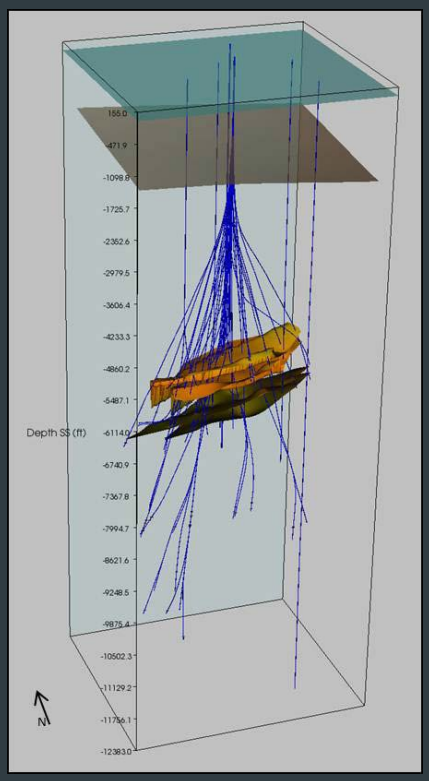
NATIONAL ENERGY TECHNOLOGY LABORATORY

Research Portfolio Report



Ultra-Deepwater: Geologic Uncertainty

U.S. DEPARTMENT OF ENERGY

Cover Image: **3D visualization of directionally drilled boreholes in the Gulf of Mexico, field MC109, showing NETL's interpretation of two reservoir sand intervals.**

Research Portfolio Report

Ultra-Deepwater: Geologic Uncertainty

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

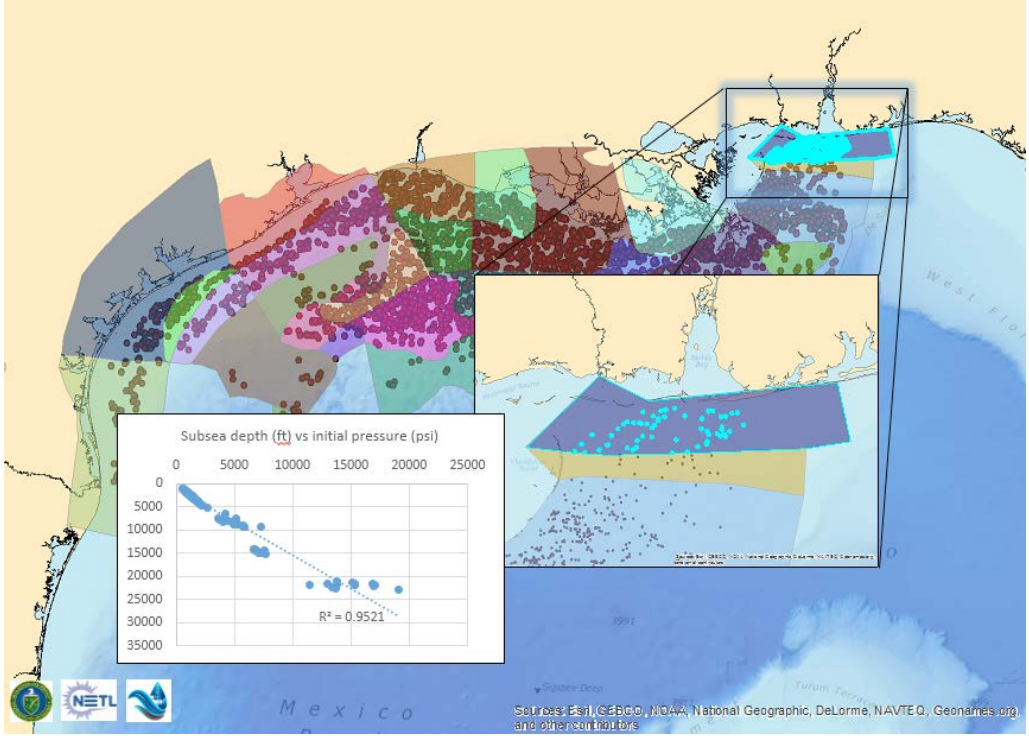

Image caption: *Examination of spatial pressure relationships on the Alabama Shelf of the Gulf of Mexico.*

Executive Summary

The Energy Policy Act of 2005 called for an Ultra-Deepwater (UDW) and Unconventional Oil and Natural Gas research and development (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, which pushes the limits of industry state of the art. This portfolio focus was changed to one of safety and environmental sustainability following the April 20, 2010, blowout on The Deepwater Horizon, Transocean's drilling platform on British Petroleum's (BP's) Macondo development, which killed 11 workers.

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

Results from the many committee meetings and hearings that followed Macondo reinforced the idea that better technologies will be required to enhance risk reduction in both operations and facilities in the UDW environment. Since many of the facilities in UDW include subsea systems that will operate autonomously on the ocean floor, a separate focus on the reliability of the components within these complex production systems was included. An additional concern was uncertainty regarding the potential to drill into geologic hazards, which remains very high for all exploratory drilling. The term "wellbore stability" was added to surface systems in recognition that the wellbore in UDW now included an engineered system from the ocean floor, 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. DOE's capabilities and competencies with simulation and evaluation of risks and impacts associated with engineered-natural systems are well-regarded by other federal agencies.

By definition UDW (i.e., 5,000 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 Geologic Uncertainty research aims to improve resource estimates, reduce hydrocarbon exploration uncertainties, minimize the drilling of unnecessary wells, develop environmentally friendly alternatives to marine seismic shooting, identify shallow drilling hazards through better pressure prediction, and identify deep, over-pressured or under-pressured reservoirs before encountering them.

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

DOE's National Energy Technology Laboratory (NETL), RPSEA, and industry and academic partners continue to carry out research into technologies that can reduce the chances of environmental impacts from ultra-deepwater production activities. This effort includes research funded through Section 999 of the Energy Policy Act of 2005 (Section 999) which directed 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.

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

- Designed and tested a new seismic sensor that is 100 times as sensitive as state-of-the-art geophones and capable of identifying geologic areas within the reservoir containing "stranded" oil
- Analyzed data from more than 80 oil fields and 450 reservoirs to identify geologic parameters that would help operators determine improved oil recovery opportunities during the early stages of oil field development and planning
- Developed a new geological modeling framework based on multiple-point geostatistics to accurately represent characteristics of depo-elements and reservoir architecture that impact performance
- Formulated a novel multiple point proxy function that represents well test response in terms of flow connectivity
- Created "data cubes" for sub-salt exploration that will be the industry standard for the next decade

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 Geologic Uncertainty 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.

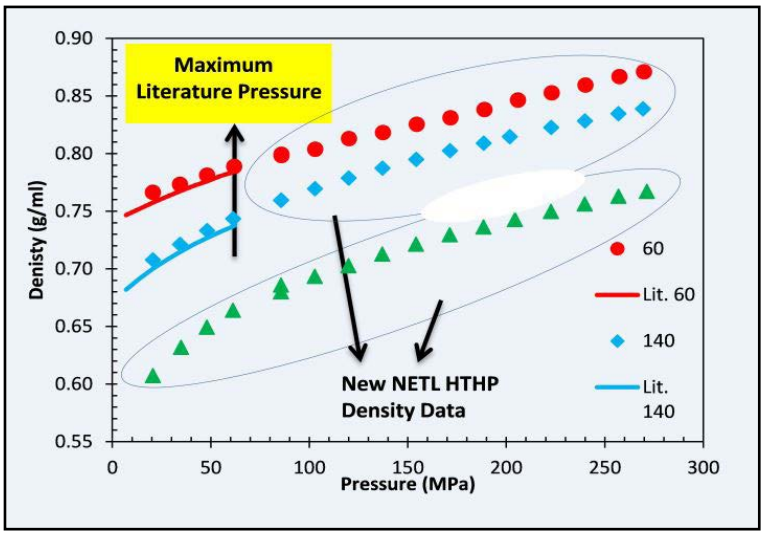

Image caption: *NETL researchers continue to extend existing density data to extreme pressures and temperatures.*

What is Geologic Uncertainty research?

