NATIONAL ENERGY TECHNOLOGY LABORATORY

Research Portfolio Report

Ultra-Deepwater: Surface Systems and Umbilicals (Wellbore Stability)

U.S. DEPARTMENT OF ENERGY

Research Portfolio Report

Ultra-Deepwater:
Surface Systems and Umbilicals (Wellbore Stability)

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The project data, photos, and graphics provided in the project summaries that follow the introduction come from available project documentation—including final reports, fact sheets, NETL project summaries, RPSEA monthly reports, and project websites—and through the generous assistance of Principal Investigators, industry partners, RPSEA, and NETL staff.

Image caption: *Polyester mooring ropes testing apparatus at Stress Engineering Services Test Facility.*

Executive Summary

The Energy Policy Act of 2005 called for an Ultra-Deepwater (UDW) and Unconventional Oil and Natural Gas R&D program that also included a focus on helping small oil and gas producers. The UDW portion of the research was initially focused mainly on the production challenges as producers continued to develop resources in water depths in excess of 10,000 feet. This portfolio focus was changed to one of safety and environmental sustainability following the April 20, 2010, blowout on The Deepwater Horizon, Transocean's drilling platform on British Petroleum's (BP's) Macondo development, which killed 11 workers.

DOE creates and supports partnerships that drive the development of new ultra-deepwater technologies, data sets, and methodologies.

Results from the many committee meetings and hearings that followed Macondo reinforced the idea that better technologies will be required to enhance risk reduction in both operations and facilities in the UDW environment. Since many of the facilities in UDW include subsea systems that will operate autonomously on the ocean floor, a separate focus on the reliability of the components within these complex production systems was included. An additional concern was uncertainty regarding the potential to drill into geologic hazards, which remains very high for all exploratory drilling. The term "wellbore stability" was added to surface systems in recognition that the wellbore in UDW now included an engineered system from the ocean floor, supported by the drilling platform, which undergoes continual stresses and corrosion during drilling. In order to ensure wellbore integrity throughout the well, analysis of cumulative fatigue in that system must be accounted for in design and maintenance.

UDW (i.e., 5000 or more feet of water depth) is one of the areas of the world where potentially significant oil and natural gas resources remain to be discovered and produced. Producing systems employed to extract oil and gas from UDW areas include floating facilities (surface systems) as well as subsea trees, other subsea production equipment, and the flowline and power components that connect elements on the seafloor (umbilicals) and connect the seafloor assemblage with the surface facility (risers). The Surface Systems and Umbilicals (Wellbore Stability) research area supports research into improved safety and performance of all of these system components.

The overarching goal of the UDW R&D portfolio is to "ensure that the understanding of the risks associated with ultra-deep-

water operations and associated mitigation methods keep pace with the technologies that industry has developed to tap reserves in increasingly challenging conditions." Because of the potential for environmental impacts to marine life and coastal communities, UDW research must develop inherently safer surface and subsurface designs to reduce the risks of accessing UDW oil and natural gas resources, while expanding the capabilities of facilities and other equipment. Specific to these challenges is the need for enhanced topsides facilities, improved hulls, stronger moorings and risers; advanced subsurface tools and monitoring equipment; improved modeling tools for safer vessel designs from explosion hazards and violent sea events; as well as the development of "next generation" metocean and meteorological predictive techniques— all with the goal of reducing or eliminating risks and uncertainties and increasing the likelihood of seamless operation under a wide range of environmental conditions.

DOE's National Energy Technology Laboratory (NETL), RPSEA, and industry and academic partners continue to carry out research into technologies that can reduce the chances of environmental impacts from ultra-deepwater production activities. This effort includes research funded through Section 999 of the Energy Policy Act of 2005 (Section 999) which directed royalties be used to fund an oil and natural gas R&D effort, the Ultra-Deepwater and Unconventional Natural Gas and Other Petroleum Resources Research Program. This program was designed to focus on technology challenges in three areas: ultra-deepwater production, challenges commonly faced by small producers, and challenges related to "unconventional natural gas and other petroleum resource exploration and production technology." A key part of this program has been developing technologies to reduce or mitigate environmental impacts associated with production in all three areas.

Surface systems and umbilicals (wellbore stability) research carried out by the Department of Energy (DOE) over the past decade has accomplished some significant results that are enhancing our ability to advance ultra-deepwater (UDW) oil and gas development. Among the many accomplishments highlighted in the following pages are examples of how DOE, RPSEA, industry, and academia partnered and:

- Developed new hurricane and climate variability models that may drive improvements to surface system designs, decrease risk to surface systems, and improve planning for severe weather;
- Studied seafloor stresses that impact mooring rope integrity with the goal of improving mooring rope performance;
- Developed new designs for flexible composite risers and tested the designs for strength and ease of deployment;
- Developed new structural health monitoring techniques for deepwater risers to track damage due to vibration and fatigue;
- Built prototypes of two different UDW flexible composite riser designs that may prove easier to deploy; and
- Created system requirements for a real-time, telemetry-based marine Riser Lifecycle Management System (RLMS): a system of hardware and software tools comprised of sensors located on riser joints, a wireless subsea communication system for linking a surface vessel with instrumented risers, and software for data collection, processing, riser fatigue analysis, visualization and operator alerts. A commercially-viable RLMS has the potential to reduce the likelihood of riser failure events, thereby enhancing safety and reducing the risk of environmental damage.

Introduction

One goal of the UDW program is to improve the reliability of conditionally-accessible systems located on the ocean floor, up to 2-¼ miles beneath the surface of and 100-plus miles from the nearest service/control vessel. This research focuses on improving risk management, increasing safety, advancing new surface systems components and connecting umbilicals, and developing new inspection platforms, sensors, models, tools, and techniques that improve subsea measurement and system assessment capabilities.

The research projects within the UDW portfolio have been categorized into "bins" of projects that are focused on a common topic. This Research Portfolio Report provides a snapshot of results and accomplishments to-date for active and completed projects in the UDW portfolio that are grouped into the Surface Systems and Umbilicals (Wellbore Stability) bin. The first section of this report provides an overview of the bin. Project summaries that include the objective, research conducted, results, and other pertinent information for each of the projects are provided in the pages that follow.

What is surface systems and umbilicals (wellbore stability) research?

The surface systems and umbilicals (wellbore stability) research area recognizes that, for offshore wells, the borehole (in the form of a drilling/production riser) is now exposed to corrosion and unknown subsea current loads as it rises as much as 10,000 feet or more above the ocean bottom; and both the riser and all control umbilicals essential to well control are supported by the surface facilities. Conventional ultra-high strength steel systems used to support such loads are at their design limits and much more subject to failure due to corrosion and fatigue. In addition to known loads, recent metocean studies have made it apparent

that everyone is still learning about subsea phenomena (such as loop current vortices) that have the potential to materially impact these systems and offshore operations in general.

The major areas of focus in this Ultra-Deepwater research bin include:

- More stable platform designs
- Inherently safer topsides designs resulting from computational fluid dynamics (CFD) analyses of explosive force mitigation potential
- Ignition source design impact studies
- Improved metocean 100-year design criteria
- Improved loop current design criteria
- Lighter/stronger riser materials
- Riser inspection technologies and standards/best practices

Why conduct this research?

Surface Systems and Umbilicals (Wellbore Stability) research provides the tools and methodologies that the offshore industry can use to develop better floating facilities, risers, and controls to safely and effectively produce oil and natural gas resources in UDW Gulf of Mexico and Arctic environments.

Furthermore, the predictive tools created through the projects in this research portfolio will assist the industry and others in avoiding potential catastrophes, whether related to nature's forces or engineering design and construction flaws. DOE creates and supports partnerships that drive the development of new technologies, data sets, and methodologies; coordinates complementary research; and encourages the transfer of technologies for commercialization.

Accomplishments

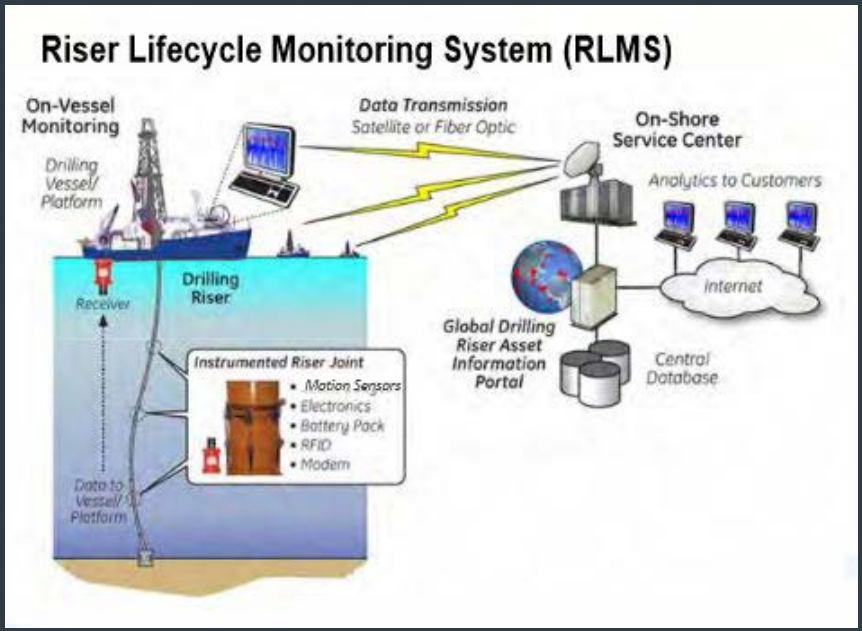
Accomplishments from surface systems and umbilicals (wellbore stability) projects include novel technologies and the results of analysis using predictive models that provide valuable

Integrity Management of Risers to Support Deepwater Drilling and Production Operations

The objective of this project was to develop a reliable and commercially-viable solution for a real-time, telemetry-based marine riser lifecycle management system (RLMS).

At the completion of this project, it is anticipated that industry will carry the research to a commercialization stage (TRL5-6). A commercially-viable RLMS has the potential to reduce the likelihood of riser failure events, thereby enhancing safety and reducing the risk of environmental damage.

Additional details about this project are available on **p. 36.**



contributions to industry understanding. Some of the projects in the Surface Systems and Umbilicals (Wellbore Stability) bin are already completed; therefore, the project deliverables have already been submitted.

The following selected examples of accomplishments recorded by these research projects illustrate how they are influencing UDW producing system development:

- ***State-of-the-art hurricane modeling*** –Applied Research Associates, Inc. is mapping Gulf of Mexico hurricane risk—as expressed by n-year wind speeds—to offshore and coastal locations for current and future climate scenarios. This risk model will provide a more reliable means of assessing the risk associated with rare events than standard hind-cast techniques. This research supports the Bureau of Safety and Environmental Enforcement (BSEE) development of standards-based design parameters for extreme winds, waves, current, and water levels at an acceptable level of risk. These design standards will in turn be applied by all manufacturers of offshore structures to ensure safe operation and human survival.
- ***New concepts for very large floating systems*** – Det Norske Veritas is evaluating design concepts for very large floating systems suitable for production in up to 10,000-foot waters using conventional dry trees. These alternative designs for deepwater platforms could lead to lower costs and improved safety.
- ***New study of fiber rope integrity*** – Stress Engineering studied the effects of repeated seabed contact on fiber mooring rope, including the degree to which the cyclic-wear process reduces the strength of fiber ropes. This research could lead to qualifying mooring rope for pre-installation on the seabed. Pre-installed rope could greatly reduce risk by reducing the time required to hook up mooring lines to a floating facility, thus reducing the time required for safe mooring before severe weather arrives.
- ***Climate variability impact study*** –University Corporation for Atmospheric Research is conducting a follow-on study to RPSEA Project 07121-1801 on the effects of climate variability and change on hurricane activity in the North Atlantic. This project is quantifying future changes in the frequency, duration, and intensity of Gulf storms and hurricane impacts using a combination of theoretical, statistical, and enhanced dynamical modeling. Hind-cast tests conducted through this project have been able to predict 7 days out where a hurricane will come ashore within 25 kilometers. An assessment of the potential future increase in the number of intense hurricanes will inform the structural design process and lead to improved operating procedures and reduced environmental and safety risks.

