimate holding capacity of anchors, with greater information of soil properties;

- There is a need to instrument some semi-submersibles in order to benchmark mooring analysis assumptions and methodologies;
- Structures in the GOM that are deemed to be of high importance should be designated as vital structures, which would allow for the facilitation of future risk studies that could examine specific mooring locations with greater precision;
- A basic manual should be developed to show critical components of jackup structures and their inspection regimes to maintain maximum capability;
- Caution about higher crest height to wave height ratio for breaking waves should be added to the Marine Operating Manuals for jackups, as to date there is little guidance on this phenomena.

II.3.2.3 Current State of Knowledge

Since Hurricane Lili there have been a number of other significant hurricanes in the GOM, including Ivan (2004), and Katrina and Rita (2006), allowing for further understanding of hurricane events and the updating of the codes of practice.

II.3.3 PROJECT NO. 466 – VALIDATION AND CALIBRATION OF API-RP-2A USING HURRICANE LILI TO UPDATE THE HURRICANE ANDREW JIP RESULTS

II.3.3.1 Introduction

II.3.3.1.1 Background

When hurricane Lili passed through a region of fixed oil platforms in September 2003, it provided an opportunity to better understand the performance of fixed based platforms in extreme hurricanes. While a large majority of fixed platforms performed adequately during Lili with no damage reported, a smaller set were damaged significantly and in several cases the platforms collapsed.

Extreme hurricanes, such as Lili, that pass through an area of densely populated offshore platforms are rare. The last such event was Hurricane Andrew in 1992, which resulted in the damage of several platforms. Studies conducted following the Hurricane Andrew event resulted in several lessons learned, resulting in updates to the offshore industries platform design and assessment approach.

II.3.3.1.2 Technical Scope

Based on the background of hurricane events, the performance of fixed jackets during Hurricane Lili was investigated. The scope of the investigation consisted of two parts;

- *Qualitative Assessment* – of platform performance, to cover the general nature of the platform survival, damage and failures,
- Quantitative Assessment – use of probabilistic techniques to determine the performance of platforms during Hurricane Lili to compare against predicted damages using analytical techniques as outlined in the API RP 2A standard.

II.3.3.1.3 Study Limitations

While Hurricane Lili made landfall as a borderline Category 1/Category 2 hurricane [3], no more than 500 fixed platforms were exposed to level Category 3 and 4 storm waves similar to those as those used for the design of new structures. This study verifies the quantitative risk based on 2 hurricane events of fixed platforms only; consequently further studies are required to further validate the Recommended Practice.

II.3.3.2 Project Conclusions

II.3.3.2.1 Key Conclusions and Results

Conclusions of the qualitative assessment are:

- Age is a critical factor in determining platform performance; with platforms installed before 1980 experiencing significantly higher damages due to lower decks, smaller members and weaker joints than post-1980 platforms due to being designed in an era when the RP was evolving;
- Platforms with low decks are at the greatest risk of failure in hurricanes due to the large forces exerted on a platform should an extreme wave crest hit the deck structure;
- Underwater inspections lead to the identification of further damages, as a number of platforms were indentified to have significant damage that had not been seen in previous inspections highlighting the usefulness of such a survey;
- Multiple platforms in an operators fleet can be put at risk from a single event as there is a tendency for operators to have a large number of platforms grouped together in a relatively small geographical area leading to a significant risk of damage;

- The usefulness of API RP 2A Section 17 was demonstrated, providing operators with a clear methodology for the reassessment of existing platforms. The RP enabled a decision on the economic viability of upgrading the platforms;
- The cost of platform damage and cleanup can be significant, as novel and sometimes expensive methods are required to safely decommission damaged platforms.

Conclusions of the quantitative assessment are:

- API RP 2A is satisfactory tool for estimating platform performance, with conservatism in the range of 10 to 20 percent;
- The API RP 2A approach provides for well designed platforms in terms of hurricane response;
- Statistical bias factors of approximately 1.2 and 1.1 were obtained for Hurricane Lili and Andrew respectively;
- A combined bias factor for the two events of just under 1.2 was obtained.

Note: The bias factor reflects the effectiveness of API RP 2A in the prediction of platform behavior under extreme loading. A factor greater than 1 indicates conservatism, while a factor less than 1 is un-conservative.

II.3.3.2.2 OSER Goals

This study attempted to provide a descriptive summary of the main platform damages and local component damages caused by hurricane events. To this end this was achieved, in that the report provides a definitive, although non-exhaustive, review of observed damages highlighting specific findings and trends.

Secondly, the report aimed to provide a verification of the effectiveness of using API RP 2A for damage prediction during extreme loading. Using the probabilistic "Bayesian" approach the effectiveness of the API standard was demonstrated.

II.3.3.2.3 Recommendations

The authors recommended:

- Operators should consider diversity in their platform fleet locations so as they are not to be significantly affected by any one event;

- Operators should consider the potential cost of platform failures in their economic decision process.

API RP 2A appears to provide a suitable approach for well designed platform with adequate conservatism and should as a minimum be adopted in the design of fixed platform.

II.3.3.3 Current State of Knowledge

Hurricane Lili provided a unique opportunity to study the structural performance of offshore platforms under extreme metocean loading conditions. This has enabled a greater degree of understanding on hurricane effects of structural strength for the design of offshore platforms, and has added to the original learnings of Hurricane Andrew.

II.3.4 PROJECT NO. 591 – EVALUATE ACCURACY OF POLYESTER SUBROPE DAMAGE DETECTION PERFORMED BY ROVS FOLLOWING HURRICANES AND OTHER EVENTS

II.3.4.1 Introduction

This report was produced for the MMS by Stress Engineering Services Inc. in alliance with TTI Ltd.

II.3.4.1.1 Background

ROV inspections are used by the offshore industry to detect damage to polyester mooring systems and estimate the remaining fatigue life if damage is found. This work was to address permanently moored floating production systems, rather than Mobile Offshore Drilling Units (MODUs).

The specific objective of the work was to evaluate the accuracy of the non-invasive damage detection methods. To meet this objective, the following issues of polyester rope mooring systems were considered:

- Structural mechanics;
- Factors that reduce structural integrity;
- Qualification for service;
- Characteristics of structural damage;

- Assessment of current and new methods for determining fitness for service.

