NATIONAL ENERGY TECHNOLOGY LABORATORY

Research Portfolio Report

Ultra-Deepwater: Subsea Systems Reliability / Automated Safety Systems

U.S. DEPARTMENT OF ENERGY

Research Portfolio Report

Ultra-Deepwater:
Subsea Systems Reliability / Automated Safety Systems

DOE/NETL-2015/1695

Prepared by:

Mari Nichols-Haining, Jennifer Funk, John Oelfke, and Christine Rueter
KeyLogic Systems, Inc.

National Energy Technology Laboratory (NETL) Contact:

James Ammer
james.ammer@netl.doe.gov

Contract DE-FE0004003
Activity 4003.200.03

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed; or represents that its use would not infringe privately owned rights. Reference therein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ACKNOWLEDGEMENTS

The authors would like to express appreciation to all the individuals who contributed to this project and the preparation of this report, including Karl Lang of Leonardo Technologies, Inc. The authors thank the reviewers, including James Pappas [Research Partnership to Secure Energy for America (RPSEA)], Roy Long (NETL), James Ammer (NETL), John Oelfke (KeyLogic Systems, Inc.), and William Schuller (AECOM); their constructive comments are greatly appreciated. The authors would also like to thank the numerous industry technology developers and practitioners who developed the technology, conducted field tests, and attempted to expand the application of the technology to wider applications. This work was funded by the U.S. Department of Energy Office of Fossil Energy through the National Energy Technology Laboratory.

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.

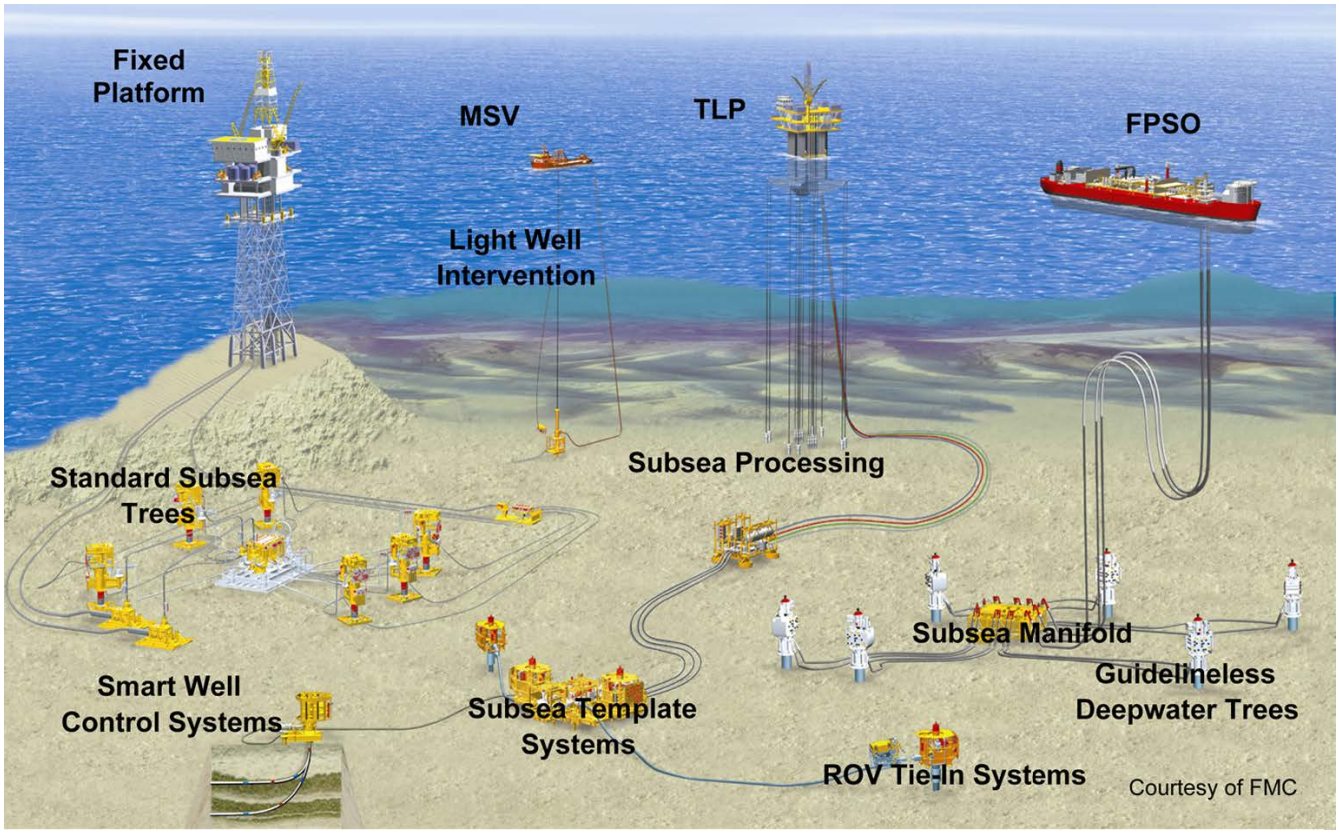


Image caption: *Surface and subsea systems.*

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.

UDW research must develop inherently safer surface and subsurface designs to reduce the risks of accessing UDW oil and natural gas resources

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 Subsea Systems Reliability / Automated Safety Systems research area is a critical component for reducing risk and enhancing safety in UDW exploration and production.

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

Subsea systems reliability/automated safety systems 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 are:

- Developed a new autonomous underwater vehicle that can be used for rapid on-site assessments;
- Developed new subsea sensing capabilities that can be used to inspect underwater structures and detect potential safety issues more effectively and more quickly; and
- Created new technologies for detecting and inhibiting microbially-induced corrosion in subsea systems.

Introduction

The goal of the UDW program is to improve the reliability of conditionally-accessible systems located on the ocean floor, up to 2-¼ miles from the nearest service/control vessel. This research focuses on improving risk management, increasing drilling safety, providing 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 Subsea Systems Reliability / Automated Safety Systems bin. The first section of this report provides an overview of the bin. Project summaries for each of the projects 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 subsea systems reliability / automated safety systems research?

Subsea systems reliability/automated safety systems research combines expertise from many fields—including oceanography, engineering, remote sensing and imaging, and geology—to collect and analyze datasets, improve existing modeling techniques, and build new vehicles, sensors, and tools that will improve safety and reduce the environmental impact of offshore drilling.

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

- Increasing safety and improving capabilities for inspection of subsea systems through new underwater inspection platforms; sensors; and tools, methods, and models.
- Addressing the problem of hydrate formation through hydrate characterization and simulation of hydrate formation and dissipation dynamics.
- Making power systems more efficient and cost-effective.
- Improving underwater communication capabilities.

Why conduct this research?

Subsea Systems Reliability / Automated Safety Systems research develops the tools, techniques, and methods to minimize the impact of ultra-deepwater drilling on marine life and coastal communities and to prevent/minimize the impact of accidents. This research could substantially decrease the risk of environmental impacts associated with deepwater drilling.

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. The demonstration of new technologies—including advanced equipment packaging, improved sensor and system reliability, standardization, and advanced flow assurance understanding—may help to ease public concern about the risks of impacts from UDW drilling after the Macondo well blowout.

Accomplishments

Accomplishments from subsea systems reliability / automated safety systems projects include novel technologies and the results of analysis using predictive models that provide valuable contributions to industry understanding. Some of the projects

High Resolution 3D Laser Imaging for Inspection, Maintenance, Repair, and Operations

For this project, researchers applied 3-dimensional (3D) laser imaging technology underwater to improve subsea inspections, maintenance, and repair. The researchers developed an operational underwater laser sensor to scan targets in a pool environment and then integrated the laser sensor with the power and communications from an industry leading remotely operated vehicle (ROV).

The project fully validated the capabilities of underwater laser imaging to collect accurate 3D data of objects found in deepwater oil and gas production systems. This technology will be commercially marketed in late 2014.

Additional details on this project are available on p. 31.

in the Subsea Systems Reliability / Automated Safety Systems 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 subsea drilling and production:

- ***Flow Phenomena in Jumpers and its Relation to Hydrate Plugging Risk*** – University of Tulsa performed transient flow experiments in pipe geometries typical of low spots encountered in "jumper" systems (the seafloor piping used to connect subsea wellheads to subsea production manifolds prior to its transmission to the surface) where methane hydrate plug formation can be a serious safety problem. The water displacement was measured as a function of operating parameters and compared to state-of-the-art transient simulation results. An accurate prediction of the water phase location and behavior during flow restart conditions is necessary to properly simulate hydrate formation and evaluate the risk of plug formation in jumper systems following shut-ins. This project will improve confidence in the performance of transient flow simulators when applied to jumper geometries and/or the identification of their shortcomings. The phenomena resulting from this work was incorporated into existing commercial modeling tools and is now being utilized by industry.

- ***Improving Inspection through Laser Scanning*** –3D at Depth, LLC developed laser scanners that can conduct more-effective underwater inspections. The researchers used an operational underwater laser sensor to scan targets in a pool environment; this capability was integrated with the power and communications from an industry ROV developed through another project and will be commercially marketed. It is also being adapted and tested on an automated underwater vehicle developed in a separate UDW research program project by Lockheed Martin.

- ***Modeling Shows Impact of Hydrate Dissociation under Different Conditions*** – University of Tulsa developed an engineer's estimation tool for designing appropriate methane hydrate dissociation methods for different operational conditions. This tool has been released for public use and is being used in the field for selecting the best dissociation method for application in specific situations.

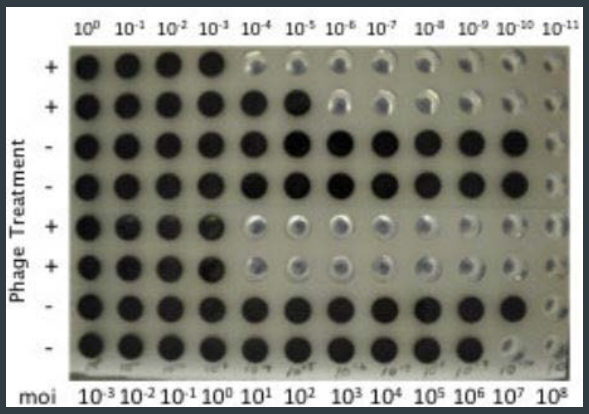
- ***Small-Scale Sensing Technologies Improving Pipeline Monitoring*** – University of Tulsa developed a prototype small-scale sensing "capsule" with encased electronics that is compatible with hydrocarbon fluids and can be used inside pipeline maintenance pigs of any size and configuration to measure fluid conditions, map pipeline features, and identify potential wall buildup or defects. The tool can be used in pipelines that conventional in-line-inspection tools cannot traverse, significantly reducing deployment cost and risk. It can also be used to provide near real-time monitoring of critical pipeline characteristics. The prototype is scheduled to be tested in a major long distance pipeline soon. If the trial is successful, plans are to incorporate the design in commercial applications within 2 years.

- ***Using Bacteriophages Rather than Biocides to Inhibit Bacteria*** – Phage Biocontrol, LLC tested the use of bacteriophages (bacteria-killing viruses) to reduce the prevalence of corrosion causing sulfate reducing bacteria (SRB) in production equipment and pipelines, as an alternative to the traditional method of controlling bacteria by injecting

Replacing Chemical Biocides with Targeted Bacteriophages in Deepwater Pipelines and Reservoirs

The objective of the project was to evaluate the use of bacteriophage, or phage, the natural viral predators of bacteria, in a focused approach to reduce the agents of microbially-influenced corrosion from the production wellhead to the refinery, including pipelines. Phage are highly specific to their target bacteria and are harmless to any other cells, or non-targeted bacteria. Phage targeting problem bacteria can be injected at the head of the pipeline for long term biological control, thus reducing the environmental impact by negating the use of biocides for bacteria control.

Additional details are available on p. 42.



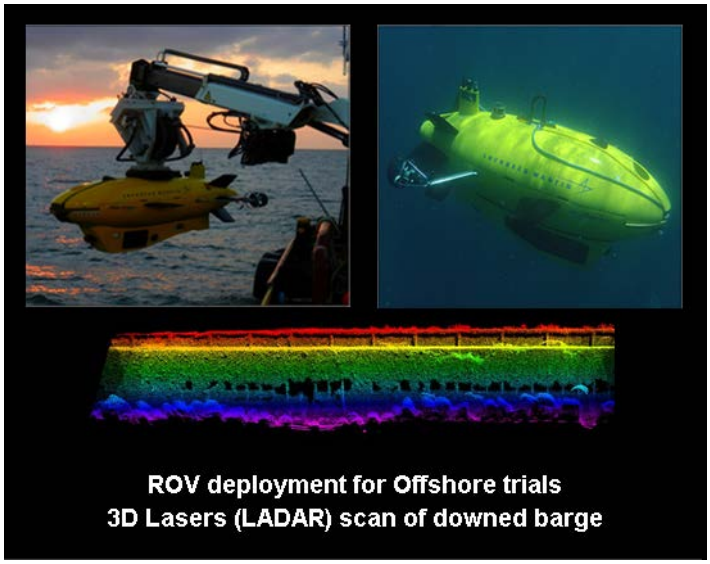
chemical biocides into the flow stream. Researchers used a novel sequencing approach to identify the diversity of bacteria in samples. Naturally-occurring phages were located, isolated, and determined to be effective against bacterial concentrates. Individual phages were found to not only inhibit SRB growth by six orders of magnitude or better, but, unlike biocides, were long lasting.

