TOPIC PAPER #20

DEEPWATER

On July 18, 2007, The National Petroleum Council (NPC) in approving its report, *Facing the Hard Truths about Energy,* also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the Task Groups and their Subgroups. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached Topic Paper is one of 38 such working document used in the study analyses. Also included is a roster of the Subgroup that developed or submitted this paper. Appendix E of the final NPC report provides a complete list of the 38 Topic Papers and an abstract for each. The printed final report volume contains a CD that includes pdf files of all papers. These papers also can be viewed and downloaded from the report section of the NPC website (www.npc.org).

NATIONAL PETROLEUM COUNCIL

**DEEPWATER SUBGROUP
OF THE
TECHNOLOGY TASK GROUP
OF THE
NPC COMMITTEE ON GLOBAL OIL AND GAS**

TEAM LEADER

Russell J. Conser
Manager, GameChanger
Shell International Exploration &
Production Inc.

MEMBERS

Ronald M. Bass
Senior Staff Engineer
Deepwater Research & Development
Shell International Exploration &
Production Inc.

Chryssostomos Chryssostomidis
Professor of Mechanical and
Ocean Engineering
Massachusetts Institute of Technology

Elmer Peter Danenberger, III
Chief, Offshore Regulatory Programs
Minerals Management Service
U.S. Department of the Interior

C. Christopher Garcia
Deepwater Theme Manager
Gulf of Mexico USA
Schlumberger Oilfield Services

Michael G. Grecco*
DeepStar Director
Energy Technology Company
Chevron Corporation

James Longbottom
TEES Associate
Research Scientist
Texas A&M University

Robert E. Sandström
Research Supervisor
Offshore Division - Marine Engineering Section
ExxonMobil Upstream Research Company

Paul Tranter
Vice President
Performance and Operations
Transocean Inc.

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* Individual has since changed organizations but was employed by the specified company while participating on the study.

Deepwater Technology Report

Going Deep

Team leader: Russell J. Conser

Date submitted: February 5, 2007

I. Executive Summary

Deepwater oil and gas are simply conventional reserves in an unconventional setting. They constitute a resource class of their own largely because they face a common set of technological challenges in the course of their identification, development, and production.

Deepwater is a success case for both technology and policy that is still in the making. We believe the data continue to support significant scope for economic oil and gas resource development in both U.S. and global deep oceans. On the road ahead, we conclude that the top priority deepwater-specific technological challenges are:

1) Reservoir characterization – Predicting and monitoring the production behavior of increasingly complex reservoirs with fewer but more costly direct well penetrations
2) Extended system architecture – Subsea systems for flow assurance, well control, power distribution and data communications that improve recovery and extend the reach of production hubs to remote resources
3) High-pressure and -temperature (HPHT) completion systems – Materials and equipment to reliably produce the growing number of deepwater resources in corrosive environments with extraordinary pressures and temperatures

4) Metocean forecasting and systems analysis – Integrated models to predict both above and below surface "weather" and engineering system response.

Within these four priority areas, we believe HPHT completion systems and metocean forecasting and systems analysis represent opportunities for material government, academic, and industry cooperation.

Additionally, although perhaps not a distinct technology area in its own right, we believe safety and environmental performance improvement has been and will continue to be critical to the future of deepwater.

Furthermore, we believe it is important to understand that deepwater is tightly related to topics discussed elsewhere in the full report:

1) Subsalt imaging (Exploration technology subtask)
2) Gas to liquids (Supply task)
3) Arctic (Baseline technology subtask).

We have also identified two issues that we conclude are critical to the continued successful development of oil and gas resources in ever harsher ocean environments:

1) Future marine technology leadership
2) Valuing technology to enable access.

Finally, we conclude that the coming decade will be pivotal in determining the fate of our ability to safely and economically develop both the United States' ocean energy resource endowment, and also the world's. At the very time that the drive to ultradeepwaters is increasing both the magnitude and complexity of the challenge, the technological capacity of the human resource base faces untimely impairment by "the great crew change." The future of deepwater depends on industry and governments successfully co-navigating this linked technology and policy transition.

II. Overview of Methodology

The deepwater technology subtask conducted their work in accordance with the design principle of utilizing existing data and insights. As such, a core team of currently knowledgeable experts in the field was assembled from the NPC member community:

Name	Organization	Title
Russell Conser (Chair)	Shell	Manager – EP GameChanger
Ronald Bass	Shell	Senior Staff Engineer – Deepwater R&D
Chrys Chryssostomidis	Massachusetts Institute of Technology	Director, Sea Grant College Program
Elmer (Bud) Danenberger	U.S. Minerals Management Service	Chief, Offshore Regulatory Programs
Chris Garcia	Schlumberger	NGC Deepwater Theme Manager
Michael Grecco	Chevron	DeepStar Director
Jim Longbottom	Texas A&M University	Research Scientist – Energy Engineering
Robert Sandström	ExxonMobil	Supervisor – Marine Engineering – Offshore Division
Paul Tranter	Transocean	Vice President – Performance & Operations

Background information from public literature was assembled and reviewed. Key technologies from these references were discussed and developed into a short list for further investigation by team members. Finally, these technologies were prioritized based on a matrix of relative additional resource potential versus cost or effort to progress development. The focus of this report is the top four technologies and two issues that the core group considered most important to the future development of the world's deepwater resource.

Key reports utilized include:

"Deepwater Gulf of Mexico 2006: America's Expanding Frontier," OCS Report MMS 2006-022, U.S. Department of Interior. Available at http://www.gomr.mms.gov/homepg/whatsnew/techann/2006/2006-022.pdf.

"Assessment of Undiscovered Technically Recoverable Oil and Gas Resources of the Nations's Outer Continental Shelf, 2006." Available at http://www.mms.gov/revaldiv/PDFs/2006NationalAssessmentBrochure.pdf

"Report to Congress: Comprehensive Inventory of U.S. OCS Oil and Natural Gas Resources," Energy Policy Act of 2005 – Section 357. Available at http://www.mms.gov/revaldiv/PDFs/FinalInvRptToCongress050106.pdf

"Gulf of Mexico Oil and Gas Production Forecast: 2004-2013" OCS Report MMS 2004-065.

"The Future of Deepwater – Analysis of Possible Scenarios" WoodMackenzie & Fugro Robertson (April 2004). Available at http://www.woodmacresearch.com/cgi-bin/wmprod/portal/energy/productMicrosite.jsp?searchStr=%22future+of+deepwater%22&productOID=664076&cpSessionID=@@@@0720125341.1164225234@@@@&cpEngineID=ccceaddjglkkgefcflgcegjdffjdgih.0.

Bell JM, Chin YD, and Harahan S: "State-of-the-Art of Ultradeepwater Production Technologies," paper OTC 17615.

"Ultra-Deepwater Oil and Gas Technology Workshop Report," Final Report on the Ultra-Deepwater Technology Workshop Held at the Houston Hilton Post Oak, University of Houston, Texas A&M University, Louisiana State University, RPSEA. (Nov 29, 2005). Available at http://www.ultradeepwater.org/pdf/Ultradeep report final.pdf.

III.Background

Deepwater technology reduces the finding and development costs associated with this large resource base (Figure III.1). This allows more of it to be developed economically. Deepwater technology is best seen as a continuously accumulating extension of the oil and gas industry's earlier move into offshore environment that initially accelerated in the 1960s. The early years led to the development of marine seismic methods, floating drilling systems, and fixed marine production structures. Later years drove developments in 3D and 4D seismic, dynamically positioned drilling systems, measurement while drilling, and remotely operated vehicles. As the push into ever deeper waters grew, the industry continued to respond with a novel array of development concepts, such as tension leg platforms, spars, and subsea production systems, which hybridized the positioning of engineering systems above and below the water line in what amount to truly modern engineering marvels.

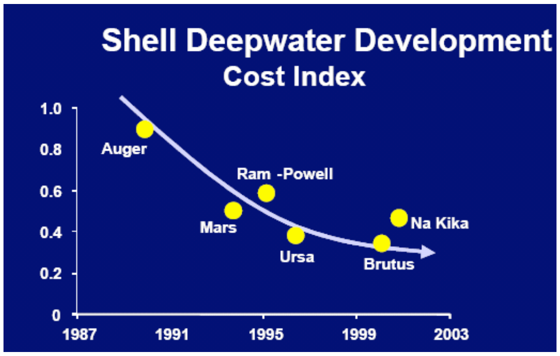
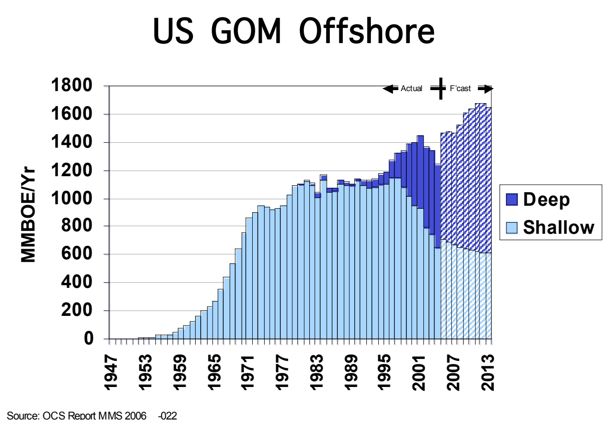


Figure III.1. Shell deepwater development cost index.

The U.S. Gulf of Mexico (GOM) deepwater region is clearly a success case at the intersection of technology and policy. Although the deepwater resource base itself was in doubt even 20 years ago, the large and prolific reservoirs have accounted for an increase of roughly 30% in oil production above historical norms (Figure III.2).[1]



The continuing march into even deeper and more remote waters is expected to increase production a further 20% over the next decade where reserves are both harder to find and much more expensive to develop and produce.

Figure III.2. U.S. GOM production [reference 1].

Nonetheless, the U.S. GOM represents a clear case where the more we know, the more attractive the opportunity becomes. Figure III.3 illustrates that our appreciation for the scope of the potential total Gulf of Mexico resource has grown dramatically as deepwater production has come online.[2]

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[1] "Deepwater Gulf of Mexico 2006: America's Expanding Frontier," OCS Report MMS 2006-022, U.S. Department of Interior. Available at http://www.gomr.mms.gov/homepg/whatsnew/techann/2006/2006-022.pdf.

[2] "Report to Congress: Comprehensive Inventory of U.S. OCS Oil and Natural Gas Resources," Energy Policy Act of 2005 – Section 357. Available at http://www.mms.gov/revaldiv/PDFs/FinalInvRptToCongress050106.pdf.