II.3.4.1.2 Technical Scope

A variety of tasks were undertaken to assess the state of the art in damage assessment for polyester rope mooring systems. Significant tasks completed during the project included:

- "20-hurricane" cyclic wear testing of subrope design;
- Assessment the effect of creep and cyclic wear on rope integrity and remaining life;
- Conducting a polyester mooring risk workshop with participants from the industry;
- Using results from the industry, assembly of a Failure Mode and Effects Analysis (FMEA) model to assist in semi-quantitative risk assessment;
- Development of concepts for non-invasive damage assessment, to improve the offshore energy industry's ability for detection and its impact on mooring system performance.

II.3.4.1.3 Study Limitations

A polyester mooring rope can contain between 10 to 70 individual subropes, dependant on the rope manufacturer and design. To date the current practice is to test single ropes. In this report multiple subropes are tested together to obtain the mechanical properties. The mooring rope performance is then derived from these subrope tests by comparison with pre-production rope break test results.

II.3.4.2 Project Conclusions

II.3.4.2.1 Key Conclusions and Results

In summary the results are:

- The only major cause of rope structural loss during a 20 year project life is thought to be third party damages, as analysis in which 20 repetitions of loads simulating equivalent loads of 20 hurricane Katrina's indicated mechanical integrity was maintained. This can only be determined by conducting *in-situ* ROV video analysis;
- Creep testing analysis of yarns, using the SIM method, in this report have shown major concerns of rope creep and cyclic wear damage to be unfounded;
- Based on risk / benefit analysis, insert recovery and testing is determined to have no benefit in reducing the risk of normal operations;

- Current detection methods of subrope damage (ROV video fly-byes) should be sufficient to detect rope jacket damage;
- A mooring rope found with jacket damage should be considered a critical inspection zone, and damaged rope segments should be replaced as soon as possible;
- A rope cycling test based on being subjected to 20 hurricanes (strength of Katrina) should be adopted as a benchmark for qualification testing of different designs and manufacture of polyester rope.

II.3.4.2.2 OSER Goals

This project evaluated accuracy of polyester subrope damage detection performed by ROVs following hurricanes and other events (i.e., loop current) that exceed the 100-year design criteria. ROV inspections are used to detect damage to polyester mooring systems and estimate remaining fatigue life if damage exists. This is inline with the OSER program goals part of which is to best assess, retain or restore the integrity of offshore energy assets.

II.3.4.2.3 Recommendations

The authors recommended;

- Only in-situ inspection of mooring ropes by ROV video can effectively discover third party damage;
- The current practice of recovery and testing of inserts in installed mooring systems should be discontinued;
- Subrope damage detection using ROV video inspection should be more utilized;
- For critical locations along the rope length, either digital video (2D or 3D) or LVDT measurements of local rope diameter are recommended to assess damages.

II.3.4.3 Current State of Knowledge

The recent MMS JIP on Full Scale Experiments on Damaged Polyester Rope [4] has shown how damaged subrope behavior affected full rope strength, while a DNV JIP on damage assessment and acceptance criteria [5] also investigated subrope behavior. Currently, API 2SM is being prepared for issue of the second edition of the Recommended Practice for Synthetic Mooring Systems.

This report outlines the latest knowledge and recommended practices as summarized by the conclusions and recommendations above.

II.4 ASSESSMENT OF OFFSHORE STRUCTURES IN HURRICANES

II.4.1 PROJECT NO. 549 – ASSESSMENT OF FIXED OFFSHORE PLATFORMS IN HURRICANES IVAN, ANDREW AND LILI

II.4.1.1 Introduction

II.4.1.1.1 Background

Hurricane Ivan (Ivan) was a major hurricane that passed through the Gulf of Mexico on September 14 and 15, 2004. It destroyed and damaged numerous offshore oil and gas platforms. This research project describes a method that used the results of Ivan to determine the current state of performance of API and MMS regulations in terms of the design of fixed offshore platforms. The project collected Ivan fixed platform damage information into a database and evaluated trends, performed a quantitative assessment that compared analytically predicted platform damage to actual observed damage, and made recommendations for suggested studies of key fixed platform design issues. The focus of the effort was on wave-induced damage to the structural systems (foundations, jacket and deck) and not on wind damage to topsides.

II.4.1.1.2 Technical Scope

This project describes the qualitative and quantitative assessment of damage and destruction incurred by hurricanes Andrew, Lili and Ivan since 1992 to 2005. The research addresses the data collection on several platforms that incurred damage or complete destruction in the US Gulf of Mexico, and assesses the API RP 2A design standard against the observed data to determine where the API RP lacked in its predictions for accurate damage assessment, and what further provisions need to be made in order to avoid or minimize destructions in future.

II.4.1.1.3 Study Limitations

The key limitations of the study are as follows:

- The research has not addressed the details of the provisions recommended to be made in API RP 2A;

- The research has not quantified the individual main structural members that can affect the performance in the hurricane season.

II.4.1.2 Project Conclusions

II.4.1.2.1 Key Conclusions and Results

The key conclusions of the study can be summarized in the following:

- The research project highlights the damaged and destroyed platforms in GOM to determine the structural causes of failures;
- The research quantifies the API RP 2A effectiveness by computing a parameter called Bias Factor for combined and individual effects of hurricanes Andrew, Lili and Ivan.
- Through quantitative assessments and data collection, the research identifies various causes of failures of the structures during the hurricanes, ranging from braces, members, secondary members, foundation piles to the top of deck.

II.4.1.2.2 OSER Goals

The research project addresses the damage incurred by hurricanes and the preventative measures that need to be observed either through design guidelines or procedures; thus, it addresses the second goal of OSER, which is related to protection of integrity of ageing subsea structures.

II.4.1.2.3 Recommendations

The recommendations of the research project are as follows:

- Investigate the minimum deck elevation curves for design of new platforms in API RP 2A;
- Investigate the possible changes to the 100 year wave height curves used in API RP 2A;
- Investigate damage to secondary structural members;
- Provide metocean instrumentation on fixed offshore platforms.

II.4.1.3 Current State of Knowledge

The research addresses the API RP 2A provisions and recommends amendments with further investigations on several design issues. Currently, this is an important starting step with qualitative and quantitative assessments for long term integrity of the structures in the events of hurricanes.