Research focused on reducing geologic uncertainty is often conducted by interdisciplinary teams of scientists and engineers from the oil and gas industry service sector, producers, and academia. For these research projects, cross-cutting research and development (R&D) efforts capitalize on the strengths of the interdisciplinary teams and combines laboratory-based experiments with the development and integration of field-based datasets and numerical simulators. As a result, they develop the scientific basis necessary for assessing, reducing, and quantifying potential risks, as well as designing equipment and drilling specifications and providing science-based prediction methods that will allow rapid responses and successful mediation of potential hazards associated with exploration and production in offshore environments.

Why conduct this research?

Geologic uncertainty research increases our understanding of UDW subsurface environments and related geohazards, which leads to more accurate and effective prediction and early detection methods, guidelines, and tools. Because a certain degree of geologic uncertainty exists, the possibility of encountering geologic hazards is present for all exploration drilling operations. Reduced geologic uncertainty can lead to spill prevention, improved safety, and reduced environmental footprint over the life of a field.

Accomplishments

Accomplishments from geologic uncertainty projects contribute to safety and environmental sustainability and improve the understanding of the UDW subsurface environment. Some of the projects in the Geologic Uncertainty 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 geologic uncertainty:

- ***Integrated Assessment Model*** - Multiple project teams lead by NETL's in-house Office of Research and Development (ORD) build an integrated assessment model (IAM) to quantify system behavior and allow for accurate risk

A 1,000-Level Drill Pipe Deployed Fiber Optic 3C Receiver Array for Deep Boreholes

The objectives of this project were to develop, manufacture, test, and evaluate a next generation borehole seismic data acquisition system that is capable of safely deploying a 1,000 level, three-component seismic receiver array into deep offshore wells.

To achieve this, the project team developed several new technologies. First, researchers designed and manufactured a new high fidelity ultra-sensitive broad-band vector sensor. A fiber optic system in which both the sensor and the data transmission are based on optical technologies made the system intrinsically safe. Second, researchers designed and manufactured a deployment system that could handle the weight of a 1,000 level array.

The results of this work will permit more accurate seismic depictions of deepwater reservoirs, leading to reduced drilling risks and more efficient oil and gas recovery.

Additional information about this project is available on **p. 16**.

prediction in the Gulf of Mexico. The IAM, in combination with the existing Energy Data Exchange (EDX), offers the first coordinated platform to allow fast, independent, science-based predications of risks and spill assessments. NETL's EDX database and IAM tools are now being used to produce unbiased assessments of potential risks associated with hydrocarbon development in deep offshore settings. The design of these tools allows researchers to more accurately characterize the complexities of deep offshore environments that are currently developed or have the potential for future petroleum development.

- ***Hydrocarbon Spill Transport and Fate Model*** – Developed by ORD researchers, BLOSOM is the first offshore hydrocarbon spill model that can simulate the transport and fate of hydrocarbon spills from the point of failure to the shore. In addition, the simulations provide information that supports spill prevention and response. In addition, ORD compiled an improved set of scientific data necessary to predict the behavior and fate of hydrocarbons in a water column coupled with tested predictive models and a remotely operated vehicle that allow for independent assessments, spill volume estimates, and rapid response to deepwater hydrocarbon releases.
- ***Multiphase Flow Dynamics Improves Deepwater Drilling Safety*** – NETL ORD researchers developed a new method to estimate the flow rate of oil leaking from Deepwater Horizon oil spills. The method used the velocity of visible features on the boundary of the leak plume that were captured on ROV video.
- ***High Pressure/High Temperature Fiber Optic Array*** - An ultra-sensitive, ultra-large-bandwidth, ultra-high-temperature fiber optic seismic vector sensor capable of 30,000 psig and 608°F was successfully developed by Paulsson, Inc. and integrated into a borehole fiber optic seismic sensor (FOSS) system.
- ***Hydrocarbon Thermodynamic and Transport Properties at High Pressures and High Temperatures*** – An ORD lead research team developed methodologies and equipment to measure the thermodynamic and transport properties (density, viscosity, and phase compositions) of hydrocarbons and their mixtures at the extreme temperatures and pressures (260°C and 40,000 psi) representative of the conditions found within ultra-deep oil reservoirs. To achieve this, the team designed, developed, and commissioned a specialized density cell and rolling-ball viscometer.

  NETL researchers, working with cyclic (ring-structured) hydrocarbons, measured liquid-solid transition phases in a range of pressures and temperatures that had not previously been investigated. The data is important in developing accurate equations of state models that do not exist for environments over 69 MPa. They have integrated their results with

Geophysical Modeling for Studying Acquisition and Processing Methods in the Deepwater Gulf of Mexico

The project objective was to develop a suite of synthetic "simulated" geophysical datasets and a benchmark geological model representative of the deepwater Gulf of Mexico that can be used by industry and researchers to improve reservoir imaging.

To achieve this, the Society of Exploration Geophysicists (SEG) Advanced Modeling (SEAM) corporation brought together senior technical leadership from 24 companies, both oil and service, active in deepwater subsalt geophysical imaging.

These representatives had previously designed a numerical representation of an area that represents 60 Gulf of Mexico blocks. This project extended this model and design parameters to "acquire", through leading edge computer simulations, realistic geophysical datasets.

Several project simulations demonstrated that very few entities (including commercial vendors, universities, , research institutes, and U.S. national laboratories) have the capability to cost effectively create large volume simulation software.

Additional details on this project are available on **p. 13.**

existing lower pressure and temperature data, resulting in a comprehensive database. *These researchers are the first group in the world to test and discover a viable chemical to serve as the standard and to provide viscosity data at the ultra-deep reservoir conditions. Eight internationally recognized rheology research groups are using the results of this work.*

- ***Geologic Model of Deepwater Gulf of Mexico*** - The model, developed by the University of Texas at Austin, incorporates structural and stratigraphic complexity characterized in terms of geophysical parameters for density, compression velocity, shear velocity, anisotropy, and horizontal and vertical resistivity. It is now available and is being used by industry and researchers to improve reservoir imaging and analytical techniques.
- ***Ultra-Deepwater Assessment Database*** – Knowledge Reservoir, LLC developed a database, of deepwater and ultra-deepwater assets in the Gulf of Mexico, coupled with an analysis of improved recovery options and possibilities. The analysis recommends technical focus direction, incentives, research needs and identified concepts for improved recovery techniques. The database provides a better understanding of current technology gaps; aids facility optimization and well design; and serves as a guide to future research.

What are the benefits of Geologic Uncertainty research?

NETL carries out geologic uncertainty research to predict what will be encountered during exploration and development drilling and provide a broader understanding of the potential resource extent. Reduced geologic uncertainty can lead to spill prevention, improved safety, and reduced environmental footprint over the life of a field. The success of NETL projects in providing these benefits will help ensure UDW operations are conducted responsibly, which in turn protects our communities, the environment, and this critical domestic energy resource. NETL's development of databases and improved models will minimize the uncertainty associated with fluid quantity and flow in the UDW environment, as initial risk assessments require an understanding of the geologic landscape, possible hazards contained within the landscape, and the behavior of materials in those extreme environments.

Lessons Learned

As with any type of research, geologic uncertainty 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.