- ***Improved Evaluation Technology for Identifying Microbially-Influenced Corrosion*** – For this project, Livermore Instruments, Inc., along with many industry partners and universities (including Phage Biocontrol, LLC; Texas A&M University; ConocoPhillips Company; and Shell International Exploration & Production) completely redesigned an existing single particle aerosol mass spectrometer (SPAMS). Its optical system was simplified, reducing the system's nine lasers to only two with a corresponding decrease in the complexity of laser alignment and completely rewritten driver software. The redesigned SPAMS was deployed to Ecolyse, Inc's (now Phase Biocontrol, LLC) research laboratory, where it was successfully used to analyze eight species of microorganisms prepared in dozens of cultures. The new device was able to discern different microorganisms with minimal preparation at concentrations of up to roughly 10^9organisms/ml. The SPAMS 3.0 instrument is now commercially available.

What are the benefits of subsea systems reliability / automated safety systems research?

Protecting marine ecosystems and coastal communities from ultra-deepwater drilling impacts is a top priority. NETL carries out subsea systems reliability/automated safety systems research to improve existing safety systems; develop tools that can quickly, effectively identify problems; and identify way to mitigate the potential environmental risks of ultra-deepwater oil and gas development.

Extreme variations in temperature and pressure in the ultra-deepwater environment present unique challenges to software and equipment designers. The projects in this research bin are designed to address those and other challenges. The benefits range from improving our understanding of how processed fluids behave in subsea environments and improving existing equipment, to developing and applying state-of-the art technologies. NETL also carries out this research to improve industry's understanding of ultra-deepwater production processes and help ensure that these systems operate safely and effectively.



Lessons Learned

As with any type of research, subsea systems reliability/automated safety systems 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.

- **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 for understanding how equipment operates under deep subsea conditions where hands-on field testing is impossible.
- **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.
- **The most likely prospective energy source for subsea power generation is not oil or gas**: Small pressurized-water reactors with low-enrichment fuel, similar to those used on commercial ships, will most likely become the subsea power sources for subsea equipment located remotely from deepwater platforms.
- **Alternatives to chemical biocides can be effective in reducing corrosion due to sulfate reducing bacteria:** Phages, viruses that attack bacteria, can be identified and used to target specific types of microbes that cause corrosion in enclosed producing systems. This approach could reduce the need for toxic chemicals in subsea systems and thus reduce the potential for environmental impacts.

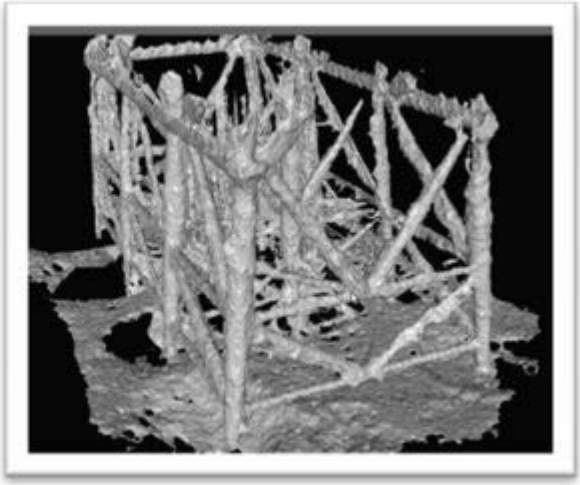


Image caption: *3-D modeling of subsea structures.*

Subsea Systems Reliability / Automated Safety Systems Projects

Bin sub-area / project	Report page no.
SUBSEA SYSTEM RELIABILITY / AUTOMATED SAFETY SYSTEMS	
Improvements to Deepwater Subsea Measurements	13
Subsea Systems Engineering Integration	15
Deep Sea Hybrid Power System	17
Heavy Viscous Oil PVT	18
Ultra-Reliable Deepwater Electrical Power Distribution System and Power Components	19
Wireless Subsea Communications	21
Ultra Deep Water Seabed Discharge of Produced Water and/or Solids	22
Corrosion and Scale at Extreme Temperature and Pressure	23
More Improvements to Deepwater Subsea Measurement	24
All-Electric Subsea Autonomous High Integrity Pressure Protection System (HIPPS) Architecture	25
Construction and Testing of Deepwater Permanent Subsea Pressure Compensated Chemical Reservoir	26
Subsea Produced Water Sensor Development	27

Bin sub-area / project	Report page no.
Subsea DC Connectors for Environmentally Safe and Reliable Powering of UDW Subsea Processing	28
INSPECTION AND REPAIR	
Technologies of the Future for Pipeline Monitoring and Inspection	29
Autonomous Inspection of Subsea Facilities	30
High Resolution 3D Laser Imaging for Inspection, Maintenance, Repair, and Operations	31
Sensors and Processing for Pipe, Riser, Structure, and Equipment Inspection to Provide Detailed Measurements, Corrosion Detection, Leak Detection, and/or Detection of Heat Plumes from Degraded Pipeline Insulation	33
Autonomous Underwater Inspection Using a 3D Laser	34
GAS HYDRATES IN THE ENVIRONMENT	
Wax Control in the Presence of Hydrates	35
Flow Phenomena in Jumpers-Relation to Hydrate Plugging Risk	36
Hydrate Characterization & Dissociation Strategies	38
Displacement and Mixing in Subsea Jumpers	40
Hydrate Modeling & Flow Loop Experiments for Water Continuous & Dispersed Systems	41
MARINE CHARACTERIZATION	
Replacing Chemical Biocides with Targeted Bacteriophages in Deepwater Pipelines and Reservoirs	42
Enumerating Bacteria in Deepwater Pipelines in Real-Time at a Negligible Marginal Cost Per Analysis: A Proof of Concept Study	43

Improvements to Deepwater Subsea Measurements

Objective: To develop a suite of measurement technologies capable of addressing pivotal gaps in flow measurement during deepwater production.

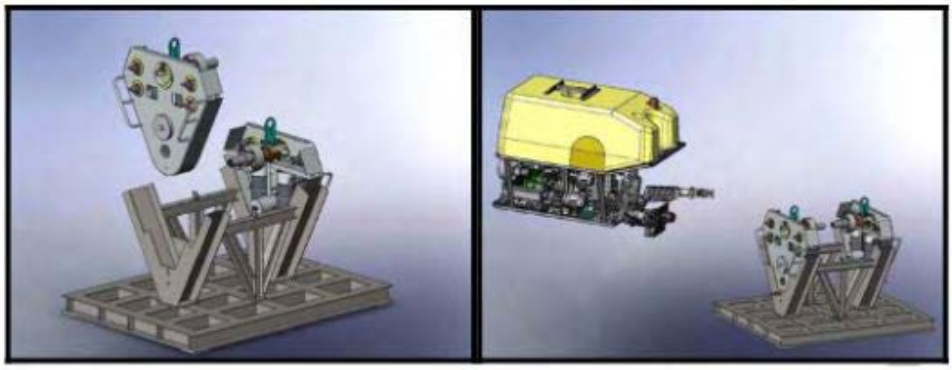


Image caption: *Operational concept-subsea sampler module and deployment frame.*

Research Conducted: There is a critical need for better measurement techniques and technology for measuring ultra-deepwater well rates. Although there are many reasons for subsea metering, the most universal is that deepwater production is driven by economics. The cost of equipment governs how the fluids will be produced and conveyed to the surface, forcing measurement practices to adapt to this reality. Given the fact that the cost of deepwater, high-pressure oil or gas flowlines is typically $10–20 million per mile, the business driver is the need to minimize subsea pipelines in any given situation. By commingling production as soon as feasible, test lines—commonly used in shallow waters—can be eliminated, saving tens of millions of dollars; however, the implications of comingling on well production are significant. Tests on individual wells through production flowlines are simply not practical; therefore, some form of subsea measurement is the only way to obtain individual well rates.

The joint industry project comprised six individual sub-projects:

- Development of methods for standardized deepwater fluid sampling
- Development of techniques for conveyance by remotely operated vehicle (ROV) of clamp-on measurement to the sea floor
- Development and qualification of sensors that measure pressure, temperature, and differential pressure for high pressure–high temperature applications
- Evaluation of the effectiveness of wellbore flow models such as virtual flow meters
- Understanding of how fouling of meters affects their response
- Development of tools to model uncertainties in a subsea-topside measurement system

The project sought to address gaps in industry's ability to deploy and operate multiphase and wet gas meter technology in deepwater production systems. Continuous measurement information collected on individual subsea wells using this technology will help better assess well performance and thus improve recovery from deepwater reservoirs beyond current capabilities. Better and more extensive measurement could be critical as well for increasing both the safety of deepwater production and protection of the environment.

Results:

- Seven of the world's major deepwater operators cooperated in this project in addressing the critical challenge of subsea flow measurement
- Means for implementing subsea sampling were developed without incurring any potential patent liability
- The industry's first high-pressure, high-temperature, differential pressure sensor was developed for use in deepwater .
- The first catalog of fouling effects (erosion, scale) on flow measurement through differential meters (Venturi, cone, wedge) was created.
- A software simulation tool to model the flow rate uncertainty in a multiphase pipeline network, and calculated the uncertainties of various important quantities (e.g., system balance) was developed.
- The subsea industry was informed of the need for sampling strategies and mechanisms for sampling production streams in deepwater.

Improvements to Deepwater Subsea Measurements

- The first method of using an ROV for conveying and deploying clamp-on flow measurement equipment to the sea floor was developed.
- The effects of erosion and scale buildup can be modeled, permitting the prediction of the magnitude of the effect if the extent is known. Virtual flow meter (VFM) performance varies widely among vendors and can be evaluated in such a way that insight into their use can be provided. Lessons in ROV-conveyed sampling and measurement tasks and major portions of the designs are available as a download to manufacturers and industry.

Ongoing Research: A follow up project, 10121-4304-01: More Improvements to Deepwater Subsea Measurement, is in progress (p. 24 of this report).

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

Lead Performer: Letton-Hall Group, LLC

Winsor Letton, The Letton-Hall Group, (713) 974-7328, letton@letton-hall.com

Project Number: 07121-1301

Period of Performance: 10/2008–5/2012

Read/download the final report.

Subsea Systems Engineering Integration

Objective: To produce an open access process simulation tool (simulator) suitable for modeling Subsea Processing Systems for oil and gas. The goal was to (1) provide an industry standard to evaluate SPSs performance and (2) help bridge technology readiness level gaps between operation engineers and facility suppliers.

Research Conducted: Producing the substantial but challenging oil and gas resources in water depths greater than 1,500 meters requires a complex and integrated systems approach, where the time from first discovery to first production can range from six to nine years, and individual well costs can exceed $100 million. Lack of good analytical process models, dependence on field relevant testing, relevance of laboratory data, and the ability to extrapolate from new conditions resulted in a need to develop physics-based analytical process models. Risk reduction through a lab-scale facility designed for reliability will improve Subsea Processing Systems field development by offering a tool that can be used to verify subsea – topside controls, search for errors, add redundancies, and instantaneously view results to determine capabilities and feasibilities.

The study was divided into activities to develop:

- A library of robust analytical models for compact separation devices operating in subsea multi-phase flow environment
- A robust process simulator combing the analytical models in such a fashion as to provide a prediction of both steady-state and transient performance, user configurability, and interface with existing upstream industry standard production simulators
- A lab-scale test facility and testing protocols for validation of both the analytical models and simulator performance
- A methodology and associated procedures for using the simulator to determine the operational envelope for various process designs
- Simulator performance validation by executing a test plan to evaluate over a wide range of conditions using the lab-scale test facility and protocol
- A technology transfer plan that provides for rapid dissemination of the simulator, including a plan to improve the simulator by incorporation of end-user feedback

Results:

- An architectural model was developed upon which subsea processing simulations can be developed. It is a general-purpose process simulator featuring minimal architectural overhead that puts all the functionality in user-developed unit models. It removed unnecessary impediments to allow the user full modeling license. Hierarchical modeling was enabled by standardized unit model interfaces, arbitrarily expandable data structures, tag-based calls, and an organization that aids documentation.
- Numerical Propulsion System Simulation (NPSS) was used as the framework for the simulator architecture. NPSS was developed by the NASA Glenn Research Center as an object-oriented engineering environment for use in analysis and design of complex systems and includes an open architecture with a flexible user interface. NPSS is a state-of-the-art simulation tool that is becoming the gold standard for system modeling in the aerospace industry.
- A MATLAB version was developed as a bottom-up tool to help drive the development. MATLAB is a high-level language and interactive environment for numerical computation, visualization, and programming.
- The simulator has the capability to interface with commercial codes such as AspenTech's HYSYS. Aspen HYSYS is a comprehensive process modeling system used by the world's leading oil and gas producers, refineries, and engineering companies to optimize process design and operations.