II.4.2 PROJECT NO. 551 – ASSESSMENT OF DRILLING AND WORKOVER RIG STORM SEA FASTENINGS ON OFFSHORE FLOATING PLATFORMS DURING HURRICANE IVAN

II.4.2.1 Introduction

II.4.2.1.1 Background

Drilling and workover rigs on Floating Production Systems (FPSs) are fastened to the decks of offshore structure sea fastenings to prevent movement during hurricanes. Sea fastenings include bolts, weldments, braces, or other means. During Hurricane Ivan, a number of drilling or workover rigs shifted. These movements are being assessed along with the current design philosophy and criteria for storm sea fastenings, rig and storm sea fastening installation practices, and onboard storm operational practices to ready FPSs for a hurricane. Results will provide information that can be used to assess any needs to revise tie-down criteria or practices to avoid future damage. Phase 1 is being sponsored by MMS. The objectives are to collect information on FPSs that had drilling rig movements during Ivan and complete preliminary analyses to understand the observed movements relative to existing codes and practices. A Phase 2 study is envisioned as a JIP that would complete additional and more detailed analyses of rig tie-down failures and successes, and evaluate tie-down options for preventing observed movements.

II.4.2.1.2 Technical Scope

This project describes the data collection on FPSs on Gulf of Mexico followed by analysis and calculations for determining the movements of the drilling rigs and adequacy of sea fastening devices on board. The data collection encompasses the FPSs under the operatorship of Murphy, Shell and BP. The majority of platforms studies post-damaged in this report are spars; only one is a TLP. From Murphy, Medusa and Front Runner are

studied. From BP, Holstein, Mad Dog and Horn Mountain are studied. From Shell, Brutus and Ram Powell are studied. The quantitative models for calculating the rig movements and sea fastening loads are performed in analysis report.

II.4.2.1.3 Study Limitations

The key limitations of the study are as follows:

- The research is focused on the rig movement only, and considers the loadings only due to hurricanes. It does not address any other potential causes of rig movements/ failures.
- The research does not address other components of the platforms, and thus applicable only to the drilling rigs.

II.4.2.2 Project Conclusions

II.4.2.2.1 Key Conclusions and Results

The key conclusions and results of the research project are as follows:

- The research shows that the majority of the platform rigs were intact during Hurricane Ivan;
- 100-year Hurricane design criteria was used for intact rigs;
- Skid-base structure was part of the drill package on BP Horn Mountain and Holstein spars, which featured the welded drilling rig;
- Shell had damage incurred to its Ram Powell TLP. The main reason described is that the bolts were not torque properly.

II.4.2.2.2 OSER Goals

The research project addresses the damage incurred by hurricanes and the preventative measures hat need to be observed either through design guidelines or procedures; thus, it addresses the second goal of OSER, which is related to protection of integrity of ageing subsea structures.

II.4.2.2.3 Recommendations

The recommendations of the research project are as follows:

- The project recommends redundancy wherever possible;
- The project recommends advanced and secured monitoring and measurements before the arrival of a hurricane.

II.4.2.3 Current State of Knowledge

The research addresses the API RP 2A provisions and recommends amendments with further investigations on several design issues. Currently, this is an important starting step with qualitative and quantitative assessments for long term integrity of the structures in the events of hurricanes.

II.4.3 PROJECT NO. 578 – ASSESSMENT OF FIXED OFFSHORE PLATFORM PERFORMANCE IN HURRICANES KATRINA AND RITA

II.4.3.1 Introduction

II.4.3.1.1 Background

Hurricanes Katrina and Rita passed through over approximately 3,000 platforms in the Gulf of Mexico during the fall of 2005. The need for this research is to address the reasons of why some platforms performed satisfactorily while some others failed during the hurricanes. This research sheds light on the usefulness and recommendations into API RP 2A, which is an industry-wide and accepted offshore platform structural design code.

II.4.3.1.2 Technical Scope

This project presents a comprehensive study of the performance of fixed steel jacket platforms in Katrina and Rita. Much of the work is based upon data collected from the MMS, API HEAT (Hurricane Evaluation and Assessment Team) and specific operators on how their platforms performed (survived, damaged or destroyed), the specific destruction and damage observed, and how this compared to analytical results based upon structural analysis where available.

The study also used results from metocean studies to compare the estimated wave height and wave crest conditions at some of the platform locations to what was observed at the platform. Particular focus was also applied to how and why such a large number of platforms were destroyed and damaged. Explanation regarding the strengths and

weaknesses in the design of some of the platforms is explored. The study also ties-in findings of the API HEAT work and to RP 2A design practices.

II.4.3.1.3 Study Limitations

The key limitations of the study are as follows:

- The research has not addressed the details of the provisions recommended to be made in API RP 2A;
- The research has not quantified the individual main structural members that can affect the performance in the hurricane season.

II.4.3.2 Project Conclusions

II.4.3.2.1 Key Conclusions and Results

The key conclusions and results of the research project are as follows:

- Overall findings indicate that there was no life-loss or major environmental problems as a direct result of the hurricanes. This is attributable to the prior evacuation of the platforms and to the use of sub-surface safety valves and shut-in of wells prior to the hurricane arrival;
- The fact that most of the destroyed platforms were older vintage structures of 1960s or 1970s design when there was little or no industry guidance on how to properly design a platform;
- Destruction of newer generation platforms installed in the year 2000 or later. Further study determined that these failed platforms were medium and low consequence (of failure) platforms designed to lower environmental criteria.

II.4.3.2.2 OSER Goals

The research project addresses the damage incurred by hurricanes and the preventative measures hat need to be observed either through design guidelines or procedures; thus, it addresses the second goal of OSER, which is related to protection of integrity of ageing subsea structures.

II.4.3.2.3 Recommendations

The recommendations of the research project are as follows:

- Sudden Hurricane conditions need to be updated properly in API RP 2A, since the majority of the destroyed structures were of API RP2A A-2 category, defined as medium consequences.
- Owners need to be better educated that platforms designed to L-2 and L-3 are lower cost, but are designed to lower criteria and are susceptible to damage and destruction in large storms. For example, describe limits on production rates, water depth, loadings etc.
- Platforms owners need to be better educated that a platform that passes A-2 assessment may still be destroyed or damaged in a large storm. The A-1 criterion is a better assessment target for platforms critical to the owners operation.
- Platform owners should be educated on the destruction or damage and associated potential downtime that can occur for platforms that have lower decks.
- The detailed probabilistic assessment that has been used since hurricane Andrew continues to show that RP 2A is adequate for design of fixed offshore platforms. This quantitative approach to assess the accuracy of RP 2A (through bias factor) should be continued for future large hurricanes.

II.4.3.3 Current State of Knowledge

The research addresses the API RP 2A provisions and recommends amendments with further investigations on several design issues. Currently, this is an important starting step with qualitative and quantitative assessments for long term integrity of the structures in the events of hurricanes.