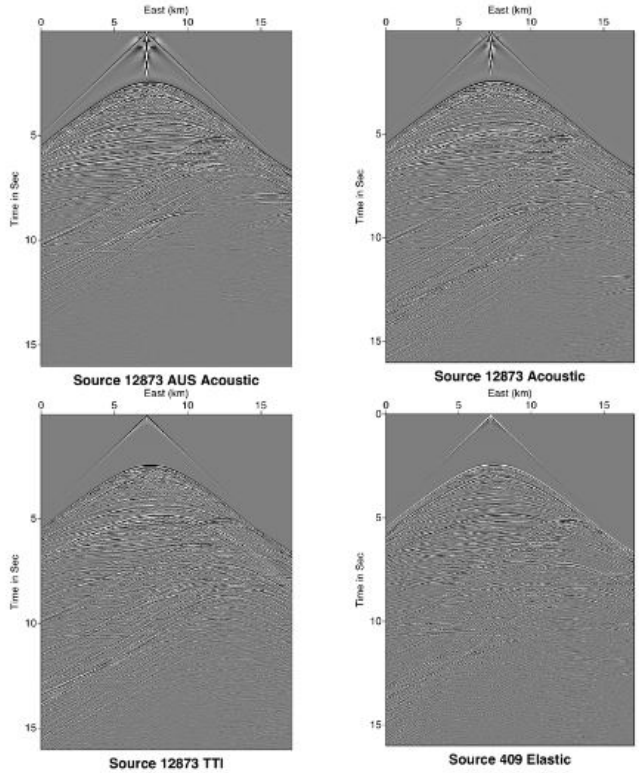

Image caption: *Acoustic, elastic, and tilted transverse isotropy (TTI) testing. Common shot East-West gathers through the source for a common shot location but with different simulation approaches.*

- Researchers at the University of Texas at Austin found that predictive methods of reservoir performance using neural logic are useful when estimating actual formation performance relative to geologic control hydrocarbon flow. Industry will most likely continue this experimentation, and the software created will likely be incorporated into a tool kit for producers.
- Initial tests conducted by Paulsson, Inc. showed that the fiber optic sensors have greater sensitivity and broader functional bandwidth than regular coil geophones.
- NETL researchers discovered that maximum lipressure data found in iterature on the density for a cyclohexane-hexadecane mixture was nearly 70 MPa. They were able to extend existing density data to approximately 270 MPa.
- Another in-house research project showed hydrate formation on the surface of a bubble lowers the rise velocity for smaller bubbles which may impact bubble plume modeling.

Very few enterprises in the oil and gas industry have the capability to create large-volume simulation software at a reasonable cost; thus, **datasets are expected to be the industry standard for at least another decade**.

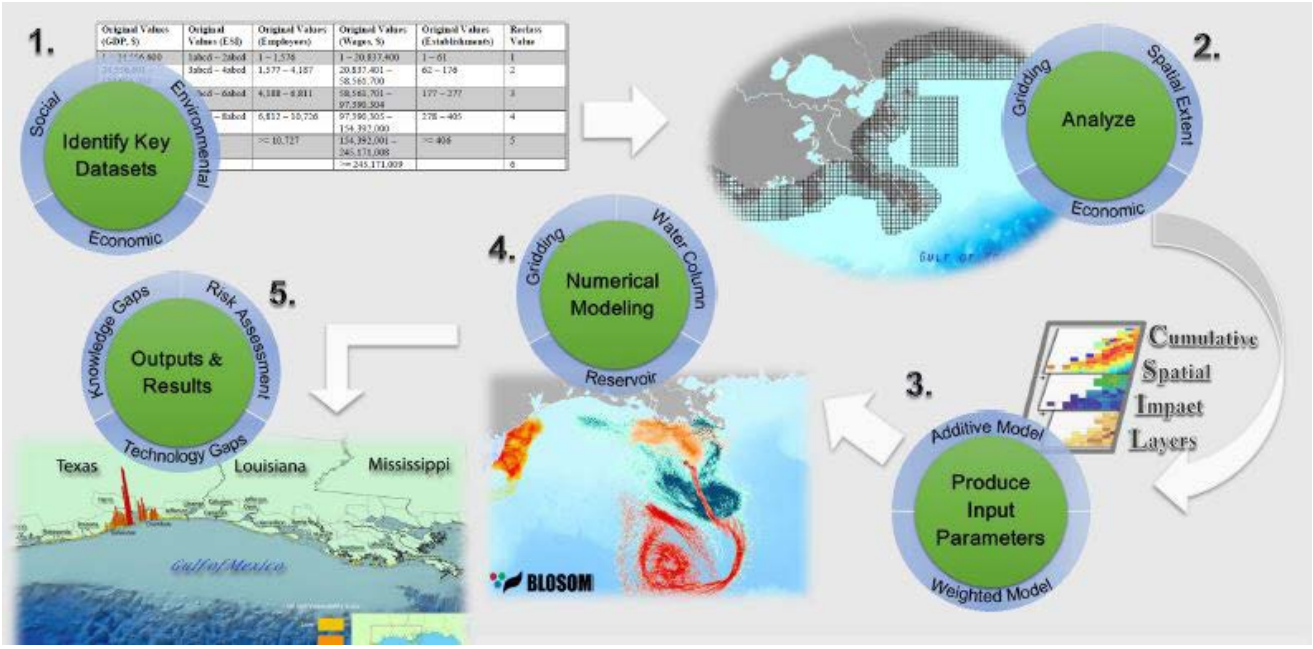

Image caption: *Integrated Risk Assessment modeling –Analyses & evaluation using spatial & temporal data for spill prevention, subsurface to shore.*

Geologic Uncertainty Projects	
Project title	**Report page no.**
Development of a Research Report and Characterization Database of Deepwater and Ultra-Deepwater Assets in the Gulf of Mexico	12
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Development of a Research Report and Characterization Database of Deepwater and Ultra-Deepwater Assets in the Gulf of Mexico

Objective: To identify improved oil recovery (IOR) opportunities in the early stages of field development planning in the ultra-deepwater reservoirs of the Neogene and Paleogene Period formations, such that facility and well designs can be optimized to take advantage of those opportunities.

Research Conducted: A critical petroleum exploration frontier is the deepwater Gulf of Mexico (GOM), where the mobility of gas in subsurface reservoirs allows for a high ultimate recovery factor. As exploration has moved into deeper waters, oil reservoirs represent an increasing portion of the discovered hydrocarbon reservoirs. As reservoir depth and water depth increases, recovery becomes more challenging, and the percentage of resources left behind tends to increase. Oil producers are highly motivated to maximize recovery to recoup massive initial investments. However, some 40 billion barrels of oil will be left behind in the deepwater GOM.

This project sought to identify the most promising IOR processes for deepwater GOM, the technological hurdles which must be cleared to apply of those processes, and avenues for future research to make IOR processes more cost-effective in the deepwater GOM.

Studies focused on designing modified surface and subsurface infrastructure that can be applied in the early stages of field development in the Neogene and Paleogene Period formations. The top causes of trapped and remaining hydrocarbons in these reservoirs were listed and categorized. Technical challenges to IOR concepts were addressed and prioritized to seek viable concepts for research and development.

Results:

- 80 oil fields and 450 reservoirs in the deepwater GOM were analyzed and the results were studied for potential improvement of recovery processes.
- Nineteen different IOR principles were evaluated for the Neogene and 10 were evaluated for the Paleogene. Recommendations for further research were made.
- Water injection and low-cost alternatives like aquifer dump flooding and seafloor injection were found to provide the greatest IOR benefits in the short term.
- Pumping and artificial lift solutions were shown to be essential. Lower overall well cost is also a necessary ingredient for all incremental projects.
- Low-salinity water injection, microbial enhanced oil recovery, nitrogen injection, riserless light intervention, and fracturing technology were all identified as areas of promise for future development.