Image caption: *RPSEA test separator.*

Subsea Systems Engineering Integration

- A flow loop with a three-phase separator was developed as a vehicle for validation. A model of the loop was built with the simulator, a test matrix was simulated, and the tuning process was used to match data to simulation.
- The program deliverables include simulation architecture, functional simulator, procedures and documentation, experimental validation, and experimental facility availability.
- The study found that a general-purpose process simulator featuring minimal architectural overhead that puts all functionality in user-developed unit models can be based universally. With an architecture that is a viable framework to simulate subsea processing, the two logical next steps are to tackle a process that more closely stimulates desirable produced flow management requirements in the Gulf of Mexico and to stimulate fluids that come closer to real produced fluids. In modeling these processes, it is suggested that physics such as surface tension due to pressure changes or more complex physical models for the gravity separation be considered (i.e., considering droplet packing, foam formation, film drainage, etc.).

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

Lead Performer: GE Global Research Center

Christopher Wolfe, General Electric Global Research, (518) 387-5106, wolfe@research.ge.com

Project Number: 07121-1901

Period of Performance: 12/2008–7/2011

Read/download the final report.

Deep Sea Hybrid Power System

Objective: To evaluate alternatives and recommend equipment to develop into hybrid energy conversion and storage systems for deep ocean operations. The power systems would supply all power needs for the location so that there would be no electrical umbilical from a 'host' platform.

Research Conducted: As oil and gas reserves onshore or in close proximity to shore are exhausted, it will be necessary to develop fields further from shore and at greater depths.

Subsea facilities will require ample supplies of power to operate machinery on the ocean floor, ranging from control modules to pumps and compressors to supplying power for an entire drilling vessel.

The initial study considered numerous power generation/energy conversion and energy storage technologies to support the exploration and production of oil and gas reserves remotely located offshore in the deep ocean. Detailed analyses of the technologies were then conducted. The parameters evaluated at each site included the following: estimated component weight, total weight, and total volume; initial investment, annual cost, and cost of electricity; and the economy of scale.

Results:

- The top two candidates for power generation were selected.
- Both are based on a small modular pressurized water reactor. One candidate couples the pressurized water reactor with a secondary steam-turbine generator system, whereas the other candidate couples the pressurized water reactor with a solid-state thermoelectric generator.
- The leading candidates for energy storage were identified. Both candidates are versions of sodium-beta batteries: sodium/sulfur and sodium/nickel-chloride (also known as ZEBRA batteries).
- The weight of the hybrid energy conversion and storage systems for the three largest sites studied were between 10,000 and 100,000 metric tons. Thus, the largest hybrid systems will have weights comparable to nuclear powered ships.
- The capital costs were dominated by parameters that were insensitive to the size of the site. Subsea vehicular options were the most expensive and least practical. The subsea vehicle that ferries stored energy from the surface to the site via batteries was by far the worst option, and was not given any serious consideration.
- Like the initial capital cost, the annualized costs were dominated by parameters that are insensitive to the size of the site. The least expensive option for power at all of the concept-of-operations sites was the electrical grid, with an assumed cost of approximately $2.5 million per kilometer.
- Regarding the cost of electricity, hybrid power options that were considered comparable to the grid option were the pressurized water reactor and a fuel cell on the ocean floor fueled with wellhead methane and a line to the surface for compressed air. As the systems become larger, the cost of electricity produced by the system becomes less expensive, regardless of the hybrid system assumed. The two largest sites were of sufficient size so that power can be supplied for less than $1 per kilowatt-hour, comparable to the cost for grid power.

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

Lead Performer: Houston Advanced Research Center
Rich Haut, Ph.D., Houston Advanced Research Center, (281) 364-6093, rhaut@harc.edu

Project Number: 07121-1902

Period of Performance: 10/2008–10/2010

Read/download the final report.

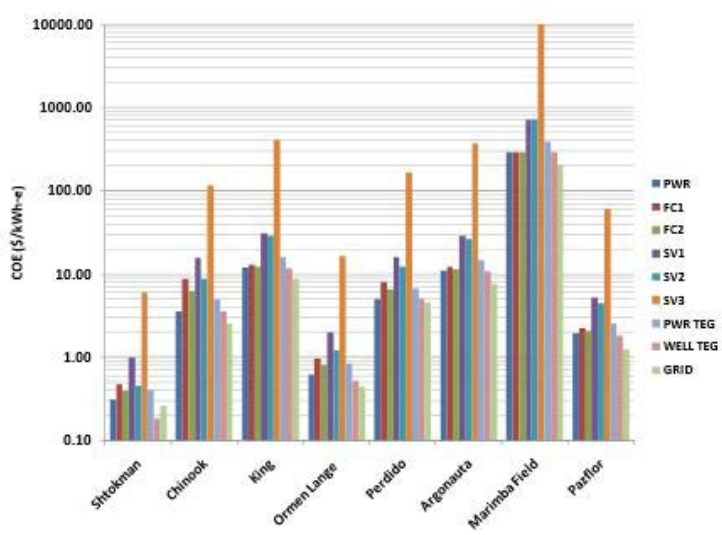


Image caption: *Estimated cost of electricity for each site.*

Heavy Viscous Oil Pressure, Volume, and Temperature

Objective: 1) To evaluate current practices for heavy viscous oil (HVO) dewatering and measurement and investigate how solvents change oil viscosity and 2) to develop best practices for handling samples and measuring sample dewatering and viscosity in the laboratory. The scope was expanded during the project to include an additional objective: creating procedures for reconstituting live heavy oil and measuring its viscosity and density.

Research Conducted: Most oil produced by wells is accompanied by gas. Even after the gas and oil are run through a separator and placed in a holding tank, gas often remains trapped in the oil and can be seen bubbling to the surface. This oil is known as "live oil." Conversely, "dead oil" is relatively thick and does not carry formation gas. It is obtained through the distillation of coal tar and is heavier than water.

To measure HVO viscosity and analyze HVO viscosity behavior, researchers qualified three sample dewatering methods to determine the one most suitable for preparing HVO samples for laboratory testing and analysis. The team first calibrated the three viscometer types tested—capillary, rheometer, and electromagnetic—with a viscosity standard. Next, dead oil viscosity measurements were performed with each viscometer, with the researchers focusing on validating the three types of viscometers by measuring HVO viscosities at various temperatures and pressures. Doing so enabled the team to develop guidelines on viscometer selection based on both the viscosity range and accuracy of the measurements. The team also reconstituted live oil, prepared live HVO and a live HVO solvent mixture, measured the gas-oil ratio (GOR) of live HVO samples, investigated the live oil's constant composition expansion, and documented the results in a detailed laboratory best practices document. Finally, the team measured the viscosity of the live HVO and HVO solvent mixtures under various conditions using an electromagnetic viscometer (EMV) and capillary viscometer, then measured density using a high-pressure Anton Paar densitometer.

These tests were used to create guidelines for viscometer selection and a database for viscosity model validation and development.

Results:

- Calibration experiments demonstrated that each viscometer reproduced viscosity standards within five percent. The capillary viscometer and EMV were comparable for the samples tested, repeatable to within 10 percent for all three types of dead HVO samples, with some discrepancies at high temperature and pressure conditions for live HVO.
- The open system rheometer generated viscosities for the lightest HVO that were higher than their actual viscosities. The GOR for all three prepared live HVO samples was repeatable to within one-percent variance.
- The composition of one of the dead oil samples changed under high temperature during the rheometer open system dead oil tests, which resulted in overestimated viscosities. In addition, although piston selection affected EMV-measured oil viscosities, the discrepancy was not observed during validation experiments. The EMV viscosity measurements of live oil were higher than the viscosity measurements made using the capillary viscometer. However, the order was reversed when viscosity was greater than 100 Centipoise.

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

Lead Performer: Schlumberger Technology Corporation

Hongying Zhao, Schlumberger Technology Corporation, 780-577-1932, HZhao8@slb.com

Project Number: 08121-2201/02

Period of Performance: 7/2011–12/2014

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

Ultra-Reliable Deepwater Electrical Power Distribution System and Power Components

Objective: To develop a cost-effective, high density, modular and scalable electrical transmission and distribution (T&D) system for use in deep tieback environments.

Research Conducted: Subsea electrical power transmission and distribution presents unique challenges; electricity generated at the surface needs to be transmitted safely and effectively to the seabed with minimal power loss in the transfer.

Power is generated on shore or on a platform and transmitted to the subsea AC/DC distribution system. The performer developed a Modular Stacked Direct Current (MSDC) system in which MSDC converters are connected in a series to serve as DC-to-AC converters with variable frequency output. Each converter consists of one or more MSDC modules with a standardized power rating, and the number of modules is determined by power and redundancy requirements.

This research sought to improve reliability, robustness, and cost-effectiveness of subsea power systems through the use of MSDC. The potential benefits of the MSDC architecture over conventional AC T&D and DC point-to-point solutions include a reduced number of subsea components, reduced cost, higher flexibility, increased efficiency, and affordable access to deepwater reserves.

This now-completed project was divided into two phases. The objective of Phase I was to assess the MSDC architecture against existing subsea T&D solutions and identify four technology-critical components. Phase II objectives were to design, develop, qualify, and demonstrate those components.

In phase I of the project, a high-level trade-off analysis was performed to assess conventional power T&D technologies against the proposed electrical system: GE's MSDC technology. The researchers focused on four key system components: the MSDC control architecture, system protection, packaging and thermal management, and direct current (DC) connectors. Once the technology readiness levels (TRLs) for these components were established, work on phase II began. In this phase, the team designed and built prototype hardware and performed tests to validate the four components.

During thermal resistance modeling, the researchers sometimes had to make initial guesses for non-linear systems of equations. In several cases, particularly in the studies for alternate field conditions, the researchers found that a converged solution needed to be "slowly migrated" to another converged solution for a completely different set of input parameters. For example, it was not possible to jump from a deep and cold seawater solution to shallow and warm seawater solution without determining several intermediate solutions. The EES software parametric table functionality proved useful for migrating between solutions with vastly different input parameters.

System Control and Protection

To validate the control and protection of the MSDC system, researchers built a 100 kVA lab prototype system. A proposed bypass circuit—consisting of a break-over diode (BOD) -controlled thyristor and mechanical switches—was developed to provide an alternative current path when system components fail, allowing the rest of the system to continue to provide safe and uninterrupted operations. The bypass circuit was installed in the demonstration unit so that full system operation could be emulated, and a control algorithm was implemented in an industrial control platform that is currently used in GE's gas turbine and wind turbine products. The team evaluated the system's performance under various fault conditions and corresponding fault-protection schemes.

Thermal Management and Packing

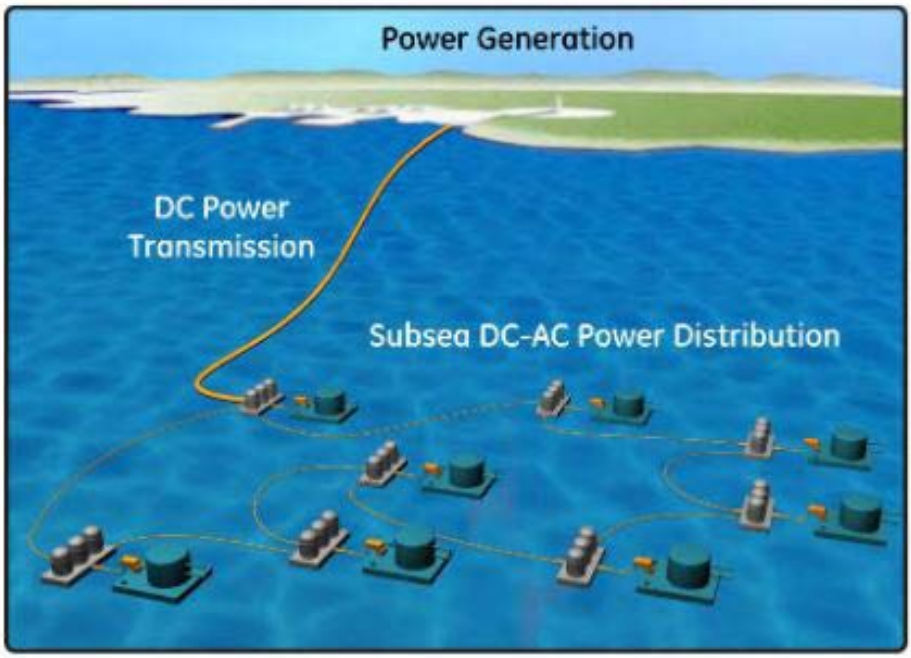
The team selected and validated a passive phase-change cooling approach. The approach, which used pool boiling as the main mode of heat transfer, was chosen based on thermal performance and high reliability. The researchers established a mathematical method for analyzing and designing a pool boiling immersion system: using the model, the researchers studied the impact of a heat sink structure on thermal performance. The result led to an optimized heat sink design for the pool boiling approach, which was tested with a sealed tank and a condenser that was built to emulate the inner condition of a subsea vessel. The team constructed a power converter stack with a press-pack diode and the proposed heat sink, and then immersed the heat sink in the tank containing the coolant. Their results validated this approach. Additionally, packing designs were validated through analytical modeling and finite element analyses.