II.4.4 PROJECT NO. 593 – JACKUP MODUS: ASSESSMENT CHECKSHEET FOR HURRICANE SEASON

II.4.4.1 Introduction

II.4.4.1.1 Background

The driver for this research was to investigate the safety of the Jack-up mobile offshore drilling units (MODUs). The research was driven by the need to find out the adequacy of

the current jack up structures, the statistics of failures in the past hurricanes such as Ivan, Katrina and Rita (in years 2004 and 2005), interpret the modes of failures and suggest design recommendations for future jack-up rigs.

II.4.4.1.2 Technical Scope

The research project assesses various jack-up rigs structures in the U.S. Gulf of Mexico, through on-site visits. Essentially, it is the data collection on various jack-up rig structures and the inspection of their mechanical conditions and locations post hurricanes that has been carried out and reported in the final project report. Various analytical calculations are performed to support the observed damages. The analytical calculations develop required air gaps and compare them with industry standards, specifically API 95J.

II.4.4.1.3 Study Limitations

The key limitations of the study are as follows:

- The research has not addressed the details of the provisions recommended to be made in API 95 J;
- The research has not quantified the individual main structural members that can affect the performance in the hurricane season.

II.4.4.2 Project Conclusions

II.4.4.2.1 Key Conclusions and Results

The key conclusions and results of the research project are as follows:

- The jack-up rigs that failed and drifted did not cause any damage;
- All failures in Katrina and Rita were in challenging situations, in the sense that the loads exceeded the structural capacity of the rigs;
- The main emphasis can be traced to the foundations to ensure that these are strong enough to prevent the air gap being lost.

II.4.4.2.2 OSER Goals

The research project addresses the damage incurred by hurricanes and the preventative measures hat need to be observed either through design guidelines or procedures; thus, it

addresses the second goal of OSER, which is related to protection of integrity of ageing subsea structures.

II.4.4.2.3 Recommendations

The recommendations of the research project are as follows:

- The research report recommends using a questionnaire post-installation of the jack-up rigs;
- This type of information will be helpful in determining the historic issues related to each of the structures;
- The questionnaire will help improve the maintenance and design issues. Some important questions are soil type, boring distance from location, distance from coastal facilities, leg penetration, mat penetration etc.

II.4.4.3 Current State of Knowledge

The research addresses the API 95 J provisions and recommends amendments with further investigations on several design issues. Currently, this is an important starting step with qualitative and quantitative assessments for long term integrity of the structures in the events of hurricanes.

II.5 POST-EVENT GEOTECHNICAL DAMAGE ASSESSMENT

II.5.1 PROJECT NO. 559 - OFFSHORE HURRICANE READINESS & RECOVERY CONFERENCE

II.5.1.1 Introduction

II.5.1.1.1 Background

Hurricane Ivan was an extremely intense hurricane that had a significant impact on the offshore oil and gas drilling and production activities and the infrastructure in Gulf of Mexico. A number of mobile offshore drill units (MODU), deepwater floating production systems, shallow water fixed jacket production platforms, and pipelines were affected by Ivan. It provided an opportunity for the industry and regulators to investigate learn and improve present design and operating practices, technology, regulations and standards.

II.5.1.1.2 Technical Scope

This project was to examine the impact of Hurricane Ivan on the offshore infrastructure and develop information useful in assessing the adequacy of the present design and operating practices, technology, regulations and standards:

- Examine and advance our understanding of metocean conditions for extreme storms;
- Assess the performance of the Gulf of Mexico oil and gas infrastructure (fixed and floating production systems, MODUs, and pipelines) during Hurricane Ivan; and
- Identify gaps or opportunities to improve design and operational standards to enhance the performance of the infrastructure in severe hurricanes.

The project also aimed to investigate and confirm the preparation and recovery plans for the impact of Hurricane Ivan.

II.5.1.1.3 Study Limitations

The evaluation of the impact of Hurricane Ivan on the Gulf of Mexico oil and gas infrastructure in this study was primarily based on the observations of the performance of the infrastructure. Detailed investigation on the gaps between API design and operational standards and the actual performance was not allowed due to the restrained time. All the

results associated with the assessment of adequacy of the present API design standards in this study were qualitative, rather than quantitative.

II.5.1.1.4 Method Used to Conduct the Research

A two-day 2005 Hurricane readiness and recovery conference was held to assess the metocean conditions of Hurricane Ivan and the performance of offshore infrastructure during Hurricane Ivan.

II.5.1.2 TA&R Project Conclusions

II.5.1.2.1 Key Conclusions and Results

In summary, the results of this study were:

- Hurricane Ivan was a category 3-4 storm and hindcast maximum waves were ~96 feet and winds were 92 knots. The wave conditions significantly exceeded the API RP 2A design wave height of 72 feet.
- Hurricane Ivan caused mud flows and mudslides on the seafloor near Mississippi Delta and mudslides were responsible for destroying one platform and damaging or moving a number of pipelines.
- Four MODUs went adrift due to broken mooring systems and one MODU was damaged. The damaged MODU was unable to pull its drilling riser and evacuate in advance of Ivan due to strong loop current and proximity to shallow water. The experience indicated that loop currents and proximity to shallow water features should be carefully incorporated in developing evacuation plan. The review of MODU system incidents indicated that the present design performance was understood and robust.
- For deepwater floating production systems (FPSs), drilling rigs were moved or lost on 4 FPSs and facilities on decks were damaged on 10 FPSs. However, the hulls, moorings, and risers of the FPSs were not damaged significantly, validating the hull, mooring, and riser design technology.
- A total of 7 shallow water fixed platforms were destroyed, including one toppled by a mudslide and six damaged by the environmental loads exceeding the design criteria. The facilities on decks were damaged on 31 jackets. The majority of failed and significantly damaged platforms were older platforms deigned to earlier standards with lower environmental criteria. However, no significant damage was observed in the newer

platforms with present-day designs. It illustrates the improvements in the present design practices and codes.

- More than 150 pipelines were damaged due to mudslides, anchor dragging from drifting MODU, and bottom currents. Most of pipelines damaged were smaller lines with diameter less than 12 inches and most of the damages were concentrated in the Mississippi Delta.

II.5.1.2.2 OSER Goals

The main goal of this project aimed to assess the performance of the Gulf of Mexico oil and gas infrastructure (MODUs, fixed and floating production systems, and pipelines during Hurricane Ivan and to evaluate the present design and operational standards, practices, and technology to identify needs and opportunities for improvement.