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Lead Performer: Knowledge Reservoir, LLC

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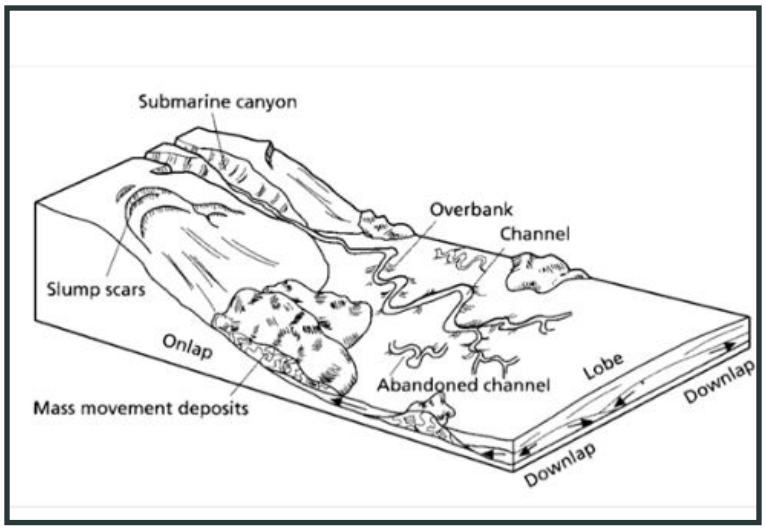
Project Number: 07121-1701

Period of Performance: 2/2009-12/2010

Read/download the final report.

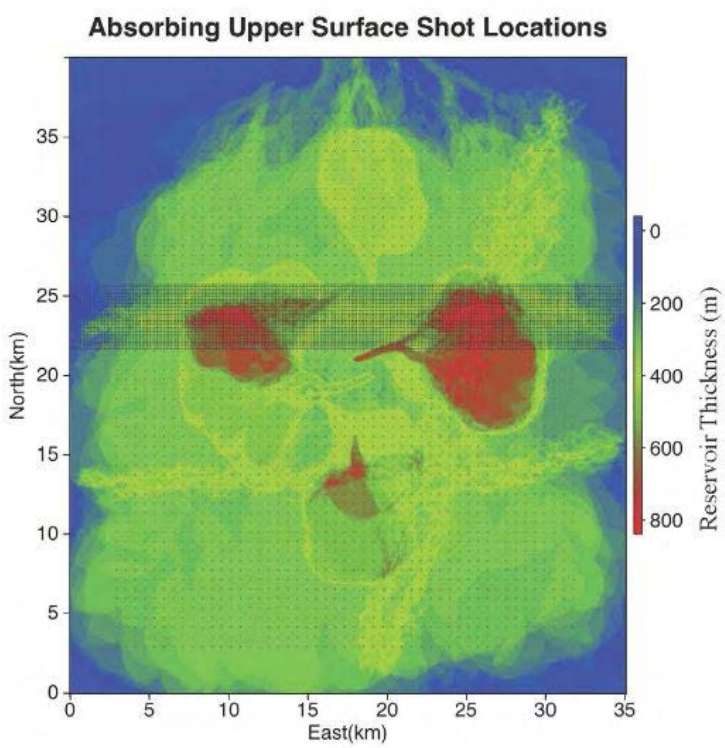


Depositional elements, deepwater Gulf of Mexico.

Geophysical Modeling for Studying Acquisition and Processing Methods in the Deepwater Gulf of Mexico

Objective: To improve geophysical imaging technology by creating realistic benchmark geological models and associated synthetic seismic and potential field data. This unified approach would allow the energy industry and the geophysical research community to effectively assess hydrocarbon reservoirs in the proximity of massive, complex salt bodies located in the ultra-deepwater GOM. Improved subsurface imaging of the GOM will increase the successful exploration and development of hydrocarbon resources.

Research Conducted: Project researchers worked to develop a suite of synthetic geophysical datasets to improve reservoir-imaging techniques. Synthetic data was acquired over an existing Society of Exploration Geophysicists (SEG) Advanced Modeling (SEAM) Corporation numerical earth model, a realistic representation of a 60-block sub-salt exploration area in the GOM.



Shot locations of the 2,793 shot grid and 28 EW line Absorbing Upper Surface (AUS) data sets. The color indicates the stacked thickness of the reservoirs.

The study simulated several key datasets: acoustic seismic with absorbing sea surface data set; controlled-source electromagnetic, magnetotelluric, and gravity data set; tilted transverse isotropic (TTI) data set; and an elastic seismic data set. The datasets were acquired using carefully-validated numerical simulation codes and have been made available to the public.

Results:

- Datasets generated during this project will be the industry standard for at least the next 10 years. The data enabled research into joint inversion methods for subsurface interpretation of structure, and rock and fluid properties. Additionally, these datasets facilitated research into the effects of TTI on data processing and imaging subsalt for exploration and into elastic effects on data quality, development of methods to remove elastic "noise" from acoustic data sets, and improved methods for the processing of elastic data. They can also be used to develop best practices for acquiring and processing geophysical imaging data in deep, complex hydrocarbon reservoirs, especially those in proximity to salt bodies and other complexities.
- An extended version of the pre-existing numerical model was used to account for the additional simulations. This unique model begins with geologic parameters such as Vshale and porosity and transforms them into geophysical parameters for density, compression velocity, shear velocity, anisotropy, and horizontal and vertical resistivity (required in controlled source electromagnetic simulations [CSEM]). An "absorbing upper surface" acoustic seismic simulation was recorded over the model's central portion to aid in de-multiple research. The simulation lacks sea surface multiple reverberations. Therefore, it can be used in conjunction with SEAM's pre-existing free surface simulation, providing a target dataset against which new de-multiple processing algorithms can be compared.
- A CSEM simulation was recorded, providing a test dataset to detect contrasts between salt and hydrocarbon reservoirs at both post and pre-salt interfaces. This dataset can be used for important research into joint inversion approaches to extract interpretations from seismic and CSEM together, since neither tool is comprehensive when used alone. Participants conducted a large anisotropic acoustic seismic simulation.

Geophysical Modeling for Studying Acquisition and Processing Methods in the Deepwater Gulf of Mexico

- Very few entities are currently capable of creating large volume simulation software at reasonable cost. Attendees at a SEG workshop demonstrated great interest in researching the methodology of data processing and the effectiveness of integrated interpretation when the exact geologic boundaries are known.

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Lead Performer: SEG Advanced Modeling Corporation

Dr. Peter Pangman, SEG Advanced Modeling Corporation, 918-497-5518, ppangman@seg.org

Project Number: 07121-2001

Period of Performance: 06/2009-06/2013

Read/download the final report.

Ultra-Deepwater Resources to Reserves Development and Acceleration Through Appraisal

Objective: To facilitate the development of ultra-deepwater resources by developing techniques to assess connectivity characteristics of deepwater sediments based on analysis of analogs, databases, and a model for a mature reservoir.

Research Conducted: This study focused on developing guidelines for acquiring reservoir information using value-of-information concepts. Additionally, it sought to determine whether geologic models can be developed using appraisal data and to determine what level of detail can be obtained from well test data alone.

The research team focused on model development and history matching of models for the Lobster Field area in the Gulf of Mexico shelf to reflect the architectural elements of the Lobster Field.

The team used GrowthSim and random walker algorithms, developed in an earlier phase of the project, in concert with other existing algorithms. They constructed a suite of geologic models and dynamic simulation models that synthesized appraisal well data and appraisal plus development well data coupled with seismic data. These models were tested and correlated with production history from the Lobster Field, using existing assisted (automated) history matching or model selection techniques.

Earlier in the project, a unique approach for the extraction of morphometric information from a seismic attribute volume was developed. The extracted information was integrated with prior geological knowledge about the depositional system, generating reservoir models that more accurately reflect the complex morphology of turbidite reservoirs. Researchers applied this methodology to the Lobster area, evaluated the influence of integrating seismic information on predicting flow performance. Seismic response was simulated using a robust forward-modeling approach.