Development of Advanced Computational Fluid Dynamics (CFD) Tools

Predicting how fires or explosions may expand and designing topside structures to withstand these maximum credible events (MCE) are essential for risk management, safer designs, and protecting human life.

The objective of this project is to develop CFD tools for the enhanced prediction of explosion pressure development in early project phase and deflagration to detonation transition risk on US Gulf of Mexico drilling and production facilities. This project will develop a reliable tool that will predict how a fire or minor explosion can grow, how fast and into what parts of a vessel that might be essential to human safety.

Additional details about this project are available on **p. 39**.

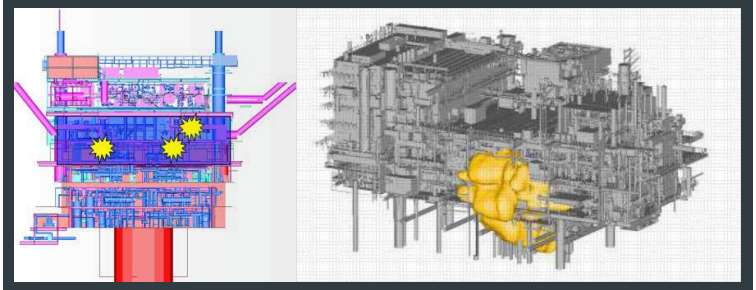


Image caption: *Computational Fluid Dynamics (CFD) model platform.*

- ***New operational prediction system for 3D ocean currents in the Gulf of Mexico*** –Portland State University generated a probabilistic predictive system for ocean currents that provides both a forecast and an uncertainty estimate for that forecast. Both estimates provide information and guidance for a wide range of applications in the public and industrial sectors. The forecast system generates probabilistic forecasts by perturbing the initial state of the ocean field as well as the surface atmospheric forcing (wind and heat flux fields). Over the course of the project, the team used the predictive model to successfully predict a break off of the loop current 4 weeks in advance.

What are the benefits of surface systems and umbilicals (wellbore stability) research?

The projects in this bin interconnect and impact each other. Hurricanes affect loop currents and vice versa, loop currents affect safe rig placement, and stable platform placement affects the outcome of the operations being carried out. Ultra-deepwater production requires long and heavy risers; heavy risers require more upward buoyant force than a large floater can achieve. The long distances from shore to UDW locations require long pipeline and power tiebacks, or proximal solutions with enough topside space and equipment to accommodate significant activity. Time on station requires vessels and gear that are able to survive storms and metocean conditions common to the Gulf of Mexico. All of this must occur with the utmost respect for personnel safety and appropriate safeguards to reduce the risk of environmental damage.

The projects in this bin include assessments of metocean influences on surface vessels as well as assessments of mooring rope integrity as a function of exposure to seabed sediments. These data can be used to enhance safe and efficient UDW operations. Lighter weight risers can enable the deployment of smaller vessels or can enable increased production from an existing vessel, lowering the net environmental footprint. The study of novel UDW vessel designs (such as paired column deep draft configurations versus conventional platforms and circular oil storage vessels versus tankers) can serve to advance industry understanding of a wide range of options for safe and effective production from UDW locations.

Lessons Learned

As with any type of research, surface systems and umbilicals (wellbore stability) research sometimes yields unexpected findings and uncovers challenges that need to be addressed through further research. The following "lessons learned" have been identified in final reports of completed projects.

- **Findings in one ultra-deepwater project can lead to improvements in design and safety across all areas of ultra-deepwater development.** Four metocean ultra-deepwater projects are working in concert to improve hurricane forecasting and improve understanding of the potential risks hurricanes pose to surface and sub-surface systems. One project involved the development of models of loop current vortices; these models demonstrated that loop currents are greatly amplified during hurricanes and that risers and other equipment are at greater risk of hurricane damage than originally thought. These findings could lead to additional design improvements to address vulnerabilities. Another metocean project is working to improve forecasting; current tropical storm forecasts are accurate to a maximum of 7 days, but industry would prefer 2 to 4 weeks advance notice.

- **Predictive modeling requires significant computing power and time.** Weather modeling and climate variability predictions in a system as complex as the Gulf of Mexico require substantial processing power. Hind-casting requires months of computer time. Algorithms designed for hind-cast have not yet been combined with forecast code to a point where a real-time hurricane forecasting capability is feasible. Much more effort is needed.

- **Industry collaboration is critical to UDW research success**. The high cost and risks of doing field research at remote UDW locations means that collaborative efforts with industry are essential if practical solutions to real-world problems are to be tackled and tested. Most of the successful efforts in this program involved integrated research teams that included offshore operators, technology developers, and academic researchers.

- **Experimentally-validated simulation models are critical for understanding UDW operations**. Using surface test systems to validate computer models is an important step in developing tools to understand how equipment operates under deep subsea conditions where hands-on field testing is impossible.

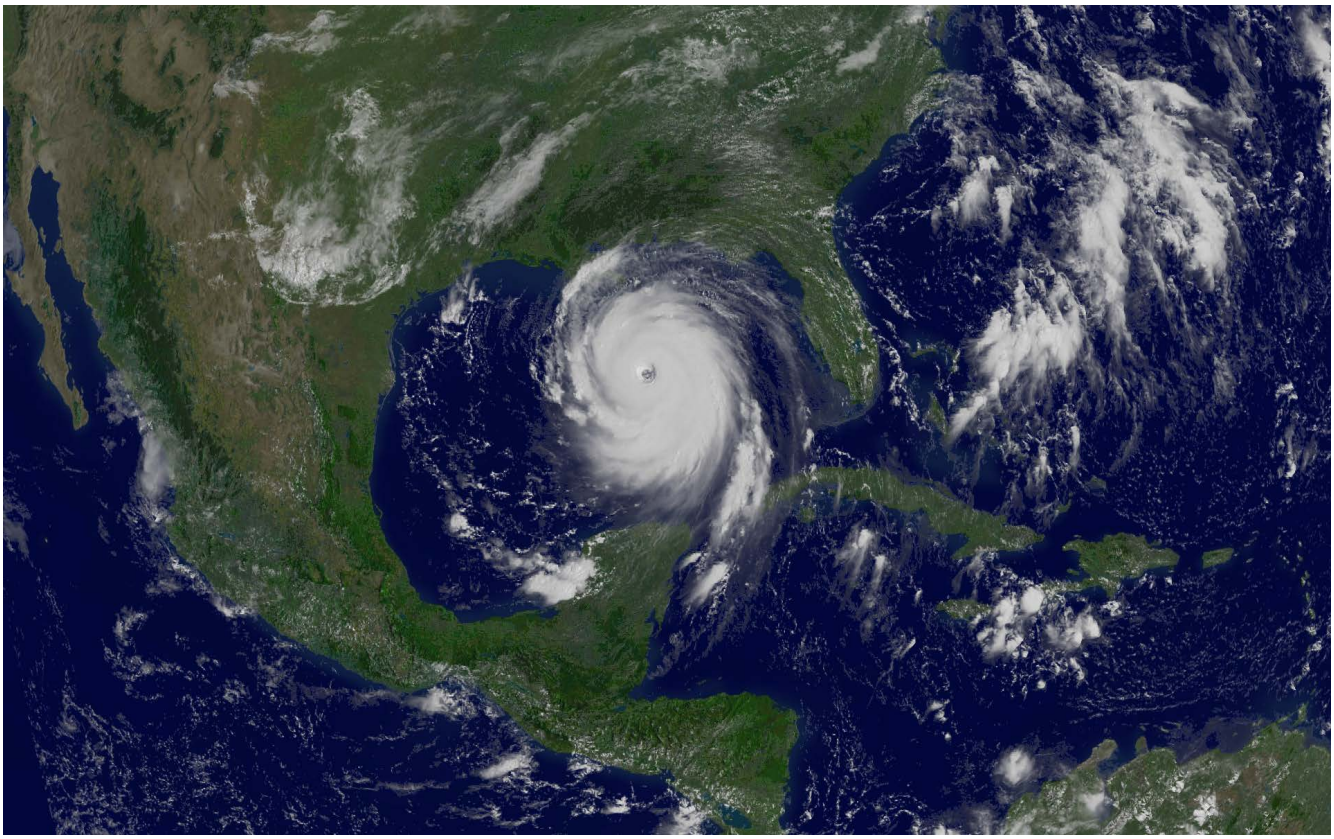


Image caption: *Satellite image of Hurricane Katrina prior to landfall.*

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Ultra-High Conductivity Umbilicals

Objective: To design, build, and test an engineering prototype of a working ultra-high conductivity 'wire' (polymeric conductor) that would be half the diameter of a pure copper conductor, could carry the same current at the same voltage, and could be incorporated into an undersea umbilical.

Research Conducted: Step-out distances are increasing as offshore development moves into deeper and deeper waters. As water depths increase, conventional copper wire umbilicals cannot support their own weight, necessitating lighter but equally effective subsea power umbilicals. Individual carbon nanotubes in polymers conduct electricity at least as effectively as copper and may conduct up to 10 times more effectively. These nanotubes are also approximately 9 times lighter than traditional copper wires.

The researchers, NanoRidge Materials, selected polyethylene as the polymer for the polymeric wire. They conducted experiments with polystyrene to enhance conductivity through melt annealing. The experiments included changing the solvent type, increasing the weight percentage of multi-walled nanotubes used, and molding samples using a vacuum oven. Research was also conducted using low and high density polyethylene to determine solvent compatibility. The researchers produced samples using medium density polyethylene and multi-walled nanotubes. Different techniques were used including autoclave, annealing samples, and dry and melted samples. Samples were characterized, measured for resistivity, and were further processed using electric fields. Materials from this research were presented at an Offshore Technology Conference.

Results:

- Two polymeric conductors were ultimately created (rather than the one conductor originally proposed); one was used to power a light bulb, and the other powered a pump.
- The polymeric conductors developed had nanotube concentrations up to 90 wt%; however, the primary focus of the program was directed toward low concentration samples.
- Testing demonstrated that the conductor carried a maximum voltage of 40V and a maximum current of 16A.
- Several new steps for lowering resistivity were identified.
- Even though the polymeric conductor was not produced in its ideal form, seventeen orders of magnitude improvement from the standard polymer material was realized. It is expected that with the use of more metallic single-walled carbon nanotubes a much higher level of conductivity may be achieved.
- The improvements achived in polymeric conductor properties with the new prototype (including wattage and current) may translate to lighter, more fatigue resistant, and more cost-effective umbilicals in the future.

Ongoing Research: A follow on project, 10121-4302-01; Ultra-High Conductivity Umbilicals: Polymer Nanotube Umbilicals, Phase 2 (p. 24 of this report) is in progress to further increase the conductivity.

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Project Number: 07121-1302

Period of Performance: 12/2008-5/2010

Read/download the final report.