II.5.1.2.3 Recommendations

Since the wave height, wave loads and wind loads of Hurricane Ivan had significantly exceeded the API design value with a 100-year return period, the study recommended that there might have a need to re-consider the API 100-year design value. Based on the investigation on the MODU damage, the study recommended that the hurricane evacuation plans should take loop currents and proximity to shallow water features into the consideration and reflect present and forecast loop currents as the hurricane approaches.

II.5.1.3 Current State of Knowledge

The extreme storms impacted the Gulf of Mexico more and more frequently in recent years, which included Hurricane Ivan, Katrina, Rita, and Ike. The performance of offshore oil and gas infrastructure system under such extreme storms has brought increased public concern considering the importance of the Gulf of Mexico production and its impact on the nation's economy. The investigation of the performance of offshore infrastructure system under such extreme storms has advanced our understanding of design and operating practices, technology, and standards and identified the needs and opportunities for improvements.

A recent geotechnical engineering research work was carried out by Dr. Gilbert et al. in Univ. of Texas at Austin to evaluate the performance of fixed platform foundation system under the impact of Hurricane Ike. The results revealed that the present API RP 2A design

codes were reasonable without conservatism, which was opposed to the initial speculation on the conservatism of API RP 2A codes by some geotechnical engineers and researchers.

II.5.2 PROJECT NO. 552 - MUDSLIDES DURING HURRICANE IVAN AND AN ASSESSMENT OF THE POTENTIAL FOR FUTURE MUDSLIDES IN THE GULF OF MEXICO

II.5.2.1 Introduction

II.5.2.1.1 Background

Submarine mudslides can be triggered by significant wave-induced pressures on the ocean floor in shallow water (up to about 400 ft) during large hurricanes in the Mississippi Delta region of the Gulf of Mexico. Based on the observation of mudslides caused by Hurricane Camille in 1969, a number research was devoted to developing model to predict the mudslides. The mudslide activities caused by Hurricanes Ivan and Katrina has been reported in the Mississippi Delta that provided a good opportunity to evaluate the existing models to predict mudslides and to re-examine the Mississippi Delta region that are expected to be vulnerable to mudslides. A methodology to assess the potential risks of future mudslides in this region needed be developed based on the investigation and analyses of these mudslide activities.

II.5.2.1.2 Technical Scope

This project aimed to investigate the potential risks of future mudslides in the Mississippi Delta region of the Gulf of Mexico by analyzing the mudslides activities during Hurricanes Ivan and Katrina. The tasks for this project were to:

- Collect the site data associated with mudslide activities caused by Hurricanes Ivan and Katrina, including bathymetric data, soil properties, and oceanographic data;
- Validate the existing limit equilibrium model to predict the mudslide initiation in comparison with the results from other analysis methods and the reported occurrences of mudslides; and
- Perform probabilistic analyses to investigate the mudslide vulnerability of the Mississippi Delta region and present return periods for mudslide occurring and mudslides impacting subsea infrastructure in a particular area based on the probabilistic analysis results.

II.5.2.1.3 Study Limitations

A lack of available undrained shear strength data (only 21 profiles available throughout the Mississippi Delta region) limited the site-specific analysis, and compromised reliability of the probabilistic analyses in which only these 21 profiles were taken to represent a random sample in the whole Mississippi Delta region.

Linear wave theory, which was used to estimate the bottom pressures induced by storm wave on the ocean floor in this study, has been determined to overestimate the bottom pressures. An empirical correlation between bottom pressures calculated from linear wave theory and those obtained from irregular wave prediction program was employed to correct the overestimation from the linear wave theory.

Investigation revealed that Hurricanes Ivan and Katrina might have caused other mudslides in the Mississippi Delta area that were not reported, which might make less validated the results from mudslide vulnerability analyses.

II.5.2.1.4 Method Used to Conduct the Research

Limit equilibrium model was used to predict the mudslide initiation. Probabilistic analyses were employed to evaluate the risks of mudslide occurring and of mudslides impacting facilities.

II.5.2.2 Project Conclusions

II.5.2.2.1 Key Conclusions and Results

In summary, the results were:

- Wave-induced mudslides are infrequent events, as they occur only in the mudslide prone area in the Mississippi Delta, and only few large hurricanes caused significant mudslide activities in past decades.
- A simple limit equilibrium model used in this study was verified to work well on the prediction of factor of safety against mudslide initiation.
- Bottom pressures calculated from linear wave theory needed be reduced by about 34% based on the correlation with the results from irregular wave simulation program.
- Wave-induced mudslides are localized features, on the order of several thousand feet long by hundreds of feet across by tens of feet deep with relation to the lengths and

widths of the storm wave that causes them. The mudslides do not likely lead to large-scale, regional mudflows due to the very flat slope in the mudslide prone area and the localized spatial variation in soil strength.

- The factor of safety against mudslide initiation decreases as the wave height increases, the water depth decreases, the slope angle of the seafloor increases, and the wave period increases.
- The return periods for mudslides impacting facilities range from less than 10 years to greater than 1,000 years and depend strongly on locations. The risk for mudslides impacting pipelines increases as the water depth decreases, the slope angle of the seafloor increases, and the amount of infrastructure in a particular area increases.

II.5.2.2.2 OSER Goals

The main goal of this project was to use information obtained from recent hurricanes to investigate wave-induced mudslide activity in the Mississippi Delta region of the Gulf of Mexico. The bathymetric data, soil strength data, and metocean data associated with the reported wave-induced mudslides were analyzed by using a simple limit equilibrium model. The analysis results from the limit equilibrium model were incorporated into the framework of probabilistic analyses to estimate the risks of future mudslide occurring in a particular area.

II.5.2.2.3 Recommendations

The study recommended that a comprehensive shear strength database should be compiled and would be extremely useful for future studies of mudslide vulnerability. It was suggested by this study that a more accurate way to calculate bottom pressures using peak wave data than the linear wave theory should be developed. The study also recommended that the risk analyses of mudslide vulnerability in this project should be updated with more information about waves and soil properties, and should be adapted for site-specific analysis by incorporating all available site-specific bathymetry, metocean and soil strength data.