Subsea DC Connector

A subsea DC connector is a critical component of the system, as it allows for underwater high voltage – high power electrical systems. Because no subsea DC connector is currently commercially available, research and development of this component is essential for the subsea processing industry. Based on their analysis of DC and transient electric field distributions in the

Ultra-Reliable Deepwater Electrical Power Distribution System and Power Components

connector, the research team proposed conceptual designs for a 50 kV, 500 A, single-conductor, wet-mate subsea DC connector. Stress grading materials were used to control the resistively-graded fields, while geometric stress grading was used to control the capacitively-graded fields. As a result, under both DC steady state and transient events, the stress concentration is minimized.



Results:

- The performance of the MSDC concept was demonstrated, and the concept was validated, including transient and fault operation, in the demonstration unit.
- A phase change cooling approach and a hybrid packaging concept were developed and validated.
- Important characterizations of the material insulation strength under DC stress were performed.
- A subsea DC connector concept was designed.

Ongoing Research: A follow up project, 12121-6302-01: Subsea DC Connectors for Environmentally Safe and Reliable Powering of UDW Subsea Processing, is developing a wet-mate subsea connector. This project can be found on p. 28 of this report.

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

Lead Performer: GE Global Research

Rixin Lai, GE Global Research. lai@ge.com, 518-387-5453

Project Number: 08121-2901-01

Period of Performance: 11/2009-11/2013

Read/download the final report.

Wireless Subsea Communications Systems

Objective: To explore the limits and capacity of wireless communications for subsea operations using radio frequency (RF) conduction, which had been shown in the literature as a promising approach for developing subsea communication technology.

Research Conducted: The ability to continuously monitor and maintain increasingly complicated subsea equipment becomes more important as oil and gas exploration and development moves into deeper water. Subsea wireless communications via acoustic, optical, and magnetic/RF technologies have been used in the past, but ambient noise and interference (acoustic), water quality and line-of-sight issues (optical), and communications limited to low frequencies (magnetic/RF) have significantly limited their usefulness under real-world conditions.

A prototype transmitter (a waveform generator) and receiver were built from commercially available components and their theoretical channel capacity was analyzed. The transmitter and receiver were subjected to lab trials in a saltwater fish tank, followed by sea trials conducted off Nahant, Massachusetts. The prototype was deployed 15 feet under a test boat in seawater having a conductivity of 4.3S/M.

The transmitter was configured to send a known but pseudo random data pattern and the receiver was designed to record what it heard. The recorded signal was later processed to determine the characteristics of the channel between the transmitter and the receiver, as well as the effectiveness of the data transmission. Various receiver algorithms were then tested, and the team was able to optimize the receiver to detect the highest data rate at the lowest error rate. This experiment was designed to enable the team to verify predicted theoretical performance against actual performance so that later optimizations can be accomplished using validated models.

Possible applications ranged from short range communications (<100m) which would be appropriate for guidance of Remotely Operated Vehicles (ROVs) and other equipment and very short range (<1m) very high speed communications for transmission of real-time data.

This research has the potential to improve subsea productivity through enhanced asset intelligence (including equipment health monitoring and maintenance) and system reliability (by eliminating connections in data transmission systems). This wireless communication can also be considered crosscutting technology potentially applicable to a broad spectrum of technologies across various energy industries.

Results:

- The feasibility of high data rate communications using RF conduction through saltwater as a mechanism for communications was proven during the sea trial, with the system demonstrating a data rate of approximately 5 megabits per second (Mbps) over a distance of 10 cm. This technology shows potential to replace connectors required for subsea applications, as well as enable temporary connection of mobile devices such as ROVs.
- Physics-based models were developed and verified for the signal propagation, and with increased transmission power further simulation and analysis predicted channel capacities near 50 Mbps.
- The prototype did not support transmission near channel capacity as predicted. Further experiments will be necessary to extend the data rate to 30 - 50Mbps. Given the channel attenuation and channel noise characteristics, channel capacity is 113 Mbps at 1 megawatt (MW) transmission power; however, data rates of 30 to 50 Mbps are more realistic.

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

Lead Performer: GE Global Research

Daniel Sexton, GE Global Research, (518) 387-4121, sextonda@ge.com

Project Number: 08121-2902-03

Period of Performance: 1/2010–12/2011

Read/download the final report.

UDW Seabed Discharge of Produced Water and/or Solids

Objective: To investigate the latest and most proven PW treatment techniques in the offshore industry and evaluated their potential for subsea use.

Research Conducted: Produced water (PW) can be formation water that is brought to the surface along with oil and gas; condensation water (water vapor condensed during production); returned injection water that is used to increase the pressure of the reservoir; or water that is used for de-salting crude. PW from oil fields, whether offshore platforms or onshore, as well as wastewater from refineries, can contain fair amounts of free-floating oil that must be removed before biological treatment and/or discharge of water to the environment.

A team of subject matter experts was assembled to review challenges regarding seabed discharge of PW and/or solids and researched many different sources to properly address them. This team formed the core of a Working Project Group to support the study. Representatives from Anadarko, BP, Chevron, ConocoPhillips, ExxonMobil, Shell, Statoil and Total helped to define a basis of design to guide the study. The team used the basis of design to conduct a thorough regulatory assessment for discharging PW throughout the industry. Seabed and marine life were studied at target water depths of 5000 to 8000 feet. The team then completed a state-of-the-art review into PW treatment process and analytical requirements. A group of subject matter experts within Fluor used that information to complete a series of conceptual design workshops to develop an initial conceptual design for treating and discharging PW at the seabed.

Produced water represents the largest waste stream in oil and gas production. It is complex and some of its components can harm the environment. This is the first study commissioned to better understand the feasibility of discharging PW and/or solids at the seabed. The study shows the latest technologies (having fewer moving parts) that can withstand the high operating pressures and remote operations that are required for subsea processing and that might cost-effectively meet increasingly stringent environmental regulations.

Results:

- The workshops identified gaps in current related technologies and helped establish a technology roadmap going forward.
- The most likely conceptual designs were determined, and the costs and timeframes needed for them to become project ready were estimated (assuming a continuous technology development program):
  - Design B (hydrocyclones, Compact Floatation Unit (CFU), and Coalescing Filters): 2017
  - Design C (hydrocyclones and Coalescing Filters): 2017
  - Design D (CFU): 2015
  - Estimated Cost and Installation, Design B: $168 MM
  - Estimated Cost and Installation, Design D: $132 MM
- After performing this study, it was clear there is a need to better understand how Gulf of Mexico deepwater marine life (whose toxicity to PW is not well understood) might react to current discharge requirements.

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

Lead Performer: Fluor Offshore Solutions

Timothy Daigle, Fluor Offshore Solutions, (281) 295-6542, Timothy.daigle@fluor.com

Project Number: 09121-3100-01

Period of Performance: 12/2010-6/2012

Read/download the final report.

Corrosion and Scale at Extreme Temperature and Pressure

Objective: To obtain the necessary data and develop the models and experimental tools needed to assess corrosion and scale formation and inhibition at the extreme temperatures and pressures encountered during deepwater production.

Research Conducted: The lack of data and models for predicting corrosion and scale under the extreme temperatures and pressures encountered in ultra-deepwater reservoirs increases the economic and safety risks of offshore production.

The team designed and constructed a highly-customized autoclave reactor and flow-through apparatus during Phase I, enabling the investigation of corrosion and scale under extreme high-pressure, high-temperature HPHT (xHPHT) conditions, allowing researchers to collect experimental data and fundamental knowledge regarding the corrosion behavior of different alloy materials. Specifically, mineral scaling, dissolution, and inhibition mechanisms were investigated at xHPHT conditions using a dynamic flow-through setup, with instruments capable of operating at 24,000 psi and 250 degrees Celsius. Researchers also explored a novel vertical scanning interferometry (VSI) technique. The VSI technique investigated for this project has great potential for localized corrosion and mineral scaling.

The project will culminate with a detailed technical manual of recommended decision support guidelines for predicting scale and corrosion formation potential in ultra-deep HPHT wells, as well as recommended equipment and procedures for scale and corrosion testing. This research will enable more accurate corrosion and scale prediction and prevention during oil and gas production, ultimately improving safety, environmental protection, and economic security.

Results:

- Experimental data at 250 °C and 24,000 psig was obtained, and validated experimental methods and procedures were developed for testing under xHPHT conditions.
- A new VSI technique was developed and applied to corrosion and mineral scaling.
- The equation of state modeling, based on statistical associating fluids theory, was advanced by including mean spherical approximation. This advancement facilitated the development of a thermodynamic model for predicting phase behavior of brine-hydrocarbon-acid gas systems at xHPHT.
- The literature review of current approaches to measuring and modeling corrosion scale and stress cracking under xHPHT conditions revealed that no comprehensive approach or techniques existed.
- Some experiments measuring the thermodynamic properties of barite in aqueous solution did not yield the expected results. The differences will be investigated in phase II.

Ongoing Research: In Phase II, the team will continue to study various alloy systems under different fluid compositions at xHPHT to further simulate realistic scale and corrosion effects occurring during ultra-deepwater production. Research on inhibitor thermal stability and treatment methodologies will continue into Phase II as well. Modeling will focus on understanding the solvent behavior in mixed electrolytes, and will expand to include the water-ion and ion-ion interactions in an effort to quantify kinetic factors such as diffusion coefficients.

NETL Contact: William Fincham, William.Fincham@netl.doe.gov

Lead Performer: Brine Chemistry Solutions, LLC

Ross Tomson, Brine Chemistry Solutions, LLC, 713-487-5813 x20, ross.tomson@brinechem.com

Project Number: 10121-4204-01

Period of Performance: 8/2012–8/2015

Read/download the Phase I Final Report.

More Improvements to Deepwater Subsea Measurement

Objective: To reliably assess deepwater well production and well control conditions, develop techniques and methods to respond to those conditions, and reduce the risk associated with uncontrolled fluid emissions from subsea drilling equipment.

Research Conducted: This project builds upon a previously concluded RPSEA project (award 07121-1301).

Phases I and II of this project are complete. The initial subcontracts have been put into place and a content management system designed and launched. Progress was made on the development of a high-pressure, high-temperature differential pressure transmitter and a system to monitor mud density to detect early kicks. Researchers compared virtual flow meter predictions with actual production data, verified results, and determined the minimal amount of data required to achieve accurate predictions.

The benefits of this project will include long-term, reliable estimates of oil and gas production rates by improving the accuracy of deepwater well condition measurements. The project will lead to new techniques and methods to reduce the risk of uncontrolled fluid emissions from subsea equipment such as blowout preventers, wellheads and Christmas trees, and risers and flow lines. This project will have a positive effect on the environment by minimizing the risk of accidents by improving sensor systems deployed to detect a loss of well control at the sea floor. Finally, improvements to the design of a subsea sampling system and the development of a sampling best practices document will encourage an open and standardized approach to subsea multiphase sampling, which will help improve the accuracy and reliability of multiphase measurements.

Results:

- Significant progress was made on several promising new technologies, including the high-pressure, high-temperature differential pressure transmitter, a measurement method using Electrical Capacitance Tomography, and a system for early kick detection through monitoring mud density.
- The design of the subsea sampling system was improved.
- A best practices document is being developed.

Ongoing Research: The project team is fabricating the subsea sampling system and will conduct sampling experiments and analyses, and is preparing the sampling best practices document. The wet sensor has been designed and a prototype measurement device manufactured. The mud density experiments have commenced in 2014 and data evaluation is in progress. Researchers have also fabricated two complete prototype sensor cells and calibrated them at lab conditions.

NETL Contact: William Fincham, William.Fincham@netl.doe.gov

Lead Performer: Letton Hall Group

Chip Letton, Letton Hall Group, 713-825-0946, letton@lettonhall.com

Project Number: 10121-4304-01

Period of Performance: 7/2012-7/2015

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

All-Electric Subsea Autonomous High Integrity Pressure Protection System (HIPPS) Architecture

Objective: To assess, develop, and advance all-electric High Integrity Pressure Protection Systems (HIPPS) technology by finding and beginning to close the technological gaps of componentsa and subsystems within the system architechture.

Research Conducted: HIPPS systems protect downstream oil and gas equipment from over-pressure by continuously monitoring line pressure and automatically closing an isolation valve if the pressure rises above a pre-set level. HIPPS have the potential to enable production from high-pressure fields and expansion of existing low-pressure subsea networks to handle newer higher pressure wells. The industry considers all-electric technologies within subsea protection systems such as HIPPS to be feasible for future subsea developments.

All-electric HIPPS installations are advantageous because they eliminate hydraulics and associated environmental concerns, as well as potentially enhance system reliability. This technology enables safer hydrocarbon extraction from high-pressure fields and the expansion of existing low-pressure subsea production networks. The project team will design and test an all-electric fail-safe HIPPS. This research addresses the unique requirements associated with safety, integrity, and reliability of practical subsea facilities. Successful commercialization and utilization of an all-electric HIPPS system will result in an additional tool to help ensure the integrity and safety of any downstream subsea equipment not rated for specific wellhead shut-in pressure, safegarding the environment from potential problems downstream of the system.

The team conducted in-depth research during the initial phase of this project to provide a basis for using improved failsafe systems and controls to reduce the risk of environmental impacts caused by subsea equipment failure. The team performed an expanded technology assessment, developed a statement of requirements, and defined a basis for design. The technology assessment evaluated the current state of the art with input from production facility providers, component suppliers, and upstream oil companies. Based on both the assessment and feedback from industry and regulatory representatives, the statement of requirements was formulated and a basis of design was crafted. The basis of design included a roadmap for the development of the HIPPS system, identification of critical gaps, and estimates for schedule and costs. This research was conducted by INTECSEA, Inc. under a GE subcontract.