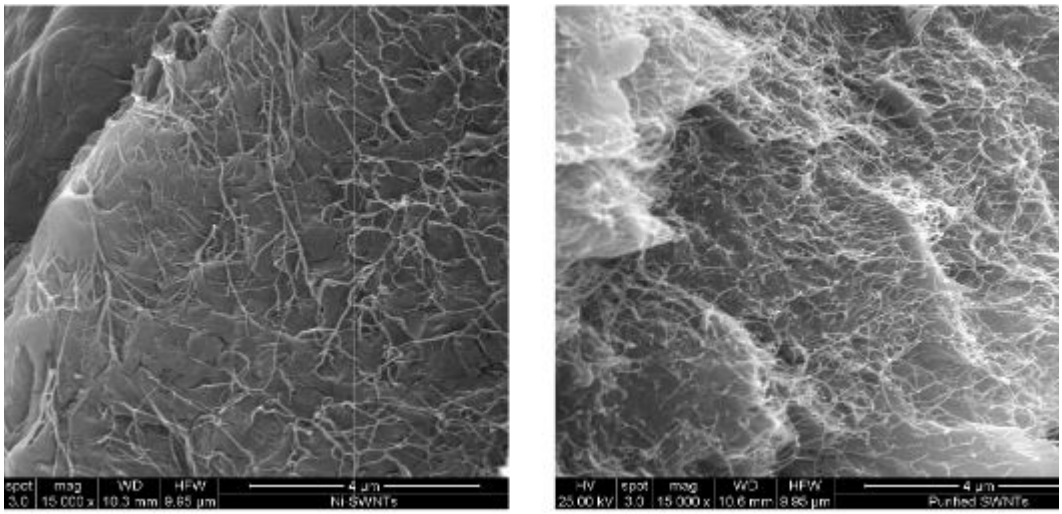

Image caption: *Scanning electron microscope images before and after application of electric field.*

Composite Riser for Ultra Deepwater High Pressure Wells

Objective: To develop and test a lightweight drilling riser system for ultra-deepwater and high pressure that is suitable for existing tension-leg or spar platforms using industry-standard equipment.

Research Conducted: Supporting the weight of steel risers is a significant engineering challenge for deepwater drilling. Risers requires an engineering balancing act; the increased riser wall thickness necessary for the deepwater environment increases weight and necessitates larger and more expensive floating structures. One solution that could alleviate the weight burden is steel pipe over-wrapped with carbon fiber epoxy. Studies suggest that this solution could yield weight savings of 40-50% in comparison to conventional steel risers. This technology also shows promise in that it can be used with lower strength steel. The weight reduction of a hybrid composite/steel riser system would enable access to ultra-deepwater high-pressure reservoirs that are cost-prohibitive or technically-impossible using conventional all-steel risers.

The researchers designed a conventional steel riser over-wrapped with carbon fiber reinforced epoxy, combing a durable and fluid tight bore with the efficiency of high-performance composites. Like a conventional riser, the steel component is an assembly of two end couplers welded to each end of straight pipe. The steel assembly was over-wrapped with composite using an automated filament winding process. The composite structure is a multi-layered, angle-piled laminate formed by winding successive layers of continuous carbon fiber roving, under controlled tension and wetted with epoxy, over the steel and subsequent curing with heat. The researchers chose a wet winding process as a cost-control measure. To protect the environment and to prevent a galvanic couple from developing between carbon fiber and steel, the composite was jacketed with a thick layer of rubber.

The researchers evaluated design loads for 100-year hurricane storm conditions. Global analysis was performed using met-ocean data and motion response amplitude operators provided by industry participants. Design verification was performed by prototyping full-diameter test articles, for the purpose of demonstrating manufacturability of the design and to test burst strength, fatigue, and tolerance. Three tests were performed: a pressure burst test, a combined tension-bending cycle test, and a dropped object impact test.

Image caption: *Full-diameter prototype.*

Results:

- The tests verified earlier findings that composite risers offer a potential 40-50% weight savings over all-steel construction.
- Full-diameter prototypes demonstrated manufacturability and an acceptable factor of safety with respect to burst strength, fatigue, and tolerance.

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Project Number: 07121-1401

Period of Performance: 12/2008-6/2013

Read/download the final report.

Fatigue Performance of High Strength Riser Materials in Sour Environments

Objective: To test potential UDW high-strength materials and collect fatigue and crack growth data on these materials.

Research Conducted: Metal fatigue can impact deepwater floating production systems, and systems in the sour environment of ultra-deepwater are particularly vulnerable to fatigue. Higher fatigue crack growth rates are expected when production fluids are sour. Sour gas—a naturally-occurring but toxic and highly-corrosive chemical—can result from production or from seawater flooding of the reservoir to enhance production yield. High-pressure, high-temperature environments further stress metal components. Although new high-strength riser steels have been developed, there is little data documenting their resistance to corrosion and fatigue. This project will provide engineers with critical data to improve riser design, especially the material selection process.

The research performed experiments on five different steels with yield strengths ranging from 848 to 1080 MPa, and one titanium alloy (Ti-29) with yield strength of 786 MPa. The materials were tested against a simulated seawater environment similar to conditions around risers and a simulated sour brine environment similar to conditions inside the risers. (Not all of the materials were tested across all environments. For example, data regarding the Ti-29 alloy's performance in sour environments is already available, so additional testing was unnecessary.) Representative cycling loading frequencies experienced by risers in service were used to simulate real-life conditions. Corrosion-fatigue performance was characterized in terms of 1) stress-life fatigue response needed for riser design and 2) fatigue crack growth rate.

Results:

- The first ever corrosion-fatigue data was produced for high-strength riser materials under representative cycling loading frequencies and environments typically encountered in UDW service.
- The Ti-29 alloy was demonstrated to be preferable in sour environments with intermediate and high-cycle fatigue regimes. These results are critical for proper selection of riser materials, as well as for preliminary design and structural integrity assessment of UDW risers.
- Material strength level and cyclic loading frequency were found to be key variables affecting corrosion-fatigue crack growth rates. For both environments, the highest strength steels were found to exhibit higher fracture growth rates and lower saturation frequencies—i.e., a frequency below which the rates no longer increased with further decreases in frequency—than the lower strength steels.

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Lead Performer: Southwest Research Institute

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Project Number: 07121-1403

Period of Performance: 12/2008-3/2012

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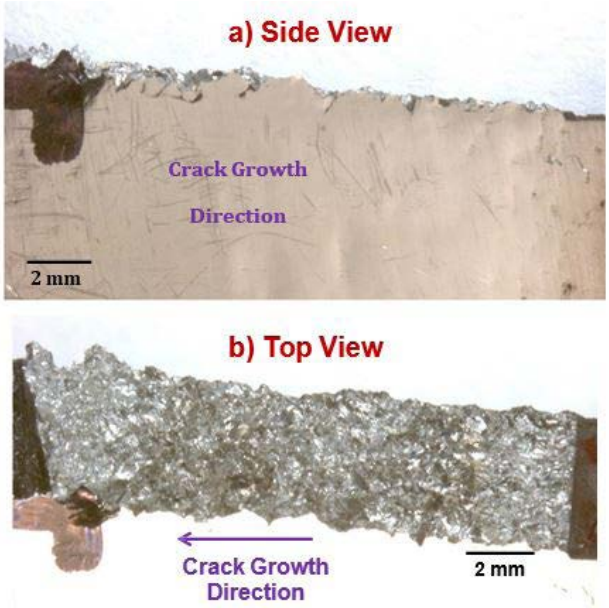

Image caption: *Rough fracture surface topography of specimen tested in sour brine environment: a) side view showing out-of-plane cracking, and b) top view showing rough fracture surface topography.*

Robotic MFL Sensor for Monitoring and Inspection of Deepwater Risers

Objective: To develop new structural health monitoring (SHM) techniques for deepwater risers, combining new global and local monitoring techniques for fatigue damage estimation.

Research Conducted: SHM systems detect deepwater riser damage and perform repairs before costly, dangerous failures can occur. The researchers used their strengths in structure dynamics, SHM, system identification, and offshore structures to explore various possible solutions for deepwater riser monitoring. The researchers studied the effectiveness of combining local inspection of risers using a robotic crawler fitted with magnetic flux leakage (MFL) sensors with global monitoring through a vortex-induced vibration system. Global monitoring was achieved using a proposed blind identification technique—Wavelet Transform (WT) and Second Order Blind Identification (SOBI)—based solely on measured riser vibrations. Global monitoring using the newly-developed WT-SOBI and fatigue estimation was verified by field data from a Gulf Stream (2006) test performed by researchers at MIT. Travelling wave properties of vortex-induced vibrations were confirmed by frequency analysis.

First, fatigue damage was located using a newly-developed method. Global monitoring was used to identify dominant modes of vibration and estimate the likely location of fatigue damage. After the fatigue damage location was estimated from global vibration measurements, the MFL sensor was deployed at the estimated damage location (depth) to determine the extent of damage and then, maintenance decisions were made. The method was validated using Gulfstream test data. Second, the extent of damage was determined by local monitoring using the robotic crawler with MFL sensors. The effectiveness of the local monitoring with MFL sensors was verified by experiments.

Results:

- Combining global and local monitoring techniques was found to enhance fatigue damage estimation. The proposed fatigue damage estimation technique can satisfactorily predict the location of global damage.
- Local inspection using MFL sensors is power-efficient and yields high resolution results that can estimate the extent of damage.
- Fatigue damage location in deepwater risers can be estimated by the developed WT-SOBI and fatigue analysis.
- Local monitoring using MFL sensors was experimentally proven to be effective in detecting wall thickness changes as small as 0.2mm. Such high resolution results show the potential applicability of MFL sensors in deepwater risers.
- The local magnetic flux leakage inspection can be improved with more accurate sensors and defect geometry models. The researchers encountered a noisy MFL signal at 5 and 10% wall thinning defects. Even with adequate filtering, noise in radial MFL signals can be difficult to process. Magnetic field resolution and spatial resolution offer potential improvement to measuring small defects.

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Lead Performer: William Marsh Rice University

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Project Number: 07121-1603d

Period of Performance: 10/2008-6/2012

Read/download the final report.

Effect of Global Warming on Hurricane Activity

Objective: To conduct an assessment of potential impacts of global warming on North Atlantic hurricane activity with a focus on the Gulf of Mexico.

Research Conducted: Climate change models are predicting a future shift in the global average hurricane intensity to fewer but more intense storms. Increased hurricane intensity in the Gulf of Mexico (GOM) could result in more-severe damage to infrastructure such as platforms, pipelines, shore bases, and refineries located near the coast; increased capital expenditures to harden existing infrastructure; and increased costs and risks for personnel evacuations. Also, stricter design criteria for new construction would have to be put in place.

Researchers used a powerful combination of the latest dynamical modeling and novel statistical methods to identify consistencies in future changes. Additional work focused on the development and application of a hurricane damage index specific to offshore facilities that translates hurricane parameters directly into quantitative damage assessments.

The modeling results suggest that there will be an accelerated increase in the number of North Atlantic hurricanes from 1-3% per decade in the near term to 4-10% per decade closer to 2050. Also, the region of maximum storm activity and formation will move equatorward over the same period, and there will be a modest increase in mean intensity, but a more marked increase in the frequency and intensity of the most intense hurricanes. The damage index shows that although storms are projected to be more intense, and therefore more damaging, changes in size and translation speed counteract this. Changes in storm activity specifically within the GOM are less certain due to the low numbers of storms—and therefore, small sample size—in the available historical data used for modeling.

One challenge of this project was the limited number of GOM hurricanes (and small sample size) recorded in the 50-year historical dataset. Future research needs to develop GOM-specific statistical modeling that can generate large numbers of forecasts.