II.5.2.3 Current State of Knowledge

A conference of "The 4th International Symposium on Submarine Mass Movements and Their Consequences" was recently hosted in Austin, Texas on November, 2009 in which the broad issues of submarine mass movements were addressed, including the topics of 1)

trigger mechanics and geotechnical properties; 2) case studies and hazard assessment; 3) margin construction and economic significance; and 4) tsunami genesis from submarine mass movements. It was found that, in addition to the mudslides induced by storm wave generating high pressure on the ocean floor, the mudslides could be triggered by the mechanism of ground acceleration due to earthquakes, increase loads due to construction, and elevated pore pressure related to gas accumulation from dissociation of gas hydrates. It was also recognized that the pre-failure conditions and the mechanics of mudslides during failure were rarely known, but numerical modeling and flume experiments could provide insightful information to these important issues.

II.6 POST-EVENT PIPELINE DAMAGE ASSESSMENT

II.6.1 PROJECT NO. 581 - PIPELINE DAMAGE ASSESSMENT FROM HURRICANE KATRINA/RITA

II.6.1.1 Introduction

II.6.1.1.1 Background

The Offshore Federal Oil & Gas infrastructure includes over 33, 000 miles of pipeline that provides the means to service and transport approximately 30% of US domestically produced oil and gas from offshore wells to onshore refineries. As the U.S. grows increasingly dependent on the steady supply of energy from offshore oil and gas reserves, MMS remains attentive to the destructive forces of hurricanes and the extensive challenges to protect pipelines in advance of and to re-start pipeline production following these catastrophic natural events.

This project was launched to analyze damage assessment reports from operators in order to determine the type, cause and extent of pipeline damage incurred during Hurricanes Katrina and Rita, and to provide guidance for improving pipeline integrity/design to reduce potential damage from future GOM hurricanes.

2005 Atlantic hurricane season was the most active in recorded history. Category-5 hurricanes, Hurricane Katrina and Hurricane Rita, in August and September 2005, respectively, moved through the U.S. Gulf of Mexico (GOM) with extreme winds and waves exceeding the 100-year storm design criteria of offshore facilities in the storm path. The Minerals Management Service (MMS) received 542 industry damage assessment reports identifying damage to the offshore pipeline infrastructure during 2005, compared to 168 reports received in the previous year. There was a need to analyze damage assessment reports in order to determine the type, cause and extent of pipeline damage incurred during Hurricanes Katrina and Rita, and to provide guidance for improving pipeline integrity/design to reduce potential damage from future GOM hurricanes.

II.6.1.1.2 Technical Scope

The scope of work involves the following main tasks:

- Investigation of the GOM pipeline infrastructure damage caused by Hurricanes Katrina and Rita. Identification and management of root causes of key areas of damage are a focus.
- Investigation of current design, operations, maintenance and hurricane preparedness and response practices by Gulf of Mexico pipeline operators.
- Collection of damage assessment results and evaluation through technical and graphical analyses in order to create recommendations that identifies best practices and potential changes to codes to better protect pipelines during subsequent major hurricane events.

II.6.1.1.3 Study Limitations

The following have affected the progress of the study and verification of its effectiveness:

- The ability to determine the actual root cause of the failures is limited by the incomplete data that available about the pipeline's in-situ condition and the actual sequence of events that occurred during the hurricane with respect to failure or loadings imposed by movement of interconnected facilities at platforms and tie-ins.
- Prior to the 2006 hurricane season industry actions were prompt to address remedial actions for the increased damages from drilling rigs that lost stationkeeping. The 2006 hurricane season produced no hurricane events in the GOM, so the testing of these recommended practices will not occur until another hurricane season produces storms reaching the intensity of the hurricane events experienced in the GOM during the 2004 and 2005 hurricane seasons.

II.6.1.2 Project Conclusions

Study report concluded that in general at that time offshore pipe design approaches in GOM and the industry practices related to human and environmental safety were satisfactory. Major negative impact of Hurricanes Katrina and Rita was the disruption in oil and gas production due to pipeline and infrastructure damage. Majority of pipeline failures were near platforms and in mudflow areas, similar to previous observations. Increased number of instances where pipeline damage resulted by drill rings that lost stationkeeping had been a characteristic related to these two hurricanes. Study has recommended knowledge sharing and further specialized studies related to the identified dominant causes of failure.

II.6.1.2.1 Key Conclusions and Results

542 failure reports from the operators have been evaluated in this study. The following are among the key findings of the project:

- Vast majority of GOM offshore pipelines performed well during the passage of Hurricanes Katrina and Rita.
- Public and personnel safety experience has been excellent during Hurricanes Katrina and Rita. Evacuations of non-essential personnel, and other operational precautions taken prior to hurricane events, including training, planning, spill response exercises, and industry alliances provided results that have protected life as the first priority.
- The impact to the environment has been minimal in hurricane events, primarily due to the design features, and similar industry practices intended for protection of life that are also focused on minimizing releases to the environment through planning, preparedness and response.
- The most significant impacts of Hurricanes Katrina and Rita appear to have been disruption of the oil and gas supply, and financial losses from the oil and gas infrastructure damage.
- The majority of pipeline damages due to two hurricanes occurred at or near platform interfaces, in areas of mudflows, or as a result of impact by an outside force other than the hurricane, such as platform failure or anchor dragging. The remaining pipeline damages were primarily due to loss of cover and movement of pipelines that are near shore and in shallow water.
- There was an increased amount of pipeline damages from drilling rigs that lost stationkeeping during the two storm events that were studied than has been experienced during other historical events that have been studied.
- Graphical internet-based mapping tools can enhance operator reporting and assist the MMS assessments of hurricane impacted areas, development of NTLs that are technically based, and enable the MMS to have the ability to easily perform visual data management of the data contained in the MMS GIS.

II.6.1.2.2 OSER Goals

This study provides an independent assessment of the existing subsea pipeline design for 100year return conditions in GOM, and post-hurricane recovery strategies.

II.6.1.2.3 Recommendations

- It is recommended to support the finalization of the efforts that have been initiated for the development of interim guidance on stationkeeping and platform design revisions to reduce damages to pipelines. Cross functional teams shall be considered to facilitate sharing of pipeline and structure damage experiences in the offshore energy industry and within the regulatory organizations.
- To expand the audience that receives the lessons learned from the valuable exchange of information and experience, it is recommended establishing contacts with non API members that do not participate in the Hurricane Readiness and Recovery conferences and study groups.
- Position data from rigs that lose stationkeeping during hurricane events shall be shared to notify pipeline operators where inspections are needed for potential impact to pipelines and risers.
- It is recommended initiating a cooperative study with industry to identify pipelines that fit the profile similar to those that were displaced as a result of the passage of Hurricanes Katrina and Rita to identify potential corrective actions or preventive measures related to on bottom stability and exposed pipelines in the shallow water region in the vicinity of the Mississippi River Delta.
- A visual user interface shall be developed for the damage database that allows the Pipeline Section engineers to visually analyze and query data for damage assessments, and NTLs shall be developed in response to hurricanes.
- It is recommended emphasizing the importance of maintenance practices at risers and platform pipeline interfaces to operators via an NTL, or other method of industry outreach.
- It is recommend identification of critical segments of the pipeline infrastructure for prioritization of restoration of service when competing interests are vying for resources.
- It is recommended continuing of the industry and regulatory oversight practices related to planning, response and recovery to achieve the same good results.