Results:

- A HIPPS Statement of Requirements/Basis of Design Report—which included detailed requirements for the design of the all-electric subsea system based on typical HIPPS configuration and functional performance—was produced. It also included all application requirements, parameters, and configurations as identified in a previous feasibility study (DeepStar Study Phase X CTR – 10304) and expanded for wider use.

Ongoing Research: Scientistis are focusing on the key-component technology gaps that limit the realization of all-electric HIPPS. They are using this information to design, develop, and evaluate a sub-scale proof-of-concept prototype.

At the highest level, the main components of an all-electric HIPPS installation include the main barrier valve, transducers, valve actuator, actuator controller, and logic solver. This research will focus on the critical fail-safe aspects of the design, and the integration of those features with existing components, with a strong emphasis on the previously identified components' technology gaps. The team will create and submit a final program report that will include conceptual designs, critical quality specifications, proof-of-concept hardware designs, test designs, and a detailed analysis of test results.

NETL Contact: William Fincham, William.Fincham@netl.doe.gov

Lead Performer: GE Global Research

Weston Griffin, griffin@research.ge.com

Project Number: 10121-4306-01

Period of Performance: 1/2013–3/2015

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

Construction and Testing of Deepwater Permanent Subsea Pressure Compensated Chemical Reservoir

Objective: The oil and gas industry forecasts a growing number of longer, subsea tie-back wells. The chemicals used at these wells for treatment or inhibition are currently stored on a host platform and pumped under high pressure through costly umbilicals to the wells, where they will be consumed. The objective of this project is to develop a functional subsea chemical storage and injection system design, with an approximate 3,000 barrel storage volume, and capable of refilling and/or retrieval, to permit the safe storage of subsea chemicals at or near well sites.

Research Conducted: The project is in its early stages. Organizational and kick-off meetings have been completed and a development team assembled. A Technology Advisory Group, consisting of subject matter experts from over 14 firm, has been assembled. The base concept has been defined and testing and evaluation has begun.

Results:

- The shuttle used to transport the chemicals from the dock to its subsea worksite must contain buoyancy materials to enable safe and efficient subsea payload deployment.
- Identified some emerging composite buoyancy products that have the potential to meet this need.
- Reduce operational risk and the potential for catastrophic environmental events.
- Reduce capital and transit costs by enabling the safe storage of subsea chemicals at or near the well site, allowing direct injection into wellheads or downhole.
- Drive the development of smaller fields that may not be able to support standalone development. In the case of brownfields, or existing fields, the subsea chemical reservoir can act as either a standalone or supplemental system to umbilical chemical delivery, so that increased volumes of chemicals can be delivered to improve hydrocarbon recovery rates, with no increased visible footprint.

Ongoing Research: The project team will develop functional specifications for the prototype design scenario, incorporating specific design requirements. They will define and specify system interfaces with the subsea production facilities as well as the required maintenance, repair, replenishment, and intervention services. The team will follow critical component and materials testing—including verification, laboratory, and qualification testing—with design enhancements and inclusion of lessons learned, operational plans, and other details. The team will identify hazards and verify expected performane following development and initial dynamic simulation of installation and recovery operations under realistic field conditions (to enable development of adequate contingency and redundancy plans).

NETL Contact: William Fincham, William.Fincham@netl.doe.gov

Lead Performer: Safe Marine Transfer, Inc.

Art J. Schroeder, Safe Marine Transfer, Inc., 713-681-1482 Art@SafeMarineTransfer.com

Project Number: 11121-5302-01

Period of Performance: 5/2014–9/2016

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

Subsea Produced Water Sensor Development

Objective: To select and oversee production of prototype sensors that analyze produced water samples using a high-resolution imaging technique: confocal laser fluorescence microscopy, as well as other promising sensors.

Research Conducted: The ability to accurately monitor the quality of produced water is one of the greatest challenges faced by the oil and gas industry. Produced water that is generated during subsea oil and gas production must be treated to reduce harmful constituents (organic and inorganic) prior to re-use or discharge at the seafloor. A change in water quality (e.g., an increase in the oil-in-water levels) may indicate the need for additional treatment, or equipment upset or a malfunction. This project seeks to respond to industry's unmet need for accurate, effective sensors to monitor the quality of produced water.

The team will test the ability of confocal microscopy to detect various concentrations of oil droplets in model systems. Samples containing hydrophilic and hydrophobic colloids, e.g., clay, non-hydrated metal oxides, sand, silt, and organic matter will be prepared as controls. Experiments will be run and repeated under various colloid concentrations to evaluate their effects on oil droplet size and ability of confocal microscopy to distinguish between oil droplets and suspended colloids.

In addition, the project team, along with a Working Project Group consisting of industry subject matter experts, will conduct a technical gap analysis of sensor technologies submitted by various vendors. The report will include a ranking of these technologies with recommendations for their selection to the next phase of the project. The team will select up to three (3) sensor technologies/vendors to advance to Phase II.

In Phase II of the project, Clearview Subsea, with the assistance of the project team, will oversee construction of up to three (3) subsea produced water discharge sensor prototypes based on approvals and conditions set forth in a previous go/no-go stage-gate. Each of the selected vendors will construct prototype sensors for bench-scale testing. Clearview Subsea will perform project management activities including, but not limited to, progress status reporting and addressing sensor interface needs.

The sensors developed through this project will help industry create a better failsafe system for monitoring produced water. These sensors will be capable of determining if the level of contamination is below, at, or above permitted levels and, when exceeded, send signals to immediately shut down operations or divert production fluids to a topside facility. This real-time monitoring and rapid response system will reduce the risk of unsafe produced water being discharged to the environment.

Results:

- Literature reviews have been conducted.
- The lab work has been planned.

Ongoing Research: Researchers will focus on Phase I tasks over the coming months, including developing technical requirements for the sensors, conducting a technical gap analysis of existing sensors, and evaluating the effectiveness of confocal laser fluorescence microscopy.

NETL Contact: William Fincham, William.Fincham@netl.doe.gov

Lead Performer: Clearview Subsea, LLC

Jianfeng Zhang, Clearview Subsea, LLC

Project Number: 12121-6301-03

Period of Performance: 9/2014–9/2016

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

Subsea DC Connectors for Environmentally Safe and Reliable Powering of UDW Subsea Processing

Objective: To 1) assess the technical requirements and technology gaps for subsea high-voltage direct-current (HVDC) connectors; 2) propose a subsea HVDC connector design that combines an innovative HVDC electrical design with a unique UDW mechanical design; and 3) construct an electrical prototype unit and testing it under ambient and simulated subsea conditions.

Research Conducted: HVDC power transmission is often the least expensive, most effective option for providing power to remote locations. (Transmitting at high-voltage ensures that minimal power is lost in the transfer.) Recently, HVDC has emerged as an environmentally-safe and reliable method for powering long step-out, UDW subsea oil and gas processing installations. A previous project focused on an HVDC concept development. Subsea DC connectors are critical components as the interface between power cables and HVDC power instruments, yet a reliable DC connector technology is currently not available.

The prototype DC connector that will result from this project will improve upon existing DC connector technology and overcome some of the existing technical hurdles to safe HVDC power transmission. The importance of HVDC power transmission lies in its increased efficiency over AC transmission in delivering large amounts of power over longer distances (e.g., > 100 miles), which is expected in future subsea tiebacks. The ability to provide adequate and reliable power to the seabed is an enabler that will reduce or eliminate the need for more and larger topsides facilities, and may result in higher hydrocarbon recoveries.

In Phase I of the project, the researchers, along with a Working Project Group consisting of industry subject matter experts, will conduct analysis and preliminary experimental studies to identify the technical requirements and developmental needs for subsea DC connectors. In Phase II, they will design, construct, and experimentally validate an electrical prototype mock-up of a subsea DC connector.

Results:

- The electrical system analysis of a simplified, generic system model has been completed. The results of the analysis help determine the steady-state ratings of different types of DC connectors and the potential impact of various fault conditions on the DC connectors.
- A draft report summarizing the results of the study on technical requirements of subsea DC connectors has been prepared.

Ongoing Research: Currently, the researchers are drafting the technical requirements for the subsea DC connectors and conducting gap analyses. Upon approval of the technical requirements, the project will move to Phase II: the design, construction, and testing of a subsea DC connector.

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

Lead Performer: GE Global Research

Qin Chen, GE Global Research

Project Number: 12121-6302-01

Period of Performance: 6/2014-9/2016

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

Technologies of the Future for Pipeline Monitoring and Inspection

Objective: To provide a sensor (mounted to a pig) for monitoring and maintaining deepwater pipelines.

Research Conducted: It is difficult to know exactly what transpires inside, or even outside, a pipeline. The consequences of not knowing, however, can be catastrophic. Challenges include excessive costs associated with conventional inspection (smart pigs) of deepwater lines and the associated long intervals between inspections. (Pigs, typically torpedo shaped devices, were initially used simply to clean the inside of pipelines. "Smart" or instrumented pigs have been around for decades and have become quite sophisticated.) Another challenge (unique to deepwater lines) lies in measuring pipeline location, since lines on the sea floor can be inadvertently dragged around by ship anchors, or moved by severe weather or by thermal contraction and expansion from changing fluid temperatures. The potential for stuck pigs presents a challenge for all types of pipe inspection, but particularly for deepwater, undulating terrain, and other long distance lines. In the deepwater environment all three of these harsh conditions can lead to plugging, and the costs associated with locating and removing obstructions are generally much greater than for onshore lines.

Researchers surveyed existing technologies for inspecting pipelines and for other uses (such as monitoring the human body). A small capsule-sized sensor capable of recording and storing multiple data types such as temperature, pressure, and acceleration was selected and adapted for use in pipelines. The sensor was mounted on a variety of off-the-shelf pigs and in several custom-designed free-floating packages. The packaged sensor made more than thirty runs in a twelve-inch steel pipeline loop. Temperature, pressure, tilt, and acceleration were measured continuously during each run and the results were presented, described, and analyzed. A field test consisting of two sensors mounted on a caliper pig was conducted in a working natural gas pipeline in July 2011.

The sensor would predict problems and facilitate proactive measures for avoiding pipeline fouling or plugging or other deleterious conditions. This project could provide the basis for economically reducing the risk of catastrophic failures of deepwater lines via better remote sensing techniques. In addition, the small size of the sensor allows for its use in smaller lines, perhaps as small as 1.5 inches in diameter, as well as in lines with tight, sharp bends and angles.

Results:

- A novel technique for inspecting pipelines using a small, capsule-sized sensor was demonstrated. This technique is capable of reliable, repeated detecting of pipeline bends, changes in pipe wall thickness, and measuring changes in temperature and pressure.
- The sensor is capable of being deployed in various packages, including on off-the-shelf maintenance pigs and custom-designed free-floating packages.
- Field tests indicated that, when mounted on a caliper pig, the sensor is capable of detecting dents and bends in pipelines.
- The sensor could not detect changes in velocity and orientation as well as it could detect pipe bends and changes in temperature, pressure, and wall thickness. More research and better packaging will be needed to reliably detect and measure these parameters.

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

Lead Performer: University of Tulsa

Michael Volk, University of Tulsa, michael-volk@utulsa.edu, (918) 631-5127

Project Number: 08121-2902-02

Period of Performance: 2/2009-12/2011

Read/download the final report.

Autonomous Inspection of Subsea Facilities

Objective: To develop, integrate, and test technology for autonomously conducting a pre/post hurricane inspection of an offshore facility.

Research Conducted: Subsea facilities must be inspected frequently to ensure that potential issues are identified quickly. The poor lighting and murky water of the deepwater environment reduce the effectiveness of costly, traditional inspection tools (e.g., underwater video reviewed at the surface by inspectors).

Key objectives of this two-phase project included the following: (1) conducting a local offshore demonstration test of an autonomous underwater vehicle (AUV) and achieving a technology readiness level (TRL) of 4—a rating that would increase operator confidence in the AUV's deepwater inspection capabilities; (2) using the AUV to inspect a production platform in the Gulf of Mexico, which includes conducting a baseline inspection and generating a 3-D model, introducing changes to the model, and re-inspecting / detecting the changes; and (3) demonstrating TRL 5 capability, including mission planning and execution, operational safety, ability to operate in typical Gulf of Mexico conditions, autonomous inspection, autonomous change detection, feature-based navigation, post-inspection analysis, and launch and recovery from a typical support vessel.

The researchers carried out Phase I of the project off the coast of Palm Beach, Florida to demonstrate that an AUV could conduct an autonomous inspection of an underwater facility. The AUV—equipped with an Offshore Platform Inspection System mission package—conducted several autonomous missions around a wreck resting on the ocean bottom in approximately 60 feet of water. In Phase II, the team used the AUV to inspect an actual oil and gas platform in shallow (<200 ft.) water in the Gulf of Mexico.

The AUV's onboard real-time 3-D modeling capability provides industry with unprecedented issue detection and the data needed for risk management. The technology now enables deepwater operators to reduce inspection costs while increasing inspection effectiveness, and its speed of deployment and retrieval allow operators to react to emergencies much quicker.