Results:

- The project generated useful scenarios of future hurricane activity in unprecedented detail that may be used by the oil and gas and maritime industries to help mitigate future costs associated with these storms. Various meteorological services and National Oceans Industry Association (NOIA) have incorporated the results of this work into their forecasting analytics. The results are helping determine how much hurricane intensity and frequency are likely to change in the GOM over the next 50 years.
- Consistent results between statistical and dynamical assessments further increase confidence in these predictions, and results are shown to be robust to details of the experimental approach. Applying the index to storms in the dynamical model resulted in production of 50 year forecast damage assessments.
- All data generated through the project was archived and made available through the National Center for Atmospheric Research (NCAR) data portal; other researchers and the public were encouraged to help analyze the over 100 terabytes of data output.

Ongoing Research: A follow up project, 10121-4802-01, Effect of Climate Variability and Change in Hurricane Activity in the North Atlantic (p. 34 of this report), is in progress.

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Lead Performer: National Center for Atmospheric Research

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Project Number: 07121-1801

Period of Performance: 2/2009-4/2011

Read/download the final report.

Deepwater Open Water Riser Intervention System

Objective: To design and develop a certified, commercial-ready riserless intervention system design for a fully-integrated subsea well intervention system (SWIS). The riserless intervention system needed to be rated for thru-drilling riser intervention operations and open water riser intervention operations on subsea wells at: 1) water depths up to 12,000 feet, 2) working pressures up to 20,000 psig, and 3) working temperatures up to 350°F.

Research Conducted: The harsh temperatures and pressures of deepwater environments strain—and sometimes break—the cables and wirelines of intervention systems. Engineers have the challenge of re-designing standard intervention systems from shallow water drilling operations to withstand these environments while keeping costs in check and meeting safety requirements.

The original scope of work was modified—partially in response to changed regulations after the Macondo accident—to specify that the system needed to be an open water riser system rather than riserless. The researchers modified their existing designs to increase the bore size in response to the scope of work changes. They completed the revised design and developed a commercialization plan for making the technology commercially available.

Results:

- The design for an open water riser system was completed, including selecting/confirming the material requirements for various components, creating the detailed designs for the components (including the surface tree), selecting prospective suppliers, and working on the commercialization plan.
- A new concept in intervention system design was developed that can extend SWIS into the deepwater environment.
- Deepwater riser intervention systems need to be designed for specific trees and internal diameters. Also, the size of the bore needed to be increased (from 5 1/8" to 6 3/8") to accommodate the internal diameters of many older subsea trees. As a result, several of the components will need further development and qualification to complement the increase in bore size.

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Lead Performer: DTC International, Inc.

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Project Number: 08121-2301-03

Period of Performance: 1/2010-7/2014

Additional information on this project is available on the RPSEA website.

Gulf 3-D Operational Current Model Pilot Project

Objective: To demonstrate a well-validated, web-based, publically available, operational 3-D modeling system that produces timely and accurate forecasts, nowcasts, and hindcasts of currents across the Gulf of Mexico of sufficient accuracy to be useful for a number of applications, including loop current/eddy forecasts, oil-spill trajectory forecasts, and similar current-dependent forecasts.

Research Conducted: Though much effort has been invested over the past decade to develop real-time ocean modeling systems in the Gulf of Mexico, forecasting of Loop Currents/eddies remains problematic. The offshore oil & gas industry's need to forecast the associated currents, which can extend over the full water column, has become even stronger as the industry ventures further south in the Gulf of Mexico and into ultra-deep water. The industry loses millions of dollars every year due to drilling rig downtime caused by the presence of Loop Currents/eddies, and none of the existing models have been demonstrated to perform at the level of accuracy required.

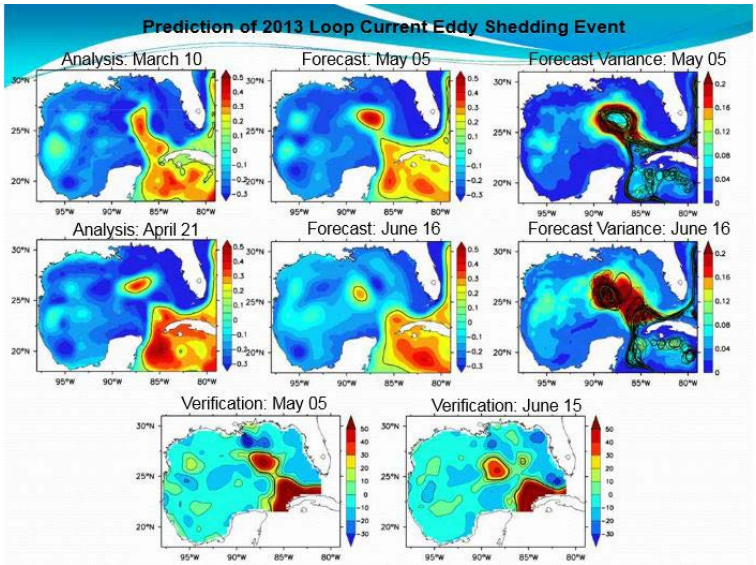
The project was conducted in two phases. In Phase I, several state-of-the-science, mesoscale eddy-admitting baroclinic ocean circulation numerical models were employed in a series of forecast experiments to assess their value relative to science-based and applications-based metrics. Also, seven ocean forecasting systems to identify the state of the art for making three-month forecasts of the Gulf of Mexico circulation and loop currents were examined during Phase I. A short-range forecast system and statistical model for the path of the Loop Current were also utilized for nowcast and Loop Current frontal position evaluations, respectively. The project team identified three modeling systems for possible application in a future real-time operational system, with one system, the Intra-Americas Sea Nowcast/Forecast System, regarded as the most mature candidate for transition to operational mode.

Based on the recommendation of the Technical Advisory Committee, Phase II modeling proceeded under an ocean prediction group at the Naval Research Laboratory that had demonstrated experience with multi- and single model ensemble forecasts, strong connections with the Naval Oceanographic Office operational prediction center, and utilized the advanced Coupled Ocean Data Assimilation System for model initialization. An ensemble ocean modeling system (Long-Range Ensemble Forecast System) comprising several component systems (i.e., the Navy Coastal Ocean Model and Navy Coupled Ocean Data Assimilation System, among others) was implemented to produce routine forecasts of the Gulf of Mexico at 60-day lead time.

There have been numerous "near-misses" documented by the Minerals Management Service in which rig operators faced potentially serious issues due to strong currents. Accurate forecasts could help operators anticipate and avoid some of these conditions and events through better planning and operations, avoid potentially dangerous surprises, and save the industry millions of dollars each year due to drill-rig downtime.

Results:

- A forecast system was developed comprising a numerical ocean circulation modeling subsystem; an ocean observing (satellite and in situ) subsystem with real-time components; a data assimilation subsystem for initializing the forecasts; and an information management subsystem for accessing, displaying, analyzing, and distributing the forecasts. The probabilistic prediction had the advantage of providing both a forecast and an uncertainty estimate about that forecast. Both estimates provided information and guidance for a wide range of applications in the public and industrial sectors. Applications for the oil and gas industry were emphasized.
- The forecast system generated probabilistic forecasts by perturbing the initial state of the ocean field as well as the surface atmospheric forcing (wind and heat flux fields).



Gulf 3-D Operational Current Model Pilot Project

- A multi-year time series of output from the Global Ocean Forecast System was used to construct a daily climatology for 3-D lateral boundary conditions associated with the inflow through the Yucatan Channel and outflow through the Straits of Florida.
- A similar method was used to construct surface boundary conditions from the Coupled Ocean Atmosphere Mesoscale Prediction System atmospheric forecast model implemented for the Intra-Americas Sea domain. Estimates of forecast uncertainty calculated over 32 ensemble members helped predict a Loop Current Eddy shedding event that occurred in spring 2013. The ensemble forecast system performs a 24-hour forecast every day and 60-day forecasts once per week and has been running quasi-operationally in real-time since January 2013.
- The results of this project are now in use by the industry and the Naval Research Lab.

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Lead Performer: Portland State University

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Project Number: 08121-2801-02

Period of Performance: 3/2010-6/2014

Read/download the final report.

Development of Carbon Nanotube Composite Cables for Ultra-Deepwater Oil and Gas Fields

Objective: To produce composite wires that can be wound together to make practical under sea (and / or in wellbore) cables able to carry the needed power for deep-sea applications.

Research Conducted: Continuously increasing power needs for deepwater exploration have prompted the oil and gas industry to perform research into developing conductors that are better than copper and able to transmit more power to the sub-sea floor. To double the electrical conductivity of carbon nanotubes (CNT)—copper composites utilizing new Acoustic Flow Cytometry and/or Acoustically Engineered Materials techniques— and develop a method to scale up the length of the composites to 100 meters while maintaining (or improving) other physical characteristics and properties. Near-term benefits include improving or enabling downhole electrical submersible pumps, operation at lower voltages to improve reliability, and increasing electrical transmissibility through the available wellhead space. Longer-term benefits exist for the development of ultra-deepwater dynamic umbilicals that have superior mechanical performance compared to existing technologies, make more efficient use of the existing footprint at the well site, enable higher power transmission efficiency leading to longer tieback distances, and reduce the power transmission voltage for addressing safety, topside space, and reliability issues.

During Phase I, the research team developed two approaches for making composite wires that were used to make more than 100 wires at least 5 cm long.

The RPSEA Technical Advisory Committee guidance for proceeding to Phase II was to pursue a 50 percent improvement in the conductivity of CNT copper composites and not scale-up the process until this objective was met. An analysis of the two processes developed in Phase I in terms of scalability and producing CNT composites conductors with the required coating thickness resulted in the down selection of the solution coating process for Phase II activities.

The CNT copper composite wires were prepared by dip-coating CNT solutions onto a copper wire former. The solutions were either water-based (prepared with one of two dispersants) or sulfuric acid-based. Solutions were stirred without ultrasonic agitation to minimize CNT damage and produce CNT solutions consisting of individual and small fibers of CNTs. Likewise, acid-based solutions of CNT have been reported (Behabtu et al. 2013) and the ones used here consisted of technical-grade sulfuric acid, with the CNTs dispersed in the solution with stirring. In some cases, additional copper was added to the CNT coatings in order to improve the electrical contact between the CNTs (Holesinger 2013). For each wire, a piece of the starting substrate was cut off and kept with the sample. This bare substrate wire was measured to determine a resistivity value for the copper wire core of each wire.

The CNT composite wires were characterized by measuring both their electrical resistance and that of the bare substrate wire at room temperature; measuring the copper wire substrate and CNT composite wire diameters with a laser micrometer, and examining the conductors by scanning electron microscopy and transmission electron microscopy.