II.6.1.3 Current State of Knowledge

When analyzing the impact of Hurricanes Katrina and Rita, similar former TA&R projects on Hurricanes Andrew, Lili (Project No. 503) and Ivan (Project No. 553) are referred to.

II.6.2 PROJECT NO. 553 - PIPELINE DAMAGE ASSESSMENT FROM HURRICANE IVAN

II.6.2.1 Introduction

II.6.2.1.1 Background

This project was launched to analyze damage assessment reports from operators in order to determine the type, cause and extent of pipeline damage incurred during Hurricane Ivan, and to provide guidance for improving pipeline integrity/design to reduce potential damage from future GOM hurricanes.

In September 2004, a category-4 hurricane, Hurricane Ivan, moved through the U.S. Gulf of Mexico (GOM) with extreme winds and waves exceeding the 100-year storm design criteria of offshore facilities in the storm path. Approximately 10,000 miles of pipelines were in the direct path of Hurricane Ivan. The Minerals Management Service (MMS) received industry damage assessment reports identifying damage to the offshore pipeline infrastructure. There was a need to analyze damage assessment reports in order to determine the type, cause and extent of pipeline damage incurred during Hurricane Ivan, and to provide guidance for improving pipeline integrity/design to reduce potential damage from future GOM hurricanes.

II.6.2.1.2 Technical Scope

The scope of work involves the following main tasks:

- Investigation of the GOM pipeline infrastructure damage caused by Hurricane Ivan. Identification and management of root causes of key areas of damage are a focus.
- Investigation of current design, operations, maintenance and hurricane preparedness and response practices by Gulf of Mexico pipeline operators
- Investigate both new and proven techniques and technologies which may help mitigate pipeline damage.
- Collection of damage assessment results, and evaluation through technical and graphical analyses in order to create recommendations that identify best practices and potential changes to codes to better protect pipelines during subsequent major hurricane events.

II.6.2.1.3 Study Limitations

The ability to determine the actual root cause of the failures is limited by the incomplete data available about the pipeline's in-situ condition and the actual sequence of events that occurred during the hurricane with respect to failure or loadings imposed by movement of interconnected facilities at platforms and tie-ins.

II.6.2.2 Project Conclusions

Study report concluded that in general at that time offshore pipe design approaches in GOM and the industry practices related to human and environmental safety were satisfactory. Major negative impact of Hurricane Ivan was the disruption in oil and gas production due to pipeline and infrastructure damage. Majority of pipeline failures were near platforms and in mudflow areas. Localized failures at pipeline crossings and excessive movements in shallow water depths had been resulted due to Hurricane Ivan.

Study has recommended careful evaluation of shallow water pipelines in mudflow areas, development of specific criteria for pipeline damage surveys to focus on the most likely undetected damage, definition of a formal process to identify and prioritize critical energy infrastructure repairs, permitting and approvals, and utilization of an efficient web-based visual data management tool to support post-hurricane rehabilitation activities.

II.6.2.2.1 Key Conclusions and Results

Available failure reports and offshore energy industry practices have been evaluated in this study. The following are among the key findings of the project:

- Vast majority of GOM offshore pipelines performed well during the passage of Hurricane Ivan.
- Public and personnel safety experience has been excellent during Hurricane Ivan. Evacuations of non-essential personnel, and other operational precautions taken prior to hurricane events, including training, planning, spill response exercises, and industry alliances provided results that have protected life as the first priority.
- The impact to the environment has been minimal in hurricane events, primarily due to the design features, and similar industry practices intended for protection of life that are also focused on minimizing releases to the environment through planning, preparedness and response.

- The most significant impacts of Hurricane Ivan appear to have been disruption of the oil and gas supply, and financial losses from the oil and gas infrastructure damage.
- The majority of pipeline damages due to Hurricane Ivan occurred at or near platform interfaces, in areas of mudflows, or as a result of impact by an outside force other than the hurricane, such as platform failure or anchor dragging.
- Localized failures at pipeline crossings and excessive movements in shallow water depths suggest that more hurricane resistant design considerations might be needed, but they appear to be site specific, and do not warrant industry wide design code revisions.
- The continued occurrences of excessive pipeline movement in shallow waters does indicate a need to evaluate the assumptions associated with burial, cover and stability analyses that may be performed for these pipelines.
- Significant numbers of the pipeline damages occurred outside of the path identified in the Hurricane Ivan NTLs.

Simple, cost effective, yet powerful mapping tools have been developed as part of this study. These geospatial tools can support the continued analyses by MMS and enhance the automation of the pipeline damage reporting without cost or specialized software acquisition by pipeline operators.

II.6.2.2.2 OSER Goals

This study provides an independent assessment of the existing subsea pipeline design for 100year return conditions in GOM.

II.6.2.2.3 Recommendations

- It is recommended that MMS provide guidance to pipeline operators and encourage them to develop integrity assessment plans in advance of hurricanes, particularly for those pipelines that are critical energy infrastructure and without alternate routes to production.
- It is recommended that the assumptions used in the design of pipelines for water depths less than 200feet may need to be carefully evaluated in mud flow areas. Special focus shall be on pipeline crossing, on-bottom stability and burial. Risk zone maps of mudflow areas can be created for use with a risk-based approach to the design and oversight of pipelines in mudflow areas.

- The criterion for post-hurricane damage surveys are typically tied to wind speeds, and while this is appropriate for surface structures, it appears that better criteria for pipelines may be based upon reverse current areas that result from the hurricane passage, and water depths. Development of specific criteria for pipeline damage surveys are recommended to focus on the most likely undetected damage (excessive movement without failure), and minimize the drain on already over-utilized recovery and inspection resources.
- It is recommended to evaluate whether a formal process should be defined to identify and prioritize critical energy infrastructure repairs, permitting and approvals. It should be evaluated if any relaxation of MMS permit or regulatory requirements is warranted, and if so – through what mechanism, for expedited return to service of pipelines, without compromising safety or environmental protection.
- It is recommended that graphical tools and mapping can be used to provide improved data management for quicker assessments of hurricane impacted areas, development of NTLs that are technically based, and visual data management. The identification of the critical data, and reporting through a web-based automated process would benefit both the offshore energy industry and MMS in the information management related to pipeline damage reporting.