Results:

- A geological modeling framework based on multiple-point geostatistics was developed to accurately represent characteristics of depo-elements and reservoir architecture.
- A novel multiple point proxy function was formulated to represent the flow connectivity in the well test response. A technique for calibrating the parameters of the proxy expression was developed.
- Addition of higher-order terms to proxy expression for well tests allowed researchers to detect important permeability features (such as transition between rock types) by analyzing the well test profile. Significant cross-flow between layers may reduce the volume of modeling information that can be inferred using connectivity-based proxy expression. Careful segregation of reservoir rock into turbidite lobes based on basement topography, and then modeling details of turbidite channel and over-bank deposits created more representative reservoir models.
- Particle tracking for capturing the effect of topographic changes on turbidite flow is a rapid, effective approach for modeling the spatial extent of turbidite lobes. 3-D seismic data cannot always match the resolution of geology or engineering information, but indicates opportunities for improvement. Training complex predictive software for these purposes is more involved than anticipated, leaving more unknowns than available equations and suggesting that further research is necessary.

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Lead Performer: The University of Texas at Austin

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Project Number: 08121-2701-03

Period of Performance: 01/2010-05/2014

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

A 1,000-Level Drill Pipe Deployed Fiber Optic 3C Receiver Array for Deep Boreholes

Objective: To develop industry-accepted technologies that will allow for the safe deployment of a 1,000-level, three-component receiver array into deep offshore boreholes using small diameter drill pipe and fiber optic sensor technologies.

Research Conducted: The longer the borehole seismic array used for borehole seismic surveys (VSP), the better the quality of the 2D and 3D images generated, resulting in superior mapping of micro seismic events. The systems must be capable of operation in vertical or deviated boreholes to 30,000 feet, withstanding pressures of up to 30,000 pounds per square inch gage (psig), and temperatures of up to 400°F. This study focused on designing and testing prototypes, for deployment of a 1,000-level demonstration array into a deepwater well.

Deployment of a 1,000-level borehole seismic array necessitated the creation of several new technologies. First, project researchers designed and manufactured a drill-pipe-based deployment system capable of supporting the weight of the 1,000-level array. Additionally, a new vector sensor was developed using fiber optic sensor technology. Sensor pod housing was developed by the application of specialized welding procedures. The fiber optic sensor was tested at ambient temperature and pressure. Optimizing the design of the new deployment system and the new sensor involved finding solutions to complex differential equations. The design system used integrated finite element modeling to create an accurate mathematical model.

Placing these sensors in the subsurface for use with VSP results in enhanced pictures of the subsurface, allowing operators to reduce drilling risks and optimize recovery. VSP also assists in profitable operation of marginal fields and enables identification and production of bypassed or "stranded" resources that may not be seen with conventional 3-D surface seismic data.

Results:

- An ultra-sensitive, ultra-large-bandwidth, ultra-high-temperature fiber optic seismic vector sensor capable of 30,000 psig and 608°F was successfully developed and integrated into a borehole fiber optic seismic sensor (FOSS) system.
- Sensors were installed in pods and successfully tested at 608°F. A deployment system strong enough to deploy a 1,000-level three-component borehole seismic array in vertical and horizontal boreholes of 30,000 ft. was constructed.
- The project confirmed that a drill-pipe based deployment system can be built to support a 30,000-foot long borehole seismic system.
- The entire borehole seismic system has been deployed twice, and the data recording capabilities represent an improvement over existing state-of-the-art borehole seismic systems. This success has led to industry adoption of the technologies.

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Lead Performer: Paulsson, Inc.

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Project Number: 09121-3700-02

Period of Performance: 02/2011-02/2014

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

Pressure Prediction and Hazard Avoidance through Improved Seismic Imaging

Objective: To deliver a benchmark simulated seismic dataset that will be used by industry and academic research institutes to investigate improved approaches for prediction of shallow hazards and deep over-pressured reservoirs and to reduce drilling risk – both safety and environmental – through improved pre-drill pressure prediction methodologies that are derived from iterative interpretations of simulated datasets.

Research Conducted: Seismic hazard surveys for planned drilling locations are commonly required for marine exploration and development programs. The surveys are particularly necessary where large and expensive drilling platforms must be built and positioned over an area to be drilled, as the sea floor must be able to sustain the forces of drilling equipment and operations. Should a failure occur, the operating personnel, platform, associated equipment, and the capital investment are all at risk, and the environmental impacts could be significant.

Methods to predict pore pressure need to be improved. Currently, pressure predictions from many data sources and the inclusion of avoidance and mitigation procedures in drilling plans are ambiguous. One of the most important technologies for pressure prediction in the early well planning stage is 3-D seismic models. A significant barrier to improving the method has been the lack of accurate and precise data of the subsurface calibrated back to either well logs that are used in prediction or 3-D seismic.[1]

This study is evaluating and advancing methods for pre-drill pressure prediction from seismic data in the deepwater Gulf of Mexico. An industry research consortium is being established to provide a collaborative forum where industry experts will prioritize current challenges in the use of seismic velocity (and other seismic attributes) to construct pore pressure and hazards forecasts for well planning.

The research team will modify SEG SEAM Deepwater Subsalt earth model to incorporate these challenges. This SEG SEAM Program is a partnership between industry and SEG designed to advance geophysical science and technology through the construction of subsurface models and generation of synthetic data sets.

1 http://www.docstoc.com/docs/58832779/Prediction-Of-Shallow-Drilling-Hazards-Using-Seismic-Refraction-Data---Patent-7796468

A seismic acquisition plan will be designed that can evaluate the potential for current and future acquisition and processing techniques to provide improved estimates of abnormal pressure regimes. This seismic dataset will be developed through advanced computer simulation. The resultant benchmark dataset(s) will be made available to industry and academia for quantifying risk and uncertainty associated with velocity models derived from current and future state-of-the-art in seismic acquisition, processing, and imaging. A proposed methodology will be developed, with recommendations for further research, assessing risk and uncertainty in pressure prediction from seismic.

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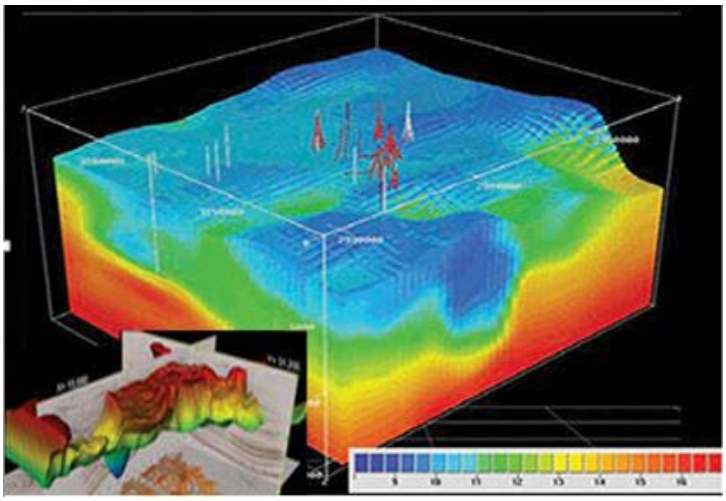
Lead Performer: SEG Advanced Modeling Corporation (SEAM)

William Barkhouse, SEAM, 918-497-5599, bbarkhouse@seg.org

Project Number: 12121-6002-02

Period of Performance: 9/2014-9/2016

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



Quantifying Complex Fluid-Phase Properties at High Pressure/High Temperature

Objective: To accurately characterize thermodynamic and transport properties of hydrocarbons over an extremely wide range of temperatures and pressures.

Research Conducted: Oil and gas production from ultra-deep petroleum formations poses different challenges than production from shallower formations. The physical properties and behavior of hydrocarbons where they reside in the high-pressure, high temperature reservoir environments change as the fluids approach the lower pressures and temperatures of the surface. One of the most significant changes is in the density and viscosity of the fluids. NETL's research focuses on defining the properties of hydrocarbons in the deep subsurface. This study will help develop safer production technologies, increase accuracy when determining reserves, and better predict production rates.