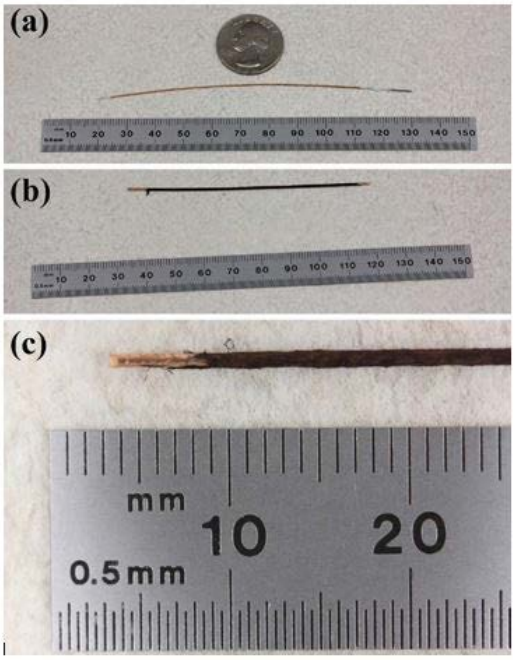

Image caption: *Optical micrographs of (a) a carbon nanotube (CNT) coated wire with a coper (Cu) coating, (b) a bare CNT coated wire, and (c) a close-up of the end of a coated wire showing the Cu core wire and CNT coating.*

Development of Carbon Nanotube Composite Cables for Ultra-Deepwater Oil and Gas Fields

Results:

- Significant progress was made towards developing a robust, industrially-scalable coated wire technology utilizing carbon nanotubes.
- The deposition of thick coatings with scalable processes was a key to developing a CNT-based wire technology and was a significant success in spite of the higher than desired resistivity values for the coatings. (It should be noted that the resistivities found for the CNT coatings themselves are some of the lowest reported in the world thus far.)
- A thorough understanding of current limiting defects was obtained during this phase of the work.
- It was demonstrated that commercial CNTs could be incorporated into processes to produce high performance wires.
- The conductors were much lighter compared to pure copper wires and offer additional advantages for applications that require lightweight materials.
- The relatively high resistivity values obtained for the composite wires and calculated for the CNT coatings were not due to a connected copper matrix within the CNT matrix that acts as a shunt. (The copper was put into the CNT matrix in the water-based samples as a possible method for improving the CNT interconnections [Holesinger 2013]). However, no significant differences were found in the coating resistances between samples that contained the added copper and those that did not. Hence, copper additions were not included in the first set of wires produced with the acid-based solutions. It appeared that the inability to produce CNT coatings that would densify after setting contributed to the lack of substantial improvement in conductivity.

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Lead Performer: Los Alamos National Laboratory

Terry Holesinger, Los Alamos National Laboratory

Project Number: 09121-3300-10

Period of Performance: 4/2011–5/2014

Read/download the final report.

Deepwater Subsea Test Tree and Intervention Riser System

Objective: To develop a certified, ready-to-fabricate design for a subsea test tree (SSTT) and intervention riser system (IRS) as part of a fully integrated Subsea Well Intervention System (SWIS), i.e. that system that provides a primary means of well control during well completion, intervention, and abandonment operations that require access to the production bore or annulus of a subsea well. The SSTT and IRS needed to be able to perform thru-drilling riser intervention operations, open water riser intervention operations, and in the future, riserless intervention operations on subsea wells in water depths up to 12,000 ft. and pressures up to 20,000 psig.

Research Conducted: The team developed a basis of design (BOD) for the SSTT and IRS, identifying the applicable industry codes and standards. The BOD also established the design, functional, operational and interface requirements for the SSTT/IRS. Based on the BOD, functional design for the SSTT and IRS, specifications including drawings and schematics, were developed. Researchers included system level drawings and completed preliminary designs and analyses of the SSTT and IRS to establish limits for the Deepwater Intervention System. Detailed general arrangement and general assembly drawings for each major component and sub-assembly of the SSTT and IRS were then developed, and interface requirements were identified and defined.

A preliminary design review and internal project team analyses were conducted to ensure that the deepwater SSTT and IRS satisfied basis of design and well barrier requirements for all operations and contingencies. An outline for a business case was developed.

Due to a lack of industry financial support and a change in the project's scope, the team halted development of the preliminary design.

The increase in the bore size, requested by Chevron and approved, will require additional development and qualification of several components as the original design was based upon scaling of existing 15,000 psig equipment designs. The increase in bore size also required changing the overall design from a slim bore system that could run through a 13-5/8 inch BOP stack and 16 inch drilling riser to a full bore system that can be run through a 18-3/4 inch BOP stack and 21 inch drilling riser.

Results:

- The designs for the slim-bore Emergency Disconnect Module had progressed sufficiently before a change in the scope-of-work that the project team had a high-level of confidence that the design could be completed.
- The design of the Upper Pack-Off Module was basically completed (with the exception of finalizing the Standard Module Connection and determining the minimum angle required for the electrical cables), and the design is ready for finite element analysis (FEA) analysis.
- The design of the spacer module was essentially completed (with the exception of finalizing the Standard Module Connection), and the design is ready for FEA analysis.
- The SSTT Riser Adapter was roughly 80% completed.

Benefits: When this project was initiated, no Subsea Test Trees rated for working pressures greater than 15,000 psig existed, and only two SSTTs were rated for working temperatures greater than 275 °F and none were designed for water depths greater than 10,000 ft. water depths. Similarly, IRSs were limited to 12,500 psig working pressures, 250 °F working temperatures, and were limited to 8,500 ft. water depths.

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Lead Performer: DTC International, Inc.

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Project Number: 09121-3500-07

Period of Performance: 1/2011-7/2014

More information about this project can be found on the RPSEA website.

Ultra-High Conductivity Umbilicals: Polymer Nanotube Umbilicals (PNUs)

Objective: To develop a unique conductor for use in subsea umbilicals and power transmission with a lighter and higher current carrying capacity conductor. Researchers will produce a carbon-nanotube based conductor with less resistivity and higher current carrying capacity than copper, at 1/6th the copper's weight.

Research Conducted: As offshore developments move into deeper water and have longer step-out distances, subsea umbilicals must be improved. Offshore umbilicals must withstand substantial installation and service loads, deliver significant amounts of power and have an extended operational life. As drilling depths increase, conventional copper wire cannot support its own weight.

The team installed a lab-scale furnace outfitted for continuous wire formation and synthesized double-walled carbon nanotubes (DWNT), drawing the as-produced material into wire form before doping and optimizing the product. At the end of Phase I, researchers delivered a conductor with 10^{-5} Ω•cm resistivity. In the second phase, the team continued production of the DWNT conductor. They jacketed the wire with polymer, developed and optimized the production process, and characterized of the wire with and without the polymer jacket. Characterization included the formation of wire connections and terminations. The team demonstrated five wire tested intermittently over a period of 120 days, to show evidence of a conductor with resistivity between 1×10^{-5} and 9×10^{-5} Ω•cm and capable of operating at pressures from 34.47 to 37.92 MPa (5000 to 5500 psig). Results of Phase II work allowed the project team to deliver a polymer-jacketed DWNT conductor with 10^{-5} Ω•cm resistivity that is operational at a pressure of 5500 psig.

The wire comprised of carbon nanotubes should be able to replace conventional copper cable and demonstrate lower weight, improved mechanical performance, and increased corrosion inhibition. The carbon nanotube product will weigh a sixth of copper, decreasing the linear mass density of an umbilical and allowing ships to carry longer umbilicals to deeper and more remote oil and gas plays. The decreased weight and improved strength allows for greater top tension on the umbilicals. Additionally, the lead that is traditionally used to protect copper from corrosion is unnecessary with a carbon nanotube wire and cable. In addition, this development may result in much more conductive and lightweight long distance land cable than currently used or available, which could increase efficiency by reducing electrical line losses by up to 90%.

Results:

- Purification, doping, and testing protocols have been optimized.
- Several wires have been characterized.
- Carbon nanotube compositions have been related to conductivity.
- Carbon nanotube wires of extended length have been continuously formed.
- Doping times were shortened at lower temperatures.
- CNT wire overjacketing with polymer was established.
- Acid washing nanotubes led to improved doping and a lower wire resistivity.

Ongoing Research: Phase III of the project is ongoing. In this phase, a prototype umbilical will be optimized and fabricated. The conductor will be comprised of double-walled carbon nanotubes in wire form and jacketed with a polymer (together, they are the polymer nanotube umbilical). The polymer adds mechanical integrity, abrasion resistance, makes the conductor easier to handle. The PNU wire will be used as the conductor in the lightweight prototype umbilical to be demonstrated in the summer of 2015.

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Lead Performer: NanoRidge Materials, Inc.

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Project Number: 10121-4302-01

Period of Performance: 8/2012-8/2015

More information about this project can be found on the RPSEA website.

Ultra-Deepwater Riser Concepts for High Motion Vessels

Objective: To establish and bring to maturity at least one safe riser system to meet the demands of both high-motion vessels and the ultra-deepwater environment.

Research Conducted: High-motion vessels, such as conventional semi-submersibles and ship-shaped floating production storage and offloading vessels (FPSOs), can have significant heave motion and roll and pitch angular motions. Pitch and roll motion directly influences strength and fatigue performance at the top of a riser, where the riser attaches to the host vessel. Heave motion is a major contributor to problems in the touchdown region of catenary risers. Both affect the long-term integrity of riser systems for offshore floating facilities. This project is investigating riser concepts in water depths approaching 10,000 feet and supported by high-motion vessels. The benefits from this project included reduced risks and increased safety for people, infrastructure, and the environment. An improved riser system will also help maintain uninterrupted production, saving money and adding to the nation's oil supply.

The project performer developed a working group to perform a concept analyses and recommend riser concepts that not only meet the demands of high-motion vessels in ultra-deepwater, but can manage 20,000 psig shut-in tubing pressure and production temperatures up to 350°F. These design parameters limited risers to those with rigid pipe construction. Following an assessment, technologies, riser geometries, and potential riser pipe materials riser concepts were developed and technology gaps associated with the newly-defined riser concepts were identified. The working group determined that riser concepts with high levels of technology readiness exist for high-motion vessels. Project researchers then performed a more detailed dynamic analysis, considering both extreme and fatigue sea states, and risk assessments for those riser concepts that made it through the concept evaluation stage. This involved:

- Analyzing the global motions of two types of high-motion vessels
- Performing dynamic analyses of a riser when subjected to extreme storm conditions in order to evaluate membrane load capacity of riser concepts and eliminate those concepts that did not meet strength criteria
- Analyzing the performance of risers under varying ocean conditions
- Estimating costs for materials and installation of riser concepts and noting items at risk for cost escalation
- Recommending riser concepts for each host vessel type

Results:

- A first-level concept evaluation (including Vessel Motion Processing and Evaluating Strength Capacity of Riser Concepts to Design Storms) and a second-level concept evaluation (with Evaluate Fatigue Performance of Riser Concepts, Riser Concept Cost Estimates, and Installation Assessment) were conducted. A comparison table in the final report shows the value of each riser system.
- The outcomes of the evaluations undertaken have shown there are riser concepts with high levels of technology readiness acceptable for high-motion vessels. Steel Lazy Wave Riser is a viable alternative to Steel Catenary Riser (SCR) for Conventional Semi-Submersible with estimated cost that is between 30% and 60% higher than an SCR. Also, viable riser concepts for Disconnectable-Turret FPSO are: Steep Wave Riser constructed of ID Clad Steel Pipe or Duplex Stainless Steel Pipe and lightweight insulation; Tension Leg Riser; and Hybrid Riser Tower. Estimated costs, in general, are comparable between the three concepts but are over double that of an SCR.

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Lead Performer: Stress Engineering Services, Inc.

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Project Number: 10121-4401-02

Period of Performance: 8/2012-8/2015

Additional information on this project is available on the RPSEA website.

Qualification of Flexible Fiber-Reinforced Pipe for 10,000-Foot Water Depths

Objective: To develop a novel 7-inch flexible fiber reinforced pipe (FFRP) for ultra-deepwater applications. FFRP is an unbonded flexible pipe with composite reinforcement layers. The final product will meet following industry requirements:

- 10,000 foot (3,000m) water depth
- 12,000 psi capability
- 120 °C fluid temperature capability
- 25-year field life

Research Conducted: The novel hybrid flexible riser technology concept consists of an engineered combination of metallic and composite reinforcing layer technologies. This design approach enables the properties of the pipe system to be tailored to yield optimal results for application conditions and offers other advantages over alternate concepts, particularly risk-prone concepts that use thermoset matrix materials and rely exclusively on composite reinforcement. FFRP advantages include being lightweight, highly flexible, and corrosion resistant.