II.6.2.3 Current State of Knowledge

When analyzing the impact of Hurricane Ivan, similar former TA&R projects on Hurricanes Andrew and Lili (Project No. 503) are referred to.

II.6.3 PROJECT NO. 503 - EVALUATE AND COMPARE HURRICANE-INDUCED DAMAGE TO OFFSHORE PIPELINES FOR HURRICANE LILI

II.6.3.1 Introduction

II.6.3.1.1 Background

This project was launched to analyze damage assessment reports from operators in order to determine the type, cause and extent of pipeline damage incurred during Hurricane Lili, and to provide guidance for improving pipeline integrity/design to reduce potential damage from future GOM hurricanes.

In September 2002 Hurricane Lili swept across GOM. It was a category 4 in the open gulf, but diminished to category 2 at landfall. The Minerals Management Service (MMS) received industry damage assessment reports identifying damage to the offshore pipeline infrastructure. There was a need to analyze damage assessment reports in order to determine the type, cause and extent of pipeline damage incurred during Hurricane Lili, and to provide guidance for improving pipeline integrity/design to reduce potential damage from future GOM hurricanes.

II.6.3.1.2 Technical Scope

The scope of work involves the following main tasks:

- Investigation of pipeline failures resulting from Hurricane Lili, including flowlines, major trunk lines and platform risers from both fixed and floating production facilities;
- Comparing and contrasting these failures with those reported from Hurricane Andrew;
- Making specific recommendations for changes in design or operations guidelines that might prevent or mitigate such failures in the future;
- Suggesting cost-effective methods for making existing pipelines designed by older guidelines less likely to fail in the future.

II.6.3.1.3 Study Limitations

The following have posed difficulties during the study:

- It was not possible to learn much about detailed riser design for these mostly-older platforms. Discussions with owner/operators were made difficult because of asset sales and personnel change.
- The marine growth that coated the risers made diver or ROV inspection of the riser difficult. Remediation of existing riser systems was made difficult because marine growth covered any evidence of riser damage.

II.6.3.2 Project Conclusions

The study showed that pipeline damages due hurricane Lili was less compared to Hurricane Andrew, because Hurricane Lili diminished to category 2 at landfall. Small diameter risers in five location groups in shallow waters experience significantly increased damage during Hurricane Lili mainly due the bending fatigue. As a part of the study clamp spacings were

recommend to address both cyclic wave force fatigue as well as oscillatory Vortex Induced Vibration (VIV) considerations. Redundant diver-installed back-up clamps were recommended to be added in addition to the original clamp to provide a secondary defense to clamp failure.

II.6.3.2.1 Key Conclusions and Results

In summary, the results are:

- A category 4 hurricane, Andrew (1992) caused 490 pipeline damages, whereas Lili caused damage to 120 pipelines as it diminished from category 4 to category 2 at landfall in the open gulf.
- While the damage due to Lili affected all ages of pipelines equally, the small-diameter risers of five location groups in shallow water (less than 200feet deep) experienced the most of the failures.
- Of the 78 incidents involving risers, data revealed that for 52 of the incidents the cause of damage was in the riser pipe (i.e. related to riser spacing) and for 11 of the incidents the cause of damage was in the clamps.
- Riser failures do not cause major spills because the lines are shut in (but probably not de-pressurized) during a storm event. It appears that the owners/operators are generally reactive (not proactive) unless forced otherwise. They shut in the system before the hurricane, turn it back on after the hurricane and then see what repairs are needed.
- The most critical failures were due to riser bending fatigue due to clamp spacing being too long, vibration of the riser due to oscillatory VIV and loose clamps, and pull-away at the riser base due to unstable on-bottom pipeline segments joining the riser. Smaller-diameter risers are vulnerable to failure not being able to span longer distances.
- Analysis methods were assembled to determine the recommended maximum clamp spacing for riser design based on both cyclic wave force fatigue as well as oscillatory Vortex Induced Vibration (VIV) considerations. Design recommendations are provided for riser/clamp spacing design, cathodic protection design/maintenance and bolted clamp design.
- Recommendations are made to design strategies to address failure in risers.

II.6.3.2.2 OSER Goals

This study provides an independent assessment of the existing subsea pipeline design for 100year return conditions in GOM. It discusses ways to improve existing risers.

II.6.3.2.3 Recommendations

The authors recommended:

- Simple questions can be raised when collecting pipe failure data by MMS for more specific root cause determination.
- Design recommendations to avoid such damage as experienced are to recognize that small-diameter riser failure is a major cause of pipeline riser failure (for Lili and Andrew), and that prudent analysis of the riser and clamp design must be undertaken to result in a more robust riser system. Additionally, Maintenance must be performed throughout the riser, and cathodic protection design must be more intentional to avoid corrosion problems, and clamp must be engineered to ensure length of bolt in tension is adequate to ensure clamp relaxation. Finally the special case of clamped risers near the seafloor must be analyzed to provide maximum tolerance for on-bottom pipe movements in storms.
- A simple check can be made by owner/operators to compare/contrast their as-built clamp spacings with the recommendations of this study. Redundant diver-installed back-up clamps can be added in addition to the original clamp to provide a secondary defense to clamp failure. If the current riser spacing is larger than advised in this report, intermediate clamps could be added (near the splash zone where wave forces are greatest)
- There is a difficult issue over reactive and proactive remediation of risers. Inspection of risers is made difficult by marine growth and by not knowing the extent of corrosion. The most prudent approach to reduce the number of failures due to hurricane would be to discover weak or under-designed risers (including small-diameter), riser/clamp systems before the next hurricane hits, rather than counting the failures after the incident. Perhaps a simple in-situ riser integrity test method could be developed to discover and replace weak risers before the storms come.
- These findings should be used as input to future recommended practices (RP) directed toward improving offshore pipeline reliability. If the pipeline reliability issue cannot be added to existing API or ASTM recommended practices, perhaps a new RP is needed.

II.6.3.3 Current State of Knowledge

When analyzing the impact of Hurricane Lili, similar former TA&R project on Hurricane Andrew is referred to. Offshore pipeline and subsea structure design guidelines are addressed and improvements are suggested to.

II.7 REFERENCES

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