The research team developed methodologies and equipment to measure the thermodynamic and transport properties ((density, viscosity, and phase compositions) of hydrocarbons and their mixtures at the extreme temperatures and pressures (260°C and 40,000 psi) representative of the conditions found within ultra-deep oil reservoirs. To achieve this, the team designed, developed, and commissioned a specialized density cell and rolling-ball viscometer.

NETL researchers, working with cyclic (ring-structured) hydrocarbons, measured liquid-solid transition phases in a range of pressures and temperatures that had not previously been investigated. They used a high-pressure, variable-volume view cell to make the measurements Repeated tests proved the results could be accurately duplicated. This work has a direct application to understanding the development of heavy hydrocarbon solids as pressures and temperatures are decreased during production.

Another area of research focused on finding a fluid to serve as a Deepwater Viscosity Standard (DVS). The standard is used to calibrate viscometers that measure fluid properties at deep reservoir pressures and temperatures; it ensures that the viscometers work correctly and that measurements will be consistent. Researchers tested and evaluated various commercially available liquids at extreme conditions.

The team also populated a database for density and viscosity measurements for hydrocarbon compounds in the high-pressure, high-temperature environment. The data is important in developing accurate equations of state models that do not exist for environments over 69 MPa. They have integrated their results with existing lower pressure and temperature data, resulting in a comprehensive database.

This research has provided to the scientific community, accurate density data and viscosity data, along with modeling tools suitable for incorporation into reservoir simulators. Data on liquid-solid phase transition phases are important to understanding the formation of solid deposits in crude oil; these solids can clog production systems and damage infrastructures. Identifying a DVS ensures that the viscometers provide accurate data for EOS, computer models, and simulations on which safe production and reserve predictions depend. These researchers are the first group in the world to test and discover a viable chemical to serve as the standard and to provide viscosity data at the ultra-deep reservoir conditions. Eight internationally recognized rheology research groups are using the results of this work.

NETL Densimeter System.

Quantifying Complex Fluid-Phase Properties at High Pressure/High Temperature

Results:

- A full accounting of technical results from this project and others in the Offshore Portfolio are available at https://edx.netl.doe.gov/offshore including publications, presentations, datasets, tools, and other relevant information. This resource is updated quarterly and reflects publically available results from this project and the portfolio as a whole.
- Developed a P-V-T-μ (pressure, volume, temperature, parameter for a the general form of a two-parameter EOS) database based on previous works for propane thru various higher hydrocarbon compounds at temperatures ranging from 2,000 to 35,000 psi and 40,000 psi to 500 °F. The database provided insights into regions where significant gaps exist.
- Designed and built a new windowed, high-temperature, high–pressure densimeter for measuring single phase fluid density to fill gaps in hydrocarbon density values at extreme conditions. The densimeter is rated for 500 degrees F and 40,000 psi. The window allows for visual verification that the fluids remain in single phase during testing. The density of linear alkanes, branched alkanes, cyclic compounds, and aromatics were measured at extreme temperatures.
- Gaps in viscosity data were solved with design and construction of a windowed rolling ball viscometer also rated for 500 °F and 40,000 psi. The window allows for visual verification that the fluids remain in single phase during testing.
- Integrated results with existing lower pressure and temperature data to develop a comprehensive database that includes density and viscosity data for hydrocarbon under high-pressure, high-temperature conditions.
- Developed 'cubic' equations of state that can accurately predict the density of hydrocarbons and mixed hydrocarbons at extreme conditions. Accuracy for density is within 1% of experimental values. Reservoir simulators have an option for cubic equations of state, and users may easily incorporate the cubic equation results into simulations.
- Developed a new thermodynamic model to combine existing low pressure, phase equilibrium predictive models with new, more accurate densities predicted at higher pressures. This information is fundamental to understanding the formation of solids in crude oil as is flows to the well head and to help determine optimum operating conditions that will prevent their formation.
- Determined that Dupont's perfluoropolyether Krytox GPL 102 oil has a suitable and stable viscosity that can serve as a standard in deep subsurface environments. Recommended it as a new DVS.

Ongoing Research: Researchers will continue testing and measuring dead crude oil samples from oil producers at high-pressure, high-temperature conditions. A computer program to predict the density of crude oil and various pressures and temperatures will undergo refinement and experimental validation. A new equations-of-state density model will be incorporated into a reservoir simulator.

Lead Performer and NETL Contact: NETL ORD

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Project Number: Task 4

Period of Performance: 2012-6/30/2015

Improving Deepwater Drilling Safety through Enhanced Understanding of Multiphase Flow Dynamics of Hydrocarbon Mixtures

Objective: To facilitate the development of better assessment and modeling tools. This study focuses on developing imaging techniques that can quickly quantify the rate of fluid leakage and to determine the role of methane hydrate formation in the leak plume. The imaging techniques will be used in remotely-operated vehicles (ROV). The rapid detection and in situ characterization capabilities will improve safety and response time.

Research Conducted: Damage caused by the Deepwater-Horizon oil spill in 2010 clearly demonstrated that response and mediation of the event was hampered by an inability to accurately estimate the amount of oil leaking, a failure to cap the well, and a lack of understanding about the role methane hydrates played with regard containing the oil.

NETL's project research team participated in a Flow Rate Technical Group (FRTG) assigned to estimate the oil rate leak. Using ROV video, researchers examined the velocity of visible features on the boundary of the leak plume.

In the lab, researchers used a ship model towing tank and a dye-colored water jet to simulate a submerged hydrocarbon leak. A laser Doppler anemometer (LDA) and an automated video analysis technique, image correlation velocimetry (ICV) were used to map jet velocities; results were compared for accuracy.

To investigate the occurrence and behavior of hydrates in deepwater leaks, researchers employed NETL's high-pressure water tunnel facility for experiments. In particular, they investigated thermodynamic controls on hydrate formation, the effect of dissolved gas exsolution, hydrodynamic behavior of hydrocarbon bubbles, and morphological changes associate with hydrates.

Researchers using ROV video and measuring the velocity of features produced an accurate estimate of the Deepwater Horizon oil leak two months before it was measured in the final capping system.

Experiments to simulate a submerged oil/gas leak confirmed that image correlation velocimetry is an accurate velocity measuring technique that can be automated.

New information concerning hydrates forming on or from gas bubble and the remarkable visualizations of hydrate morphology will significantly advance visualization techniques and plume models.

Results:

- A full accounting of technical results from this project and others in the Offshore Portfolio are available at https://edx.netl.doe.gov/offshore including publications, presentations, datasets, tools, and other relevant information. This resource is updated quarterly and reflects publically available results from this project and the portfolio as a whole.
- Developed a new method to estimate the flow rate of oil leaking from Deepwater Horizon oil spills. The method used the velocity of visible features on the boundary of the leak plume that were captured on ROV video.
- Simulated a submerged hydrocarbon leak that generated Reynolds numbers in the range of the Deepwater Horizon oil leak jets. This showed that the automated ICV video analysis technique can serve as an automated video tool to measure velocity of visible features in a plume and is compatible to be used in ROVs.
- Produced data showing pressure and temperature conditions for hydrate stability.
- Supplied data on the effect of dissolved methane on hydrate formation and demonstrated that gas exsolution eliminates a hydrate 'memory effect.'
- Using high speed, high definition (HSHD) video equipment revealed dramatic visualizations of hydrate particle morphology and hydrate skins on hydrocarbon bubbles. The results are being prepared for publication in the journal of *Nature*.