Other performance advantages include:

- Reduced risk for critical end fitting technology
- Reduction in the risk of collapse due to explosive decompression and in the risk of sheath leakage by fusing together the reinforcement and liner
- Improved matrix chemical resistance through the use of proven thermoplastic materials
- Reduced layer count leading to easier inspection

The project team's initial work involved developing the design concept. The conceptual design consisted of a composite and metallic/polymer flexible pipe optimized for ultra-deepwater applications. Researcher's performed materials testing with respect to working fluid pressures, collapse pressures, and fluid temperatures. Preliminary lifetime and fatigue assessments for the composite pressure armor were completed, as well as initial mechanical and physical property screening tests of the thermoplastic composite materials. The tensile and compressive properties of the composite lamina were measured at room and elevated temperatures, thermo-chemical ageing tests were performed on carbon fiber-polyvinylidene fluoride material system, and permeation and rapid decompression tests were conducted to assess resistance to blistering. The project team concluded the first phase of the project by assessing the manufacturability of the design concept and identifying key process parameters. They created an analytical model of the manufacturing processes used to fabricate the composite pressure armor, which will allow them to continue optimizing critical process parameters.

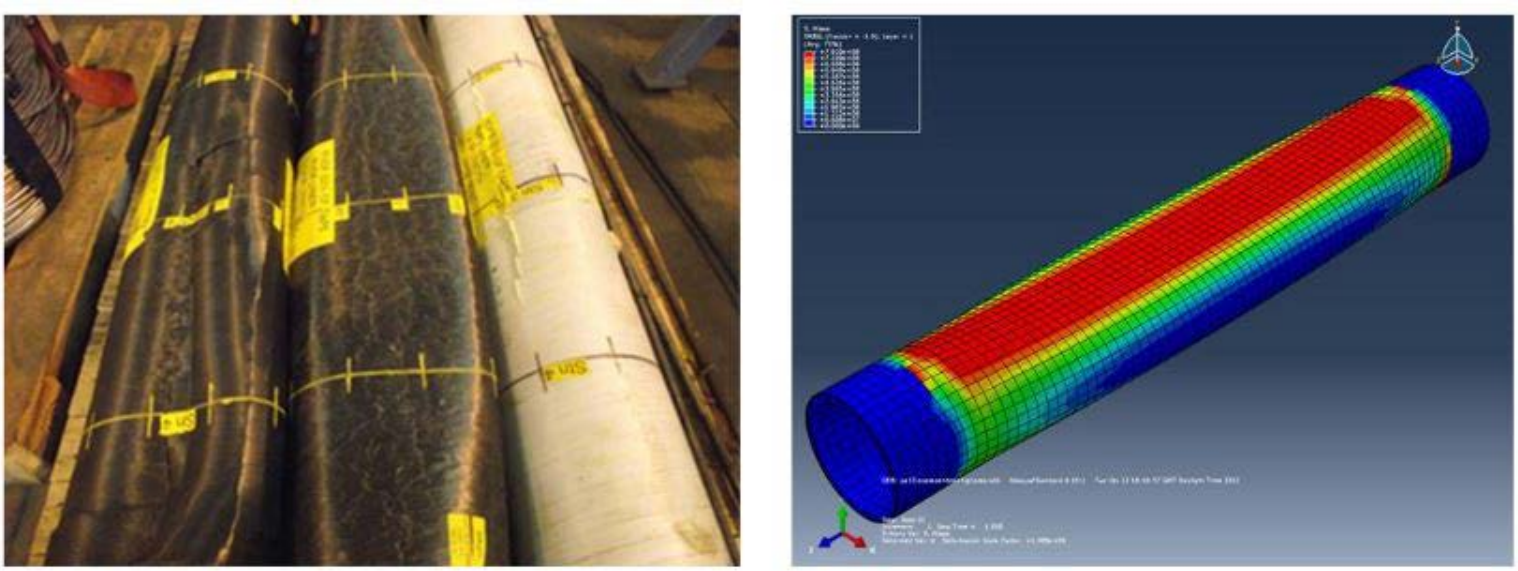

Image caption: *Selection of composite pipe (actual and FE) under collapse loading.*

Qualification of Flexible Fiber-Reinforced Pipe for 10,000-Foot Water Depths

The team fabricated initial composite smaller scale pipes for flexure and burst testing during Phase II.

Results:

- The design concept was matured through a combination of material testing and design analysis during the year-long Phase I of the program.
- Critical risks and corresponding tests were identified through a detailed "failure mode, effects and criticality analysis" (FMECA).
- The comprehensive failure modes and effects analysis used during the project were based on conventional products, so many of the identified pipe failure modes for this novel design were the same as those for conventional products. Newly-identified failure modes related to the introduction of the composite pressure armor and adjacent layers. There is no current standard for flexible composite pipes.

Ongoing Research: Researchers are focused on maturing the technology and manufacturing readiness level of the composite pressure armor, with an emphasis on manufacturing and testing sub-components and constructing prototype pipe. The FMECA was used as the basis for prioritizing the tests to be performed in this phase, and due to the incorporation of the conventional metallic carcass, key tests are being conducted to determine the burst, bending, and fatigue performance of the thermoplastic pressure armor. These characteristics will be evaluated during sub-component testing and prototype testing.

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Lead Performer: GE Global Research

Todd Anderson, GE Global Research, 518-387-5969, andersot@research.ge.com

Project Number: 10121-4402-01

Period of Performance: 8/2012-8/2016

More information about this project can be found on the RPSEA website.

Qualification of Flexible Fiber-Reinforced Pipe for 10,000-Foot Water Depths

Objective: To qualify a flexible fiber-reinforced pipe (FFRP) riser design for safely conveying hydrocarbons from wells in ultra-deepwater to a floating production, storage, and offloading (FPSO) unit without leakage to the environment. The team will qualify a novel hybrid (composite/metal) unbonded, flexible ultra-deepwater riser that meets the following industry requirements:

- 10,000 foot (3,048m) water depth
- 10,000 psi design pressure
- 120 °C fluid temperature capability
- 25-year field life

Research Conducted: The objective of the first phase of the project was to confirm the product and system design that would be used in the subsequent phases. Researchers met this objective by completing the design premise, design report, and failure mode effects and criticality analysis (FMECA). The team developed plans for manufacturing, qualification, and field development based on the FMECA. The qualification plan defined a clear qualification path that addressed more than 120 potential failure modes and mechanisms.

Results:

- The Phase I engineering study confirmed the FFRP riser and system design.
- Researchers successfully developed a feasible FFRP design to meet governing standards API 17J, API 17B, and DNV OS-C501and qualification plans to meet testing guidelines DNV RP-A203 and API 17B. FFRP offers a top tension reduction that enables the use of lightweight and small footprint installation vessels and production platforms in ultra-deepwater of up to 10,000 ft. Doing so will expand the number of existing installation vessels and floating production, storage, and offloading vessels that can be used in ultra-deepwater, reducing overall project costs and risks.
- A comprehensive FMECA that defined a path to address all known potential failure modes and mechanisms was completed.

Ongoing Research: Researchers are conducting ageing tests, designing a new pullout test rig, and investigating the use of acoustic sensors for torsion tests. Burst tests are ongoing and the team will recover the end fittings in order to repeat the tests on a second sample once the initial tests have been completed. The team will continue to fully qualify the product design for deployment prior to a field test of the riser system, deploy the riser system, and monitor its performance for six months, further qualifying the materials, pipe layer, and pipe structure.

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Lead Performer: Deepflex, Inc.

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Project Number: 10121-4402-02

Period of Performance: 10/2012-10/2016

More information about this project can be found on the RPSEA website.

Low Cost Flexible Production System for Remote Ultra-Deepwater Gulf of Mexico Field Development

Objective: To establish a safe, cost-effective, and flexible production system for ultra-deepwater reservoirs in of the Gulf of Mexico (GOM) that is far from existing infrastructure.

Research Conducted: The team identified the following possible concepts for further exploration during its initial assessment of hull types: non ship-shaped cylindrical floating production storage and offloading vessels (FPSOs) (represented by SEVAN 1000); non ship-shaped hemispherical FPSOs (represented by SSP 320 Plus); and deep draft semi-submersible FPSOs (represented by Octabuoy® 1 MMbbl). Researchers also conducted static and dynamic analyses of risers, incorporating risk assessment and regulatory requirements, to determine the most suitable, safest, and most cost-efficient riser type for each concept. The feasibility of direct offloading was determined via availability analysis and an oil export concept evaluation.

A broad summary of the research conducted is presented below:

- Performed preliminary design and analyses of hulls, risers, moorings, and topside
- Evaluated whether abandonment during hurricanes is acceptable when hydrocarbons are in storage
- Established a complete shuttle tanker oil export concept
- Determined the costs and devised a schedule for the concepts, including an export solution
- Ranked three FPU concepts: circular-shaped, semi-submersible, and spar
- Performed preliminary design and analysis of circular floater concept of topsides and FPUs, hull, and moorings
- Evaluated regulatory requirements and performed risk analysis / hazard identification (HAZID)
- Evaluated investments and installation phases
- Analyzed DP shuttle tanker operations and availability
- Established a shuttle tanker oil export scheme for the circular concept
- Completed a HAZID Report

Results:

- The deck area on a ship-shaped floater or semi-submersible unit was determined to be sufficient for safe and functional arrangement of process facilities; however, the arrangement of topsides on round floaters may be more difficult due to the reduced deck area. Advantages of having slightly shorter distances between the modules include markedly reduced pipe lengths and cable runs and greater crane accessibility.
- Steel catenary risers (SCRs) were selected based on the results of their analyses. Sevan's circular hull, which had the highest technological readiness level (TRL 7), was also selected.
- During hull selection, it was determined that the lightship weight option for semi-submersible with storage capacity, Octabuoy, is more than double that of the comparative round hull types of the same storage capacity, eliminating it from consideration because it didn't meet the low-cost project requirement.
- Sevan Marine provided input based on the knowledge they gained from wave tank experiments on circular-hull floating production storage and offloading (FSPO) vessels. These hydrodynamic data were incorporated into the FPSO design, with SCR to serve a hypothetical high- pressure, high-temperature field in an ultra-deepwater Lower Tertiary play.

Ongoing Research: The team will conduct a field study to determine the feasibility of a circular shaped floating platform unit (FPU) with a storage capacity of one-million barrels, and compare it with two current FPU concepts: semi-submergible and spar. The floater host will be located at a water depth of 2,000 to 3,000 meters. The FPU will have direct production and offloading capabilities and be capable of offloading crude oil from two separate drilling centers into dynamically positioned shuttle tankers sized for delivery to a terminal facility in the United States. The team anticipates that initial oil production will be 60,000 barrels per day.

Low Cost Flexible Production System for Remote Ultra-Deepwater Gulf of Mexico Field Development

The team will submit a regulatory requirements report, Preliminary Design and Analysis of Topsides report, and a Final Report on Preliminary Design and Global Performance, which will complete Phase 1 of the project. As part of Phase 2, researchers will also design and prepare to implement a test model and will provide the results of a model test in its final report.

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Lead Performer: Doris Inc.

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Project Number: 10121-4404-03

Period of Performance: 10/2012-3/2015

More information about this project can be found on the RPSEA website.