This technology will provide more accurate data, which will reduce the risks and costs of building and maintaining environmentally safe production and product transportation systems. It will reduce environmental risk through more accurate inspection and improve the quality and reliability of construction through sharable survey-quality as-built data during all phases of construction.

Results:

- The ability of the AUV to inspect an underwater facility was demonstrated during Phase I.
- With little information known about the condition of the study wreck, the Marlin AUV constructed an accurate 3-D model of the barge and detected structural changes from the previous model. Real-time modeling was possible because of the AUV's onboard 3-D sonar and patented autonomy technology. This successful integration and test phase resulted in a TRL of 4, which should increase operator confidence in the AUV's ability to inspect underwater facilities.
- The success of the Phase I shallow water test was duplicated in the deepwater Phase II test in the Gulf of Mexico. The AUV demonstrated that it could detect facility issues without the need for existing data with which to compare against, and (2) compare baseline data against follow-on inspection data and flag anomalies. The technology achieved TRL 5 because of successful Phase II deepwater testing.
- Although the AUV had a proven/tested design, the large mission package added to the bottom of the vehicle for facility inspection affected the vehicle's drag, requiring a re-characterization of the vehicle dynamics and subsequent control gain adjustments. After the vehicle control gains were set, the next portion of testing focused on evaluating the new autonomy that was developed for inspecting the facility.

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

Lead Performer: Lockheed Martin

Dan McLeod, Lockheed Martin, dan.mcleod@lmco.com, (561) 494-2305

Project Number: 09121-3300-05

Period of Performance: 9/2010 –4/2012

Read/download the Phase I final report.

Read/download the Phase II final report.

High Resolution 3D Laser Imaging for Inspection, Maintenance, Repair, and Operations

Objective: To develop a fully operational sensor to scan targets in a pool environment, and then integrate the technology with an industry-leading remotely operated vehicle (ROV).

Research Conducted: Three-dimensional (3D) laser imaging is a powerful data collection tool that is the predominate technology for terrestrial surveying, construction, analysis, and large-scale retrofits. Successfully adapting this technology for the deepwater industry would enable high-definition subsea laser imaging using the most current state of the art in 3D metrology and related best practices developed for the terrestrial market. 3D at Depth, LLC had successfully applied a patented technology to employ 3D laser imaging underwater and had demonstrated it in a laboratory environment. Although terrestrial systems commonly have centimeter spatial and range accuracy at several hundred meters range, deepwater systems have a limited range due to the absorption of laser light by water, water conditions, and target properties. From a non-oil and gas perspective, the technology allows for the documentation of our underwater cultural heritage which can be shared for future generations.

The goal for Phase I was to complete two demonstrations to validate the ability of underwater laser imaging to collect accurate 3D data of objects in a pool that are representative of those found in a deepwater oil and gas production system. Phase II of the project involved multiple open water trials to apply the base technology to multiple industry applications.

The team's previous laboratory results provided the foundation for a fully self-contained sensor to be deployed with an ROV. Researchers reviewed the the sensor design with industry subject matter experts that comprised a Working Project Group and determined that the sensor's power and size would not meet the requirements for most ROV systems. The team applied an iterative design approach and developed a variety of sensor configurations to arrive at a suitable balance of size, weight, and power. The team produced a prototype sensor that was 8.2 inches in diameter and 28 inches long, weighed 76.1 pounds in air, and was designed for 300 meter operation. The team used the results of a 2011 sensor test to update the power, communications, and software interfaces in preparation for an additional trial. In that trial, the sensor was integrated onto a Schilling ROV and lowered into an ROV test tank to test precision imaging of targets. The results were compared with reference measurements to validate the sensor's performance.

During Phase II, project scientists upgraded the sensor's window for operation at 3000 meters, conducted open water trials of static imaging, and enhanced the receiver. Additional research included splitting the housing into two canisters to provide enhanced integration capabilities with AUV's and

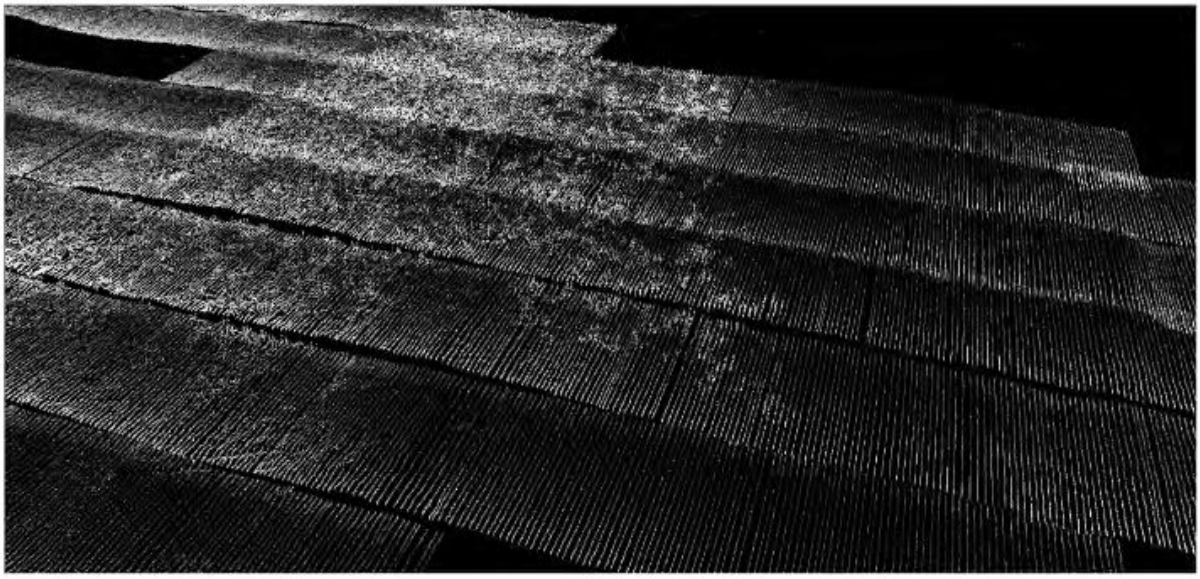


Image caption: *3D scans of clam bed on the seafloor.*

High Resolution 3D Laser Imaging for Inspection, Maintenance, Repair, and Operations

ROV's and allow the system to utilize a pan and tilt motor. This capability increased the system's field of view thus enhancing its utility for a variety of as-built and field mapping applications.

Once the core technology was established, the project then concentrated on the application of the sensor to solve additional deep water challenges. These included the development of software tools which allowed the sensor to measure the vibration of structures using the laser concentrated on a specific point. In a lab test tank, vibrations of 15 HZ were measured with amplitudes as small as 5mm at a range over 8 meters underwater. This capability can address a variety of applications for monitoring risers and other flow lines.

The final research effort was directed towards the integration of the sensor with an inertial navigation system to correct for motion. The concept of leveraging the laser scanner on a moving platform such as an ROV or AUV was considered a significant enhancement for asset management and to further enhance high resolution data collection. In a lab, the sensor was integrated to an inertial navigation system (INS) and then moved in multiple axes. The data was then corrected for motion and resolved within +/-1 cm of actual measurements of a test target. Two open water trials of seabed mapping were also conducted at a depth of 2990 meters. The laser sensor data and INS data were successfully combined to create the 3D maps of the seabed.

Results:

- The feasibility of underwater laser scanning was validated with results comparable to those obtained using terrestrial systems. The team believes this was the first demonstration of an underwater laser sensor with sub-centimeter measurement accuracy at ranges of up to 45 meters.
- In Gulf of Mexico water depths of 2800 meters, the system performed 13 spool piece metrologies for Technip US. Once fabricated, the spool pieces were installed without an issue. The process reduced the metrology collection process from 12 hours to less than 3 hours, thus optimizing the process and greatly reducing costs.
- The application of subsea laser scanning was demonstrated outside of the oil and gas market in April 2014, when the system was used to scan the USS Arizona in Pearl Harbor HI. Portions of the iconic shipwreck were scanned as part of the US Park Service's cultural preservation mission.

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

Lead Performer: 3D at Depth

Mark Hardy, 3D at Depth, 303-619-6589, mark@3datdepth.com

Project Number: 09121-3300-06

Period of Performance: 1/2011 – 12/2014

Read/download the Phase I final report.

Read/download the Phase II final report.

Sensors and Processing for Pipe, Riser, Structure and Equipment Inspection to Provide Detailed Measurements, Corrosion Detection, Leak Detection and/or Detection of Heat Plumes from Degraded Pipeline Insulation

Objective: To develop and mature critical sensing technologies for underwater structures such as pipelines, risers, platforms, and equipment that:

- make detailed physical measurements of underwater pipes and structures for inspection, metrology, and assessment;
- detect and identify external corrosion, pitting, and biologic fouling;
- detect and quantify gas or petroleum product leaks; and
- detect heat plumes resulting from cracked or degraded pipeline insulation.

Research Conducted: Pipeline failures, flow restrictions, and production downtime can increase the cost associated with ultra-deepwater production. These costs can all be reduced with faster, more efficient, and more effective techniques for underwater survey and inspection.

To date, surveys and inspections have involved visual inspections and/or the use of low frequency sonar equipment. Visual inspections require divers or video cameras, both limited by poor visibility. Acoustic measurement (metrology) solutions either take many steps to complete or lack the resolution and sensitivity necessary to enable detailed measurements and/or detection of subtle features such as corrosion, leaks, or heat plumes.

In order to verify the accuracy of the BlueView system (BV5000), the researchers conducted a series of dry dock trials to compare the output of the system to a conventional laser scanner. When these onshore spool metrology tests were successful, they conducted a series of offshore tests. They subsequently ran a series of tests using suspended oil bags to see if the system could detect and quantify gas or petroleum product leaks. And to test if the system could detect heat plumes, the researchers intentionally introduced flaws into a pipe and used the BlueView sonar underwater in a pool to see if the sensors would detect convection.

Results:

- Acoustic-based 3D scanners used during the project proved very successful for several underwater measurement and inspection operations.
- Two spool pieces were successfully installed in the North Sea in the first offshore spool piece metrology job; this job was completed in less time than would have been required using conventional long baseline acoustic positioning and diver techniques.
- Multiple technologies and applications were matured as a result of this project (scanning sonar metrology, gas in water detection, liquid in water detection, and heat leak inspection). The metrology application was rapidly matured into a new offshore operational capability, and it is now actively used globally in multiple oil and gas applications.
- Techniques developed and tested under this project significantly decrease time on-site for several underwater inspection and monitoring operations. These tools create a much safer environment by providing flexible inspection tools that can be deployed through the lifecycle of a project and provide near continuous updates.
- During heat plume detection experiments, there was only subtle evidence of convection present in the close-range amplitude imagery, static sonar output for the large – 10 in 2 and 20 in 2 – defects; there was no evidence of convection in the other sonar scans. Also, it was difficult to detect convection on the sonar output. Ultimately, a different data processing mechanism will be required in the future to help operators detect convection.

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

Lead Performer: Blueview Technologies

Dr. Lee Thompson, Teledyne BlueView, (206) 812-3009, lee.thompson@blueview.com

Project Number: 09121-3300-08

Period of Performance: 12/2010-6/2013

Read/download the final report.

Autonomous Underwater Inspection Using a 3D Laser

Objective: To develop and demonstrate the technology required to conduct 3D laser imaging from an Autonomous Underwater Vehicle (AUV) with 3D Mapping and Change Detection.

Research Conducted: The project team defined the hardware and software interface requirements for the AUV-based 3D laser, then designed and fabricated the laser before running simulation experiments. Researchers conducted laboratory simulation demonstrations before collecting open-water data. Onshore laboratory testing confirmed the 3D laser sensor and AUV software and hardware were integrated successfully. Open-water data was taken to validate the results of the simulations, allowing the team to determine the optimal beam pattern, integration times, and calibration approach for offshore trials.

Researchers used low risk-simulators and emulators in the place of actual hardware, which helped them optimize planning and performance predictions prior to offshore testing. The quantitative and qualitative results have been promising, and the project was highlighted on the cover of the January 2014 issue of the Journal of Petroleum Technology.

The integration of 3D laser imaging with AUVs will offer improvements in safety and operating efficiencies and substantially reduce overall costs related to deepwater gas and oil recovery. The advantages of this system over remotely operated vehicle (ROV) systems include 3D model generation in hours; smaller vessels with fewer crew members; the elimination of umbilical management; the ability to assess survey results and structural anomalies on-site to rapidly mitigate potential environmental damage; and the ability to generate accurate, geo-registered models for structural integrity assessment.

Results:

- Onshore integration and testing demonstrated that a 3D laser could be successfully incorporated into the AUV.
- A local offshore demonstration of 3D laser capabilities was conducted in a subsea environment. The offshore demonstration included high-resolution 3D laser imaging of subsea structures off the coast of West Palm Beach Florida from a moving AUV.
- Close-in, high resolution underwater structural inspection were demonstrated using an AUV with a 3D laser, generation of high resolution 3D models of subsea structures such as platforms, pipelines, etc., and performance of detection of flaws or damage against a priori structural models.