Improving Deepwater Drilling Safety through Enhanced Understanding of Multiphase Flow Dynamics of Hydrocarbon Mixtures

Lead Performer and NETL Contact: NETL ORD

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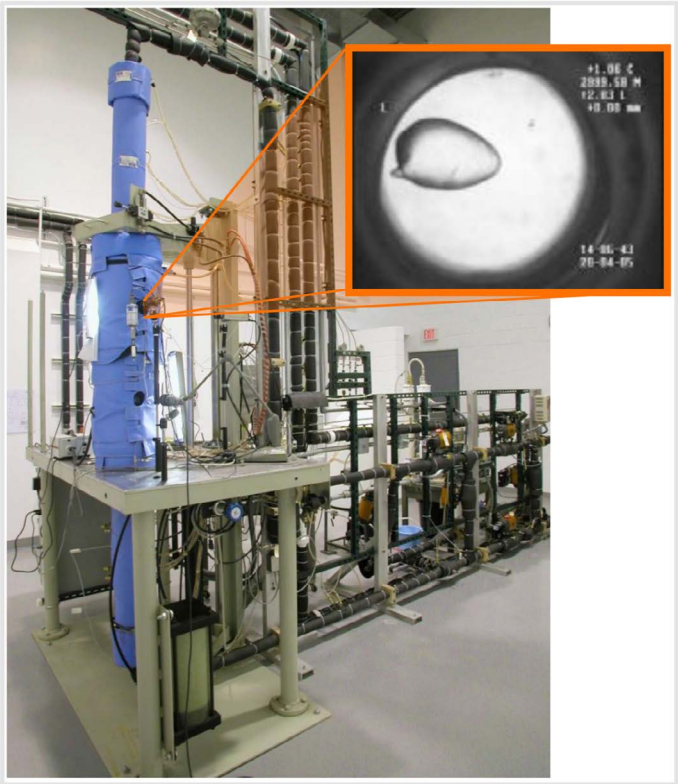
Project Number: Task 5

Period of Performance: 10/01/2011–09/30/2015



NETL's High-Pressure Water Tunnel Facility (HWTF). Inset shows a hydrate-covered CO2 drop that was stabilized by a countercurrent flow of seawater.

Assessing Risks and the Potential for Environmental Impacts Associated with Offshore Hydrocarbon Resource Development

Objective: The detrimental effects of Hurricanes Katrina and Rita in 2005, followed by the Deepwater-Horizon oil spill in 2010, demonstrated a need to resolve uncertainties and risks associated with extreme offshore exploration and production operations to support spill prevention. NETL recognizes that safe production of oil and gas from offshore reservoirs—including those in extreme offshore environments such as Artic regions and the high-pressure, high-temperature environments of ultra-deep water—requires technologies and data that specifically address the challenges of resource activities in these environments.

The objective of this project is to develop a suite of science-based tools that allows for the unbiased assessment of potential risks and environmental impacts associated with offshore drilling. Specifically, researchers are tasked with acquiring data to be used in developing an integrated method that can rapidly evaluate the entire system of related natural and man-made elements (geologic, engineering, and water column) for insights into potential risks associated with oil and gas development. Results from these analyses will help inform decision making for a range of needs, as well as highlight knowledge and technology gaps that can be addressed and reduced through future R&D.

Research Conducted: When this project was initiated, NETL's research group focused on four key needs to support successful development and implementation of an integrated risk assessment modeling (IRAM) approach for the offshore Gulf of Mexico (GOM). Specifically, i) the need for efficient and ongoing access to inputs, datasets and resources, needed for numerical simulations and assessments, ii) the need for a secure, coordinated system for inter-agency/entity assessment and evaluations, iii) need for an open-source, adaptable modeling suite spanning the subsurface, wellbore, and water column systems, and iv) need for advanced geospatial, and spatio-temporal statistical approaches (big data analytics) to support geosystem assessments. The IRAM team has addressed these needs through the following activities.

The IRAM team utilized data mining and integration techniques to assemble relevant public and commercial geospatial datasets, such as water column data, subsurface geology (reservoir properties, structure, and lithology), industry infrastructure (wells, pipelines, etc.), oceanographic data (currents, salinities, etc.), and environmental data to support assessment of offshore regions, for the GOM region and has initiated similar data collection for the offshore U.S. Arctic region as well. These data form the key attributes used in the team's ongoing IRAM evaluations for a range of questions and stakeholder needs. In addition, to support the goal of ensuring efficient and sustained access to data resources, including those available via web-services, the team produced a web-GIS tool that is available to the public and support the team's needs as well. Geocube is available online through NETL's Energy Data eXchange (EDX) and continues to evolve as more data and resources are added to the system (https://edx.netl.doe.gov/gom-geocube/). While Geocube is being expanded to include onshore data resources as well, it is a product of this project.

After compiling and analyzing the data from many sources, researchers addressed the challenging task of how best to standardize the data sets so that they are compatible geospatially and the units are consistent. Public data resides in NETL's Energy Data Exchange (EDX) – a web-based platform for scientists to access and transfer data in one convenient place. Researchers are continuing the synthesis and compilation of the surface, subsurface, physical, and biological data, geostatistical data, and geospatial data to support risk evaluation. EDX development was in part motivated by lessons learned as a result of DOE's participation in response teams associated with hurricanes Katrina and Rita, and the Deepwater Horizon event. EDX is a knowledge-sharing tool designed to house and connect users to energy-related datasets, provide key tools to support data analysis and evaluation, and host secure, private sharing collaborative workspaces that can streamline research partnerships. EDX is a tool developed by researchers for researcher related needs and to facilitate discoverability, accessibility and utility of data, and tools and functions multi-organizational teams need every day to address energy-related technical challenges. Thus, EDX addresses aspects of both the first and second critical needs identified by this project team, offering more efficient discoverability of data and resources required for the IRAM as well as addressing the need for a secure, coordinated system for inter-agency/entity assessment and evaluations.

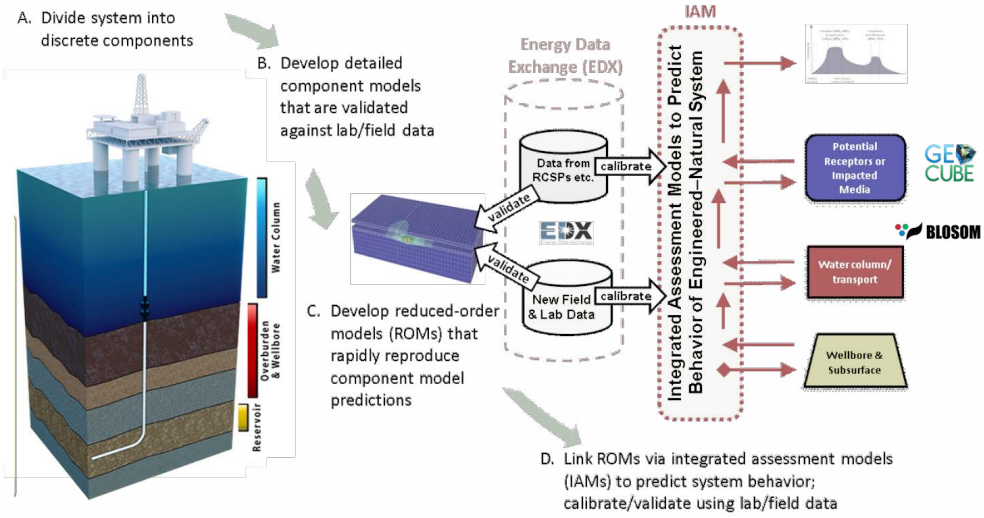
In parallel with the data and collaboration activities discussed above, the team also has worked to address modeling needs and capabilities to support the IRAM mission and goals. In order to model various scenarios and risks associated with deep-water production, researchers set forth to develop a single integrated assessment modeling (IAM) tool. The model is designed to in-

Assessing Risks and the Potential for Environmental Impacts Associated with Offshore Hydrocarbon Resource Development

tegrate data from multiple domains leading to a systems-based approach for decision making. The multi-component model ties together the subsurface, well-bore, water column, and surface geospatial datasets.