Effects of Fiber Rope - Seabed Contact on Subsequent Rope Integrity

Objectives: (1) To develop a fundamental understanding of the effect that contact with the seabed (whether accidental or planned) has on fiber rope; (2) to analyze the primary cyclic-wear process that reduces the strength of fiber rope to help mitigate risks and avoid unsafe conditions; and (3) to devise a test plan to qualify polyester mooring ropes for incidental seabed contact and seabed pre-installation.

Research Conducted: The goal of this project was to enable qualification of mooring rope for pre-installation on the seabed, which will greatly reduce risk by decreasing the time required to connect mooring lines to the floating facility, thus reducing time needed to reach a safely moored condition before arrival of severe weather.

The ingress of soil into mooring rope due to accidental contact with the seabed may affect the long-term integrity of mooring systems. It is possible for soil particles to bypass the rope's particle filtering system, become embedded in the rope core, and intensify normal fretting wear damage as the installed ropes respond to cyclic loads resulting from extreme weather events (such as hurricanes). This situation increases the risk of mooring-line failure.

Prior work established a set of wear test results for all current subrope designs used in the Gulf of Mexico. These data sets for unsoiled rope can be used as a baseline for testing soiled rope. In addition, a fundamental understanding of the cyclic wear mechanism and location of critical damage, as well as damage caused by subrope extraction and handling, was obtained. Rope samples were obtained, deployed to the seabed, and recovered for laboratory testing. Subrope extracted from both soiled and unsoiled samples was tested by cycling at 15 to 45 percent of the average break load for 20,000 cycles, then subjected to a break test.

Results:

- A test protocol was developed and improved test equipment was designed and constructed with input from industry participants and U.S. regulatory agencies.
- Rope designs with multiple layers of filtering material (as well as one alternative filtering system evaluated) can completely protect mooring ropes from soil ingression.
- Particle ingress due to hydrostatic pressure while submerging rope cannot physically occur at water depths below 2000 feet. The results show that these types of rope can be dropped to the seafloor without incurring damage.
- No significant difference was found between the break-test load of soiled and unsoiled subropes.
- Qualification of soiled mooring rope for use on the seabed will permit pre-installation, reducing risk of damage from extreme weather by decreasing the time required for mooring. Qualification will also reduce the impact on cost and schedule when mooring ropes accidentally fall to the sea floor.

NETL Contact: Roy Long, Roy.Long@netl.doe.gov

Lead Performer: Stress Engineering Services, Inc.

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Project Number: 10121-4406-01

Period of Performance: 8/2012–10/2014

More information on this project is available on the RPSEA website.

Synthetic Hurricane Risk Model for the Gulf of Mexico

Objective: To create a state-of-the-art synthetic hurricane model for the Gulf of Mexico for evaluating hurricane-related risks—as expressed by n-year wind speeds—to offshore and coastal locations under current and future climate scenarios.

Research Conducted: This project includes (1) provision of a database containing the tracks and key hurricane parameters associated with the tracks including, but not limited to, the central pressure, maximum wind speed, one or two values of the radius to maximum winds (RMW), and the Holland B parameter (expressing the pressure profile); (2) development of a 100,000-year set of simulated hurricane tracks that will be used to develop wind speeds and wave heights associated with return periods of up to 10,000 years, expanding on the model developed under previous funding from the National Science Foundation, Federal Emergency Management Agency, U.S. Army Corps of Engineers, and the American Petroleum Institute (API); and (3) redevelopment of the synthetic track model using warm climate scenarios developed at University Corporation for Atmospheric Research (UCAR) under previous and ongoing RPSEA funding.

This project builds on an existing synthetic track module that was developed from 1995 to 2008, culminating in the API version. The project research has addressed a number of weaknesses in the API model, including sampling for storm size and pressure (wind relationship/storm structure); near-shore weakening and expansion of the hurricane wind field; model increase in RMW and decrease in Holland B parameter near the Gulf coast; weakening over Caribbean islands; model memory in cases of storm backtracking; wind shear; and storm genesis locating.

- The models replace the previous modeling approach of using the historical record to initialize genesis location, heading, and translation speed. Risks from hurricanes will be better understood by developing and refining a synthetic hurricane model to improve hazard characterization. Ultimately, risks will be more effectively mitigated through the industry's improved understanding of hurricane hazards within the Gulf of Mexico. Improving the ability to accurately model and understand hurricane hazards resulting from high wind and wave conditions will result in safer designs for offshore structures, minimizing the risk of loss of infrastructure and personnel.

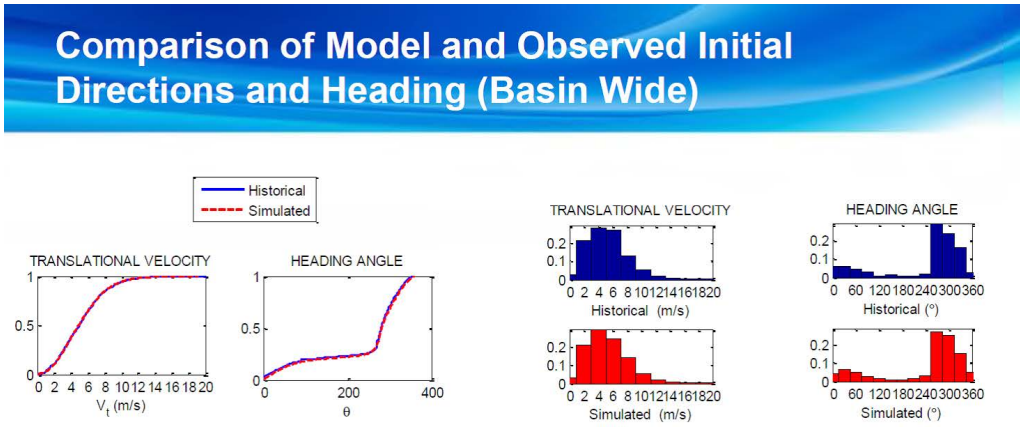
Ongoing Research: Draft reports of Task 5, *Development of Historical Gulf of Mexico Track Set*, and Task 6, *Development and/or Refinement of a Synthetic Track Model*, are being prepared.

New intensity and track models will be developed using predictions of future climatology from the UCAR projects: 07121-1801 - Effect of Global Warming on Hurricane Activity; and 10121-4802-01 - Effect of Climate Variability and Change in Hurricane Activity in the North Atlantic.

A sea surface temperature (SST) memory model for storms that backtrack to a prior location will be developed. The model will take into account SST cooling from first storm passage, as well as SST recovery due to atmospheric warming during the time between storm events.

Results:

- Developed a Gaussian Kernel model for tropical cyclone start points, which varies in both time and space, based on the "North American Tropical Cyclone Landfall and SST Statistical Model Study."
- Developed a Gaussian Kernel model for initial storm heading and translation speed, which also varies in both time and space.



Synthetic Hurricane Risk Model for the Gulf of Mexico

Other deficiencies to be addressed include:

- Need for improvement in modeling near-shore weakening. This will be handled through the use of local statistical models and the addition of environmental parameters such as humidity.
- Need for new statistical models for Holland B and RMW to enable the modeling of more complex hurricane wind fields. This improvement will enable the wind model to produce higher winds well away from the storm center that often can be reproduced in the simpler wind fields. These large peripheral winds are thought to play an important role in the magnitude of the maximum wave heights in the center of the storm.
- Need for new models to describe the weakening of storms over mountainous Caribbean terrain to replace the generic models used in the API model.
- New statistical models for hurricane intensity will be developed using the Oceanweather, Inc. characterization of historical storms coupled with an updated set of Gulf of Mexico eddies. Track models will be for a range of periods of record, including 1984 to 2012, 1940 to 2012, and 1900 to 2012.

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Lead Performer: Applied Research Associates

Peter J. Vickery, Applied Research Associates, pvickery@ara.com, (919-582-3343)

Project Number: 10121-4801-01

Period of Performance: 6/2013–6/2015

More information on this project is available on the RPSEA website.

Effect of Climate Variability and Change in Hurricane Activity in the North Atlantic

Objective: To quantify future changes in the frequency, duration, and intensity of hurricane activity in the North Atlantic region. The team seeks to provide credible projections of prospective changes in storms and the impact those changes may have on the offshore energy industry, specifically in the Gulf of Mexico (GOM).

Research Conducted: The team combined theoretical, statistical, and enhanced dynamical modeling capabilities in order to quantify the effects of hurricanes in the GOM and provide projections of hurricane characteristics critical to engineering design, production efficiency, safety, and environmental protection. Next-generation atmosphere-ocean modeling coupled multi-scale modeling systems were used with statistical extremes. Confidence levels in the results were established using multiple independent techniques, advanced statistics, and targeted sensitivity analysis.

Phase I of the project demonstrated that hurricane activity could be inferred from large-scale data. Thus, the team adapted the existing Cyclone Damage Potential (CDP) Index to enable the extraction of decision-relevant information from large-scale climate data, and they explored hurricane damage from large sets of climate data. Hurricane wind and translation speed and hurricane size were used as the key input parameters.

Additionally, the team performed a case study of coupled wind-wave-current (WWC) modeling. The Coupled-Ocean-Atmosphere-Wave-Sediment Transport Modeling System was used to provide simultaneous and interactive simulation of WWC, giving researchers access to critical hazard information needed to establish loading in hurricane environments on offshore structures. The team used data from Hurricane Katrina to perform a successful case study of the simulation system. Researchers also established a tropical cyclone climate simulation capability using the Model for Prediction across Scales (MPAS).

This project will provide insight that may mitigate the costs and environmental impact of severe weather in the GOM. Credible projections of changes in hurricane activity can lead to projections regarding industry impacts. If the projections are correct, the knowledge gained during this project will aid in revising designs for new coastal and offshore facilities and hardening older facilities in order to maintain accepted risk levels.

Results:

- A tool was developed to explore empirical relationships between hurricanes and the environment in which they occur, specifically the Gulf of Mexico.
- Extreme values related to future changes in the exceedance probability of major hurricanes were assessed.
- Evidence for a saturation in the proportion of major hurricanes was acquired, with further warming indicating no further increase in the proportion of major hurricanes.
- Forecasts of cyclone damage potential were developed (in real-time) for Hurricanes Isaac and Sandy.
- Credible predictions of hurricane activity over the next few decades and predictions of industry impacts were developed.
- Combined decision tool with statistical downscaling techniques were developed.
- An initial case study testing of coupled wind-wave-current simulations was conducted.
- Expanded wind-wave-current simulations to include historical cases under current and future scenarios were conducted.
- Preliminary work demonstrated that season average storm size and storm intensity were closely related to the difference between the local sea surface temperature (SST) and the SST as averaged over the entire tropics.
- A new version of the MPAS system, complete with bug fixes, has been released.

Ongoing Research: The team is currently performing a set of sensitivity studies to explore uncertainty in current hurricanes, future changes in hurricanes, and the relationships among the uncertainties. In the third and final project phase, the team will create a new index, known as CDPclimate, by substituting large-scale variables into the CDP index, thus eliminating the need for information on individual hurricanes. This CDPclimate index will be applied to current and future climate simulations to identify the climate change signal above the noise of climate variability.

Effect of Climate Variability and Change in Hurricane Activity in the North Atlantic

NETL Contact: Richard Baker, Richard.Baker@netl.doe.gov

Lead Performer: University Corporation for Atmospheric Research

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Project Number: 10121-4802-01

Period of Performance: 7/2012–7/2015

More information about this project is available on the RPSEA website.

Integrity Management of Risers to Support Deepwater Drilling and Production Operations

Objective: To develop a reliable and commercially-viable solution for a real-time, telemetry-based marine riser lifecycle management system (RLMS).