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

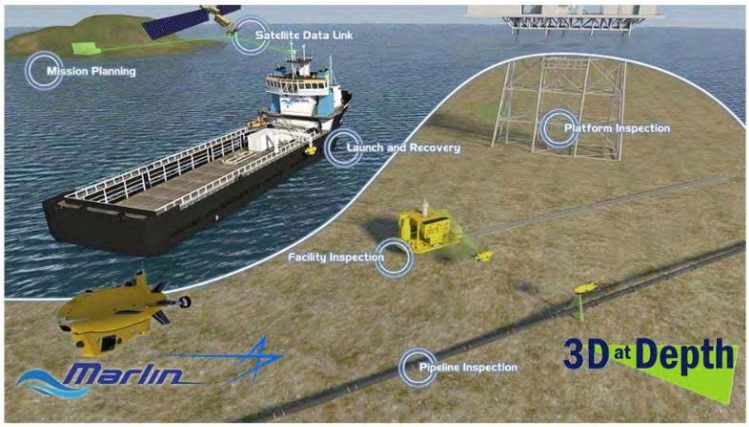
Lead Performer: Lockheed Martin Corporation

John Jacobson, Lockheed Martin Corporation, 713-243-5740, john.r.jacobson@lmco.com

Project Number: 10121-4903-02

Period of Performance: 7/2012–11/2014

Read/download the final report.



Wax Control in the Presence of Hydrates

Objective: Transporting hydrocarbon fluids through long (tens to hundreds of miles) subsea pipelines used for ultra-deep-water oil and gas transport and production presents unique challenges.

Hydrate and wax deposition in subsea pipelines caused by cold temperatures creates expensive and serious problems, such as missed delivery schedules; emergency shutdowns; bottlenecks, clogs, and shut-ins; an increase in corrosion; and build-up of rust, scale, and debris on interior walls. One means of preventing wax deposition in long subsea lines is to insulate them—an expensive solution.

The purpose of this project was to develop a fundamental understanding of alternatives for preventing wax formation in ultra-deepwater, non-insulated subsea pipelines in order to reliably produce extreme reach subsea tieback wells to host facilities.

Research Conducted: This project involved two phases: (1) a comprehensive literature review focused on finding game-changing technologies for enabling transport of crude oil in uninsulated subsea pipelines and (2) an experimental evaluation of the most promising technologies/concepts based on the review. The general approach was to explore the following broad classes of technologies: mechanical methods (cold seeding, sonic methods, scrapers (pigs), internal pipe coatings, coiled tubing services, etc.), chemical methods (inhibitor and solvent injections to prevent or minimize the rate of wax deposit accumulation), and thermal management techniques (which provide the necessary heat input to prevent deposition).

By carefully evaluating all available technologies, researchers at the University of Utah found that cold flow is a promising technology for minimizing or preventing wax formation in subsea lines. This effort may help to significantly decrease lost revenue and the risk of line failures or catastrophic events.

Results:

- The literature review revealed that there is sufficient evidence that cold flow, a technology in which oil is cooled to ambient temperature (which in the Gulf of Mexico ranges from 2 to 4 degrees Celsius), is effective in minimizing both wax and hydrate deposition.
- The review found that pigging line as a backup must be available to ensure a robust cold flow system. Pigging is the mainstay of remediation technologies and is considered a "must-use" technology for long-distance tiebacks. The effectiveness of pigs in cold flow situations has not been tested extensively.
- Chemical injection has been used as a wax/hydrate mitigation strategy. The science and practice of chemical injection is advanced; however, the mitigation strategies are typically designed to address specific chemical compositions and conditions. Very few studies address mitigating waxes and hydrates concurrently. It is unlikely that an inexpensive chemical injection strategy could be used to design cold flow, but targeted chemical injection would always be part of the total solution.
- Experiments conducted under different cold flow conditions confirmed that wax deposition is minimized under cold flow conditions. The experimental phase consisted of formulating the necessary and appropriate model oils, designing a novel dual-loop flow loop system, and conceptualizing and manufacturing a scraped heat exchanger for slurry creation. Apart from confirming the validity of the cold flow system, experiments were conducted to examine restart under cold flow conditions. It was revealed that a small heat flux also prevents deposition due to the suppression of cloud point caused by taking wax out of a solution. The restart experiments revealed that restart pressures are lower under flow conditions.
- The literature review and discussions with the project's industrial steering committee revealed a number of wax-related issues that first needed to be addressed. Thus, the scope of the project was limited to wax deposition issues, and hydrate-related experiments were not performed due to time and resource constraints.

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

Lead Performer: University of Utah

Dr. Milind Deo, University of Utah, (801) 581-7629, milind.deo@utah.edu

Project Number: 07121-1201

Period of Performance: 9/2008–8/2011

Read/download the final report.

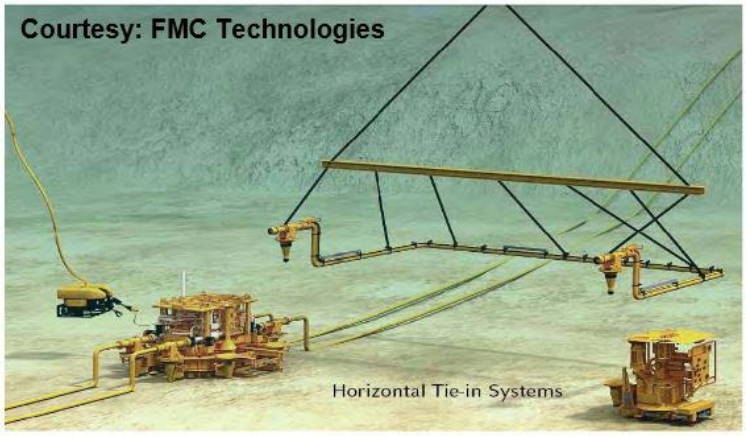
Flow Phenomena in Jumpers-Relation to Hydrate Plugging Risk

Objective: To identify these problems and design a production system and operational procedures to manage them. The objective of this project is to improve the understanding of liquid displacement and flow patterns in jumper-like systems during restart operations by performing transient flow experiments in geometries typical of low spots encountered in jumper systems.

Research Conducted: Production strategies are becoming more challenging due to the harsh environments and problems associated with drilling in deep water. A significant problem is the risk associated with flow assurance issues such as scale, corrosion, asphaltenes, wax deposition, and hydrate formation in pipe caused by cold water at the sea floor.

Wax deposition on pipe walls can reduce the pipe diameter to the point of plugging a pipe and potentially destroying a well. Hydrates are crystalline compounds formed when a hydrocarbon gas and water are combined at high pressures. Hydrate formation can also plug pipes. Scale, corrosion, and hydrates are a consequence of water production. Removing the water will eliminate most of the problems, but doing so may not be practical or economical.

There is also a high risk of hydrate plug formation in jumper sections during restart operations in part because of their geometry. (The jumper is a section of pipeline that connects the wellhead with the manifold. It is not usually insulated and has low spot sections where water can accumulate, especially during shut down operations.) Upon restart, gas contacts and displaces the water, creating hydrate plugs if no inhibitor is used. Once a hydrate plug forms, it may take a very long time to dissociate, resulting in costly production losses.



The project focused on designing and constructing a jumper-like facility that operates at atmospheric conditions. Experiments with oil, gas, and water were run using this facility to help researchers study various operating parameters and gain a better understanding of water displacement during restart in order to predict operating conditions conducive to hydrates formation. The work was conducted in five primary phases: facility simulation and design; facility construction and shakedown; experimental studies, including both gas- and liquid dominated restarts; data processing and model comparisons; and reporting.

Once the facility was completed, a jumper geometry model (incorporating two low spots with different length-to-height ratios) was constructed of three-inch acrylic pipe and used to study the displacement of water and oil from the system; each low spot was charged with a known amount of oil and water, providing different bridging conditions of the pipe. After the fluids were allowed to segregate, a restart phase was applied at the section inlet, resulting in the displacement of the liquids that accumulated in the low spot.

Results:

- The combination of restart rate, restart fluid properties (liquid or gas, liquid viscosity, and density) and bridging conditions resulted in a variety of observed flow patterns and transitions, as well as different amounts of accumulated fluids being displaced from the jumper section. The experiments provided a classification of these flow patterns as well as an estimate of the critical velocity at which most of the fluids were swept from the low spot.
- Transient gas-water tests in the jumper were conducted in which final liquid hold-up was determined to be a function of velocity. Simulations using OLGA (an industry standard multiphase flow simulator) were found to significantly over predict carry over (i.e., more liquid was left in the pipe following each experiment than was predicted by the simulations.)
- Gas restarts with oil-water mixtures were conducted. As with the single phase tests, OLGA simulations over predicted the liquid hold up. For single phase experiments, the

Flow Phenomena in Jumpers-Relation to Hydrate Plugging Risk

liquid hold up was affected by velocity, while for the two-phase displacements the liquid hold up was affected by both velocity and water cut. The results of these tests also showed that both viscosity and density affected the liquid carry over.

- Researchers found (19-Centipoise) oil to be more efficient than kerosene for removing all of the water from the jumper during liquid restart experiments. Also, it was harder to remove all of the water in the jumper at higher water cuts. Even a jumper full of water flushed with one jumper volume (at the lowest velocity tested [0.48 ft/s]) removed at least 70 percent of the water from the jumper. Higher liquid restart rates were more effective in pushing all of the water out of the jumper, but lower restart rates promoted more fluid mixing. Similarly, the liquid restart simulations over predicted the amount of water left in the jumper. (Simulations showed there was no water left in the first low spot and less than five-percent in the second.) By increasing the restart velocity or the number of jumper volumes displaced, the final water holdup also decreased.
- The results were provided to the SPT Group, so that its OLGA model can be improved.
- Five liquid restart experiments were conducted. Additional liquid restart experiments are needed using methanol and ethylene glycol and/or methanol to determine the best operating parameters for inhibiting water. Since one of the possible factors affecting simulations may be testing at atmospheric pressure, a high-pressure jumper should be built to determine the effects of higher pressure on fluid hold up or carry over.
- Knowledge gained from this project may lead to better prevention methods, such as displacing water out of non-inhibited jumpers while avoiding plug formation. Information on inhibitor distribution and displacement could lead to better design of injection points in jumpers, promoting more stable production and increasing the lifetime and recovery of a reservoir.

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

Lead Performer: University of Tulsa

Dr. Michael Volk, Jr., University of Tulsa, (918) 631-5127, michael-volk@utulsa.edu

Project Number: 07121-1603a

Period of Performance: 9/2008–3/2010

Read/download the final report.

Hydrate Plug Characterization and Dissociation Strategies

Objective: To prevent hydrate formation and provide guidelines to dissociate hydrates in the real operating environment by understanding hydrate formation phenomena and dissociation methods and efficiencies.

Research Conducted: A major concern of the offshore industry is the cost-effective elimination hydrate plugs from pipelines. An understanding of how hydrates form deposits that culminate in hydrate plug formation in subsea satellite wells, flow-lines, and risers is important to avoid plugging in deepwater production operations.

Hydrates are ice-like solid compounds, which tend to form when gas molecules are trapped in water under high-pressure and low temperature conditions. In deepwater wells, thermodynamic conditions are favorable for the formation of hydrates, which tend to agglomerate and eventually plug pipelines.

Remediation strategies, such as melting, depressurization, and the application of inhibitors, may be implemented. Little is known about the properties of the plugs themselves, in particular, their porosity and effective permeability to gas or liquids. Therefore, little quantitative information about the efficiency of dissociation methods as a function of these properties and environmental conditions is available.

Hydrate plugging in pipelines invariably creates an emergency that precludes the methodical collection of accurate data suitable for documentation. As experience-based, hydrate kinetic models were developed, they were combined with transient flow simulation tools to predict plug location and timing. The project may help to benchmark such predictions against thoroughly documented flow loop and/or field studies of hydrate plugs. In addition, the ability to model and design the most appropriate dissociation techniques is key to a quick return to production at minimal expense. Bridging the knowledge gap between plug characterization and dissociation will aid in selecting the most effective plug dissociation methods for different plugging scenarios.

To study the problem, hydrates were characterized by their physical properties and tied to various dissociation techniques by interpretation of previous experimental data. The study included modifying the University of Tulsa's high-pressure Flow Assurance Loop (FAL) to generate solid hydrate plugs to evaluate the efficiency of hydrate dissociation strategies. Project personnel formed hydrate plugs under different scenarios and determined their characteristics. Porosity and permeability, plug length, and pressure drop across the plug were measured as a function of different operating parameters, such as different sub-cooling, salinity, and gas injection rates. The FAL consisted of a 3" pipe flow loop mounted on an 80-ft long tilt table. The

Image caption: *Flow assurance loop overview*.

Hydrate Plug Characterization and Dissociation Strategies

flow path was 160 feet and fluids were set in motion by a multi-phase pump or by the rocking motion of the flow loop deck.

The Tulsa University model does not consider ice formation during dissociation. Ice formation should be incorporated into future Tulsa University models.

Results:

- Hydrate plugs were created and dissociated by heating during 18 pumping tests. In 16 low spot tests simulating a leaky valve scenario, 11 plugs were dissociated by heating, four by depressurization, and one by monoethylene glycol.
- Dissociation models were selected based on the results of the dissociation experiments and different model simulations were compared.
- The decrease of hydrate mass with time during dissociation was compared to predictions by CSM-Plug and the University of Tulsa model. Both models incorporate the same physics, but Tulsa's model was modified to account for changes in system pressure and/or temperature with time in order to model transients in the flow loop. CSM-Plug and the experimental data agreed well in situations where there was no pressure and temperature change during dissociation. Tulsa's model agreed better with experimental data when there were changes in temperature or pressure.
- A first generation inhibitor model was developed. The model has been incorporated into software for industry use as an initial approximation.

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

Lead Performer: University of Tulsa

Dr. Michael Volk, Jr., The University of Tulsa, (918) 631-5127, michael-volk@utulsa.edu

Project Number: 07121-1603b

Period of Performance: 9/2008–9/2010

Read/download the final report.

Displacement and Mixing in Subsea Jumpers Experimental Data and CFD Simulations

Objective: To conduct an experimental and computational study of mixing and displacement phenomena that occur during hydrate inhibition in jumper type configurations using MeOH and MEG, as well as assess how the findings may help prevent hydrate formation in jumper type configurations.

Research Conducted: Gas hydrate formation in offshore production and transportation pipelines is a major concern for the oil and gas industry. Hydrates may form when light hydrocarbons and water are present under certain pressure and temperature conditions. They can reduce flow and even form a solid plug that can block the pipeline and interrupt production.

Subsea jumpers are commonly employed to connect flowlines to a manifold, tree, PLET (pipeline and termination), sled, or even another pipeline and are particularly susceptible to hydrate plugging due to their characteristic configuration with small diameters and low spots where water is prone to accumulate.

The most common way to prevent hydrate formation is chemical inhibition via thermodynamic inhibitors (THI). Solutions of methanol (MeOH) and monoethylene-glycol (MEG) are most often employed as THI's. In the case of flushing jumpers with THI, an appropriate mix of water and inhibitor is needed to prevent the formation of hydrate plugs. However, the rates at which these chemicals mix completely with the aqueous phase are not well defined.

The project team utilized its experience in multiphase flow and hydrates and state-of-the-art test facilities for quantification. The team conducted experiments in a 3" jumper system at the University of Tulsa to investigate hydrate displacement and mixing patterns of hydrate THIs (MEG and MeOH in this case). Different dispersion and partitioning mechanisms were observed for MeOH and MEG, especially in vertical and low spots. Several MEG tests were conducted with data being captured using a LabVIEW® data historian system. The project team conducted MeOH displacement tests that followed a test matrix, and made conclusions based on experimental results. Simulations using the 1-D transient multiphase flow simulator, OLGA, were conducted to evaluate its capacity to predict the thermodynamic inhibitor dispersion via an inhibitor tracking module. 2-D computational fluid dynamics (CFD) simulations were performed with the commercial software FLUENT®6.3.26. Comparisons were made between the simulation results and experimental data from full fresh water loading jumper displacement tests with MeOH and MEG. CD-Adapco performed a numerical study of a water-filled jumper being displaced with one jumper volume of THI at four different rates using CFD commercial software STAR-CCM+®. The results were compared to outputs from 1D OLGA and 2D FLUENT simulation runs.

This project involved conducting experimental and modeling work to investigate and compare the suitability and effectiveness of MEG and MeOH to inhibit hydrate formation and displace hydrates in jumper type configurations during flushing procedures. Remediation of gas hydrates is expensive and can be dangerous depending on location and size of blockages. A better understanding of the displacement of hydrates and mixing mechanisms involving water and inhibitor can be used by the oil and gas industry to reduce severe line failures that may result in equipment damage, injury, and even loss of life.

Results:

- Both 2-D and 3-D CFD simulations provided reasonable prediction for THI distribution along the jumper after displacement tests in most cases.
- Large discrepancies between OLGA simulation results and experimental data were found for low injection rate cases. Neither 2-D nor 3-D simulations were able to reproduce methanol overriding the water phase at both low spots. Results obtained using Star-CCM+ generally gave better agreement with the experimental results.

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

Lead Performer: University of Tulsa

Dr. Michael Volk, Jr., University of Tulsa, (918) 631-5127, michael-volk@utulsa.edu

Project Number: 09121-3300-02

Period of Performance: 12/2010 –12/2012

Read/download the final report.

Hydrate Modeling & Flow Loop Experiments for Water Continuous & Dispersed Systems

Objective: To conduct an experimental and modeling study of the formation of hydrates in water in continuous and partially dispersed systems. This focus was to determine the effect of operating parameters, including water cut, velocity, liquid loading, and pressure on hydrate transportability.

Research Conducted: Researchers performed Phase I flowloop experiments at the University of Tulsa flowloop facility to study the hydrate formation and plugging characteristics for partially dispersed water/oil/gas systems as well as systems where the oil is completely dispersed in water. Researchers developed, tested, and validated a growth kinetic model for predicting hydrate formation and pressure drop based on flow loop measurements. The flow loop test results were analyzed in detail, and a conceptual model was developed for hydrate formation in water continuous and partially dispersed systems.

The Phase I bench-scale and flowloop experiments are complete, clearing the way for Phase II flowloop tests to validate the hydrate growth model.

Developing a fundamental understanding of the key mechanistic steps by which hydrate plugs form under different multiphase flow conditions is a key objective for the flow assurance community. The results of this project could ultimately provide new insight into hydrate plug formation and inform hydrate management guidelines to reduce the safety risks and costs caused by hydrate formation and accumulation in deepwater flowlines and facilities.

Results:

- Hydrate growth is very rapid for such systems. The plugging mechanism for these systems was caused by a combination of various phenomena (e.g., wall growth, agglomeration, bedding/settling, etc.).
- The flowloop test data provided the basis for a mechanistic model for hydrate formation and plugging in partially dispersed systems. The data and knowledge resulting from this work will be incorporated into flow assurance models to help advance production strategies for reducing or mitigating the risk of hydrate plugging in complex multiphase systems.
- In partially dispersed systems, hydrate formation is rapid and plugging mechanisms are complex. With respect to flow assurance, these systems are more severe compared to systems where the water is completely dispersed in oil.

Ongoing Research: The flow loop test matrix experiments on water, gas, and salt systems planned for phase II of the project are underway. The experimental data will be used to further quantify and validate the hydrate conceptual model. The team will continue to develop and validate the hydrate model, correct the hydrate growth models, and improve the hydrate predictions.

NETL Contact: William Fincham, William.Fincham@netl.doe.gov

Lead Performer: Colorado School of Mines

Carolyn Koh, Colorado School of Mines, 303-273-3237, ckoh@mines.edu

Project Number: 10121-4202-01

Period of Performance: 8/2012 – 5/2015

Read/download the Phase I final report.

Replacing Chemical Biocides with Targeted Bacteriophages in Deepwater Pipelines and Reservoirs

Objective: To evaluate the use of bacteriophage, or phage, in a focused approach to reduce the agents of microbially influenced corrosion from the production wellhead to the refinery including pipelines.

Research Conducted: Bacterial growth is responsible for many instances of biofouling, reservoir souring, as well as the corrosion of concrete and metal surfaces. Pipeline corrosion and reservoir souring are major issues that result in elevated costs, increased health risks, and a host of operating problems for the petroleum industry. Sulfate-reducing bacteria (SRB) pose a particular threat to the industry due to their ability to reduce sulfates to sulfides, releasing sulfuric acid and hydrogen sulfide as byproducts. Hydrogen sulfide gas is not only extremely toxic and flammable, but it causes souring or contamination of petroleum products, resulting in reduced quality and increased handling costs.

The petroleum industry uses chemical biocides to combat bacteria despite the fact that they are expensive, toxic to humans and the environment, and are not always effective. A biocontrol approach based on bacteriophage or phage, natural viral predators of bacteria, is showing great promise in reducing the need for toxic chemical biocides. Phage is highly specific to its target bacteria and is harmless to any other cells (human, animal, plant, or non-targeted bacteria). Phage targeting bacteria can be injected at the head of a pipeline for long term biological control, thus reducing environmental impact by negating use of biocides for bacteria control. Phage treatments result in extended control of SRB levels and may hold promise as bio-pesticides, thus reducing the petroleum industry's use of chemical biocides.

The project evaluated bacterial populations present in two locations: an oil brine mud sample from a crude oil salt storage cavern (COSC) and oil and water samples taken from an onshore pipeline (OSP). Both sites receive oil from the deep water Gulf of Mexico. The diversity of bacteria in the samples was determined using both a traditional method—denaturing gradient gel electrophoresis (form of electrophoresis which uses temperature to denature s sample as it moves across an acrylamide gel), and a cutting edge, next generation sequencing approach based on pyrosequencing (method of DNA sequencing) analysis.

Results:

- Forty-seven species of sulfidogenic bacteria—comprising 36 percent of all bacteria in the samples—were identified. Thirty-six species were classified as "true sulfate reducing bacteria." Iron reducing bacteria were also present in significant numbers in the OSP samples. SRB strains were cultured from the COSC and OSP samples.
- Forty-six new prophage elements were identified in the genomes of sequenced SRB. New phages capable of killing the COSC SRB were isolated.
- Individual phage were found to not only markedly inhibit SRB growth by six orders of magnitude or better, but unlike in tests conducted with chemical biocides, the test vials remained clear, indicating that inhibition is long lasting and active.
- Phage have similar inhibitory effects on SRB cultures as chemical biocides. The effective dose of phage required to control SRB growth varied dramatically between experiments. The reasons for variable dose requirements are not understood and are the subject of future research efforts. Additional work to identify or develop phage with expanded host ranges and to study any possible side effects is ongoing.

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

Lead Performer: Phage Biocontrol, LLC

Dr. Neil Summer, Ecolyse, Inc. (Phage Biocontrol), (402) 470-5017, neil@ecolyse.com

Project Number: 08121-2902-04

Period of Performance: 1/2010–2/2012

Read/download the final report.

Enumerating Bacteria in Deepwater Pipelines in Real-Time at a Negligible Marginal Cost per Analysis: A Proof of Concept Study

Objective: To provide an improved technology for identifying, in real time, microbial-influenced corrosion caused by bacteria producing iron sulfides that accumulate in and block pipelines.

Research Conducted: The petroleum industry controls bacterial contamination of its production systems with chemical biocides, which are expensive and harmful to humans and the environment. The biocide regimen depends on the number and types of bacteria present; however, bacterial identification is a slow, laborious, and expensive process that cannot be used to direct, optimize, or even verify the effectiveness of biocide applications. The high cost of an ineffective biocide regimen drives the over-application of biocides to ensure adequate bacterial control, which may in turn cause microbial resistance.

An alternative technology to identify and enumerate bacteria, pre- and post-treatment, would permit the use of far lower concentrations of biocides while signaling the need for higher concentrations in isolated cases, and provide the added advantage of enabling emerging strategies such as targeted application of bacteriophages.

Microbial influenced corrosion attacks the whole system from production wellhead to refinery. Long deepwater pipelines are particularly at risk of microbial attack due to their physical size, the pressures they bear, and the high costs of inspection, maintenance, repair, and replacement. This successful project may help the oil and gas industry safely and cost-efficiently reduce bacterial fouling that can corrode these pipelines, reducing the potential for catastrophic failure.

In 2008, Livermore Instruments licensed a biodefense technology, BioAerosol Mass Spectrometry (BAMS)—also known as Single Particle Aerosol Mass Spectrometry (SPAMS)—from Lawrence Livermore National Laboratory.

Livermore Instruments redesigned the SPAMS system by simplifying its optical systems and improving other components—including the mass spectrometer and vacuum and control systems—and rewriting the SPAMS instrument driver software. The SPAMS 3.0 system was deployed to Ecolyse, Inc.'s research laboratory in College Station, TX, where staff scientists cultured and provided at least three independent cultures of eight microorganisms known to affect petroleum recovery. The microorganisms fell into one of three categories: sulfate-reducing bacteria, thiosulfate-reducing bacteria, and acid-producing bacteria. Each culture was grown to a concentration of roughly 10^9 organisms per mL (as determined by hemacytometry) and analyzed.

Results:

- The SPAMS 3.0 system was able to perform analyses that would normally have taken days in roughly 30 minutes and, with subsequent upgrades, should be able to perform them in roughly 5 minutes. The system was able to distinguish organisms based on general class (e.g., sulfate reducing bacteria) and genus, and do so with minimal sample preparation.
- The SPAMS 3.0 is now in commercial production and use
- A review of the mass spectra analyses found that individual mass spectra tended to have high resolutions; when a single calibration was applied to all mass spectra, the mass accuracy could be off by as much as a full Dalton for peaks above 100 Daltons, depending on the spectrum. The team realized that the particles had been struck in different locations by the ionization laser, which had led to different amounts of kinetic energy being imparted to their resulting ions. A parametric time warping algorithm was written to adjust the calibration of each individual mass spectrum, and the mass accuracy was restored.

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

Lead Performer: Livermore Instruments, Inc.

David Fergenson, Livermore Instruments, Inc., (925) 215-8828, david.fergenson@livermoreinstruments.com

Project Number: 08121-2902-06

Period of Performance: 1/2010-3/2013

Read/download the final report.

This page intentionally left blank.