One critical modeling need identified and addressed by NETL researchers was the need for a 3D, full water column system oil spill fate and transport model that was open-source, so that it could be adapted and updated over time. To address this need, the IRAM team developed and built a spatially-explicit, 3-dimensional model, Blowout Spill Occurrence Model (BLOSOM). The model is able to simulate various scenarios and provide insight into the complexities of offshore blowouts in the water column. BLOSOM capabilities include simulation of near-field jet dynamics, submerged oil plumes, fate, weathering, and degradation. Started in late 2011 as a simple extension to be built on-top of an existing GIS platform, BLOSOM has developed into a stand-alone modeling suite with a high level of functionality and flexibility. It operates both on desk top systems and also has been parallelized for high performance computing use as well. BLOSOM is the first deepwater offshore hydrocarbon spill model that can simulate the transport and fate of hydrocarbon spills from the point of failure to the shore.

One challenge of subsurface studies is uncertainty and variability in data used to constrain subsurface properties and simulations. To support uncertainty quantification and communication, members of the IRAM team developed a novel and innovative spatio-temporal statistical approach, the Variable Grid Method (VGM). VGM can be used for a wide range of needs, including understand data density, interpolation error, and in association with model input and outputs to support more accurate quantification and communication of uncertainty associated with IRAM products. For example, a sparse point dataset consisting of widely spaced subsurface formation data to be used for the correlation of formations, has inherent uncertainties. It is the knowledge of these uncertainties that can affect research conclusions and/or decision-making. NETL's VGM will improve communication and science-based decision making of spatial systems that can be applied to petroleum, carbon storage, unconventional and conventional hydrocarbons, water resource, and risk assessments. A patent application for the VGM approach was submitted in February 2015. An ArcGIS plugin application to automate the VGM approach is undergoing beta testing currently by the IRAM team.



Schematic representation of technical and scientific components of Task 6.0 illustrating the relationship between the three components of the Gulf of Mexico Integrated Assessment Model (GOM-IAM) and the data delivery system (Geocube).

In addition to the VGM approach, the IRAM team has contributed to the development of several other spatio-temporal statistical approaches. To support risk reduction efforts, spatio-temporal and geostatistical approaches can be utilized to detect data trends, reduce geologic uncertainty, identify knowledge gaps, and evaluate environmental risks for systems such as geologic carbon storage, and conventional and unconventional hydrocarbons. The U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL) has created several spatio-temporal and geostatistical tools and approaches to support DOE's mission to produce science-based evaluations of engineered and natural systems, to ensure sustainable, environmentally responsible access to domestic resources. These

Assessing Risks and the Potential for Environmental Impacts Associated with Offshore Hydrocarbon Resource Development

tools and approaches include NETL's Subsurface Databook, Subsurface Trend Analysis (STA), Cumulative Spatial Impact Layers (CSILs), Spatially Weighted Impact Model (SWIM), and the Variable Grid Method (VGM). Used together or separately, these powerful, data-driven tools and approaches can be applied to various regions and at multiple scales to support risk assessment, risk prevention, and a range of scientific analytical or regulatory decision making needs. For more information on these please see http://www.netl.doe.gov/File%20Library/Research/onsite%20research/R-D201-2015Apr.pdf

NETL's EDX database and IAM tools are now being used to produce unbiased assessments of potential risks associated with hydrocarbon development in deep offshore settings. The design of these tools allows researchers to more accurately characterize the complexities of deep offshore environments that are currently developed or have the potential for future petroleum development.

Results:

- A full accounting of technical results from this project and others in the Offshore Portfolio are available at https://edx.netl.doe.gov/offshore including publications, presentations, datasets, tools, and other relevant information. This resource is updated quarterly and reflects publically available results from this project and the portfolio as a whole.
- Researchers have compiled a database for the GOM that includes subsurface geologic data, physical and biological data, and data on pore-fluids and water column attributes. In addition the database includes anthropogenic features on data on engineering infrastructures. Of particular interest is data for water depths greater than 500 meters. A spatial reference system, GOMAlbers was created to minimize distortion in mapping the data. Parameters were standardized and the data resides within NETL's EDX website. More detailed information on the datasets can be found in the technical report series publication Integration of Spatial Data to Support Risk and Impact Assessments for Deep and Ultra-deepwater Hydrocarbon Activities in the GOM on NETL's website. An interactive database of these data layers is being released through NETL's EDX. The EDX site serves as a coordination and collaboration tool for researchers. The site also serves a primary resource for the IAM datasets which are being used for new independent, rapid, and science-based prediction of offshore and ultra-deepwater hydrocarbon risks and potential impacts across the GOM.
- To date, NETL researchers have expanded the density and viscosity databases for hydrocarbon compounds to span HPHT conditions. Their results have been integrated with existing lower pressure and temperature data, resulting in a comprehensive database. This work is reviewed in the *High Temperature, High Pressure Equation of State Density Correlations and Viscosity Correlations* TRS publication on NETL's website, and an interactive database and associated application to interface with the database.
- NETL's development of the BLOSOM allows the user to design 'what if' scenarios to evaluate oil spills and strategies on how best to prevent them. It also is being used to support oil spill response strategies. BLOSOM Version I was used in a series of simulations for the GOM to support initial risk and impact assessments for that region in relation to offshore hydrocarbon release events. The Bureau of Safety and Environmental Enforcement is using the model in evaluating worse-case discharge scenarios; it is also being used to study plum dynamics and droplet-sizes.
- NETL's VGM, which provides researchers with the ability to analyze spatial data with an understanding of shortcomings in the data, is being used not only for deepwater GOM work, but is being applied to evaluate storage estimates and potential impacts for carbon dioxide storage and unconventional resource production and development. A Provisional Patent # 61938862 has been filed for the "Variable Grid Methodology" approach.
- NETL researchers are developing an integrated model that will coordinate data between BLOSOM, VGM, Geocube, and EDX. The model can be used to run trend analyses and determine technology gaps, which will support spill prevention efforts.
- Researchers have identified a number of new hydrocarbon properties:
    - First group to identify and characterize a viable fluid that exhibits the requirements of a desired deepwater viscosity standard.
    - First group to report cyclic hydrocarbon liquid-solid phase transition solidification data

Assessing Risks and the Potential for Environmental Impacts Associated with Offshore Hydrocarbon Resource Development

- First group to extend viscosity model of pure hydrocarbons to HPHT conditions.

- GOM Geocube was released. It supports timely access to current information for the offshore GOM and encompasses the natural system and engineered components from the subsurface to the shore to the atmosphere. The Geocube connects users to data and information spanning the subsurface to the surface via EDX, integrating its online search capabilities and from current data feeds. Users have the flexibility to develop maps with spatial elements of interest to them and export and download their custom web-map and/or the underlying datasets. Geocube is publically available; it is also being leveraged by the GOM IAM team for risk evaluations. The first NETL Geocube being released focuses on the offshore Gulf of Mexico region. Throughout the next year additional Geocubes for the U.S. are planned. https://edx.netl.doe.gov/gom-geocube/
- The team developed a new approach for concatenating key spatial data and information to support risk and impact assessments. It uses a cumulative spatial impact layers approach (CSILs). Key spatial datasets represent various social, economic, and environmental receptors interacting with the marine system to create cumulative spatial impacts layers. CSILs provide a qualitative and quantitative representation of various receptors' spatial extent or economic value to help evaluate potential impacts and risks associated with various uncontrolled hydrocarbon release scenarios to better inform spill prevention efforts. Researchers presented a case study using CSILs of four major socio-economic ocean use sectors in the GOM: oil and gas industry, commercial transportation, commercial fisheries, and tourism. http://www.netl.doe.gov/File%20Library/Research/onsite%20research/NETL-TRS-2-2015_CSIL_BroadImpacts.20150219.pdf

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Project Number: Task 6

Period of Performance: 10/1/2011-09/30/2015

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