Research Conducted: The RLMS comprises integrated hardware and software tools, including sensors; wireless subsea communication between the vessel and select instrumented risers; and software for data collection, processing, and riser fatigue analysis. The system also allows for visualization and alerts that enable enhanced operational decision-making. An overall system design for RLMS was developed through a combination of subsystem design elements, laboratory testing and analysis, and a customer field trial.

The first phase focused on technical solution design, development, and risk retirement. Key end user requirements were analyzed and integrated into the system design, then subsystems were developed for an integrated system, test subsystems, and subscale rig testing. An alternative approach to the communication subsystem was also investigated in an attempt to achieve lower power and higher overall system bandwidth.

Although the initial focus of this system is on drilling risers, the technology could translate to production risers. The system will increase safety and reliability while reducing costs.

Results:

- A comprehensive report was written that includes system requirements, solution designs, risk analyses, lab test results, a Phase 2 field trial plan, and a beta version software solution.

Ongoing Research: Sub-scale rig testing is underway. The plan is to reduce the risk involved in creating an integrated RLMS solution by translating the approach developed in Phase 1 into a customer field trial and then documenting findings and results. A comprehensive technical report will be written describing the customer field trial test results and will include both recommendations to improve system reliability and a commercialization plan.

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Lead Performer: GE Global Research

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Project Number: 11121-5402-01

Period of Performance: 12/2013–3/2016

More information about this project is available on the RPSEA website.

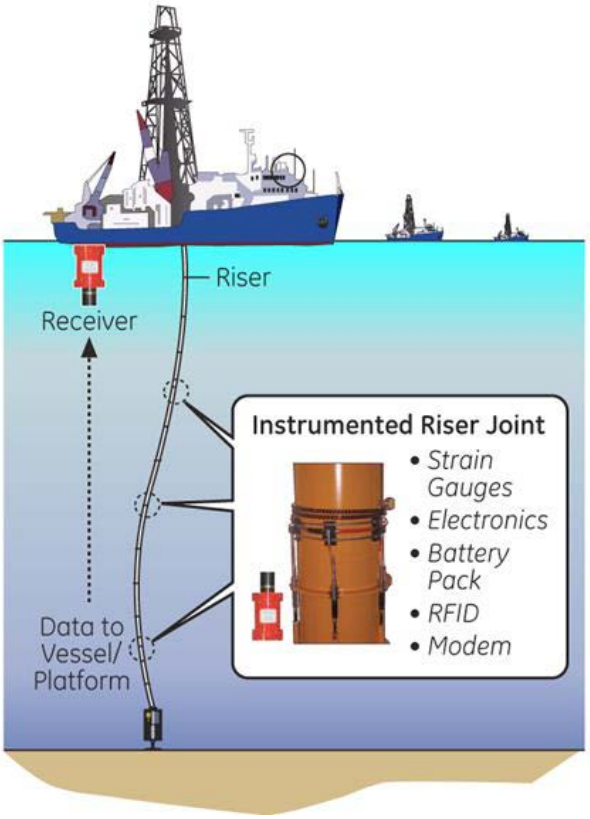

Image caption: *Riser Lifecycle Monitoring System (RLMS) design concept.*

Hi-Res Environmental Data for Enhanced UDW Operations Safety

Objective: To take near-surface ocean current measurements from a plane as well as near-bottom measurements from a weighted instrument close to the seafloor; analyze these measurements against 3-D numerical models; and develop a technique to survey surface currents in real-time over a large horizontal range (≥ 300 km per day).

Research Conducted: Stronger-than-usual ocean currents can slow riser installation, impede drilling, and increase riser fatigue in the Gulf of Mexico (GOM). The passage of Tropical Revolving Storms (TRS) over areas of relatively higher sea surface temperature [e.g., loop current (LC) or associated eddy (LCE)] may cause elevated currents.

Project researchers will use buoy-moored Acoustic Doppler Current Profilers (ADCP) to obtain high resolution measurements; this data will be analyzed, and modeling of near bottom currents in areas of complex local bathymetry. Airborne Expendable Current Profilers (AXCP) will be used by project researchers to obtain high resolution measurement, analysis, and modeling of near surface currents (100 - 300 m) following a combined TRS-LC/LCE event. Researchers will develop an accurate real-time surface current measurement service using an aerial platform to produce survey maps of greater than 300 km per day.

Once the commercial version of the Remote Ocean Current Imaging System (ROCIS) is deployed engineers in the field will have access to vital, real-time ocean current data. This real-time data can be used by engineers to anticipate surface and subsurface ocean forces and design safer, more fatigue-resistant platforms.

Results:

- Surface current data have been collected.
- Oceanographic instrumentation (i.e., the ADCPs) has been deployed to begin the in situ near-bed measurement program.
- The Navy Coastal Ocean Model (NCOM) has been configured for the region around the mooring array and a hindcast has been completed for the first set of data.
- No field collection attempt was made using AXCPs during 2014 because of a relatively quiet hurricane season.
- Researchers completed the Remote Ocean Current Imaging System (ROCIS) prototype.

Ongoing Research: The researchers have collected surface current data and are conducting the analysis and modeling. The second service visit for the near bed mooring array will be completed in early 2015 before demobilization in May. The team will monitor activity in the tropics and develop an operations plan to respond to a combined Tropical Revolving Storm (TRS)/ Loop Current (LC) event during the 2015 hurricane season. They are in the process of developing a commercial plan for deploying ROCIS.

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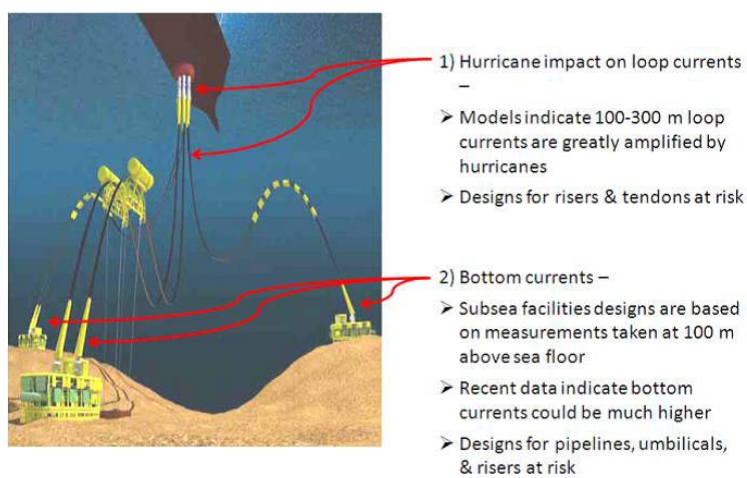
Lead Performer: Fugro Global Environmental and Ocean Sciences, Inc.

Grant Stuart, Fugro Global Environmental and Ocean Sciences, Inc., (713) 346-3642, gstuart@fugro.com

Project Number: 11121-5801-01

Period of Performance: 2/2014-9/2016

More information about this project is available on the RPSEA website.



Methodology and Algorithm Development for the Evaluation of Ultra-Deepwater or Arctic Floating Platform Performance under Hazardous Sea Conditions

Objective: To provide the methodology and algorithms that will improve the existing modeling capabilities and provide engineers with information they need to improve platform safety and performance.

Research Conducted: Dangerous conditions created by wind and ice floes, particularly in the winter, pose a great risk to Artic floating platforms. Some capabilities for modeling platform performance in hazardous seas already exist; this project seeks to improve these capabilities.

Project researchers will develop a methodology and associated algorithms for the evaluation of ultra-deepwater floating platform performance under hazardous sea conditions. Researchers will develop numerical tools and implement them for computation of ultra-deepwater floating platform performance and safety for the extreme ocean conditions.

Some initial investigations and modeling have begun. The researchers have also been studying slamming loading models and worked on modeling static ice impact loading.

The models being developed through this project will help engineers anticipate platform fatigue and stress caused by hazardous sea conditions; this information will guide engineers as they make critical design decisions and seek to design and build more-resilient platforms.

Results:

- Current Arctic offshore structures have been identified and designed specifications and characteristics have been gathered. One floating Arctic offshore platform in particular—Kulluk—stands out as an ideal candidate for algorithm development.

Ongoing Research: The researchers will continue to work on building the computational framework within which to implement the algorithms and will develop and execute a testing and evaluation program. They will test the results against the models.

NETL Contact: Gary Covatch, Gary.Covatch@netl.doe.gov

Lead Performer: Offshore Dynamics, Inc.

Dr. Shan Shi, Offshore Dynamics, Inc., (281) 989-7900, mail@offshoredynamics.com

Project Number: 12121-6402-01

Period of Performance: 7/2014-7/2016

More information about this project is available through the RPSEA website.

Image caption: *NOAA ship Delaware II in bad weather on Georges Bank. While these ocean waves are random, and not Stokes waves (in the strict sense), they indicate the typical sharp crests and troughs as found in non-linear surface gravity waves. (Image from Wikipedia)*

Development of Advanced CFD Tools for the Enhanced Prediction of Explosion Pressure Development in Early Project Phase and Deflagration to Detonation Transition Risk on US GOM Drilling and Production Facilities

Objective: To develop tools for oil and gas companies operating in the GOM that will enable them to design inherently safer offshore facilities able to survive gas explosion incidents while preventing escalation.

Research Conducted: A large vapor cloud explosion and a subsequent fire is one of the most dangerous situations for ultra-deepwater drilling facilities. This is especially true in the remote environment of the Artic and GOM, where the availability of rescue crews and external fire control is limited. Predicting how fires or explosions may expand and designing topside structures to withstand these maximum credible events (MCE) are essential for risk management, safer designs, and protecting human life. Currently, the lack of validated design tools for predicting the risk of deflagration-to-detonation transition (DDT), where the consequences can be orders of magnitude larger than typical deflagrations, prevents mitigating the problem in the design phase.

This project is in the early stages of concept development and design. Preliminary design ideas for flame acceleration simulator (FLACS) CFD simulations are being developed. A rig design process is in the very early stages for upcoming large-scale experiments. Suppliers have been contacted, and price quotes have been obtained.

This project will validate FLACS and enhance that software improve and adapt the capabilities for predicting MCE early in the design phase of GOM UDW drilling and production facilities that may be extended to Arctic environments. Guidance and recommend practices, combined with inherently safer designs, will minimize the consequences of fire/explosion incidents.

Results:

- A concept report was written and submitted. This report details the concept development, as well as design and testing procedures. A draft was submitted on January 3rd, 2015.
- Initial FLACS CFD simulations of the preliminary design were sensitive to grid cell size and the team is working to optimize the grid resolution to obtain meaning results.

Ongoing Research: The project is divided into two phases. In the first phase, DDT onset prediction capability for the industry-standard explosion modeling CFD software, FLACS, will be validated for scales and geometries relevant to GOM ultra-deepwater structures. Validation will occur through a series of large-scale experiments to assess DDT onset of methane, ethylene and propane. The test data will be used to provide data for model validation, and to improve and adapt the tools for MCE prediction in the design phase of GOM facilities. In Phase 2, an anticipated congestion methodology will be developed for offshore drilling and production facilities. Guidance and recommended practices will be developed for facility owners and designers.

NETL Contact: Gary Covatch, Gary.Covatch@netl.doe.gov

Lead Performer: GexCon, Inc.

Scott Davis, GexCon, Inc., 301-915-9922, sgdavis@gexcon.com

Project Number: 12121-6403-01

Period of Performance: 8/2014-9/2016

Additional information about this project is available on the RPSEA website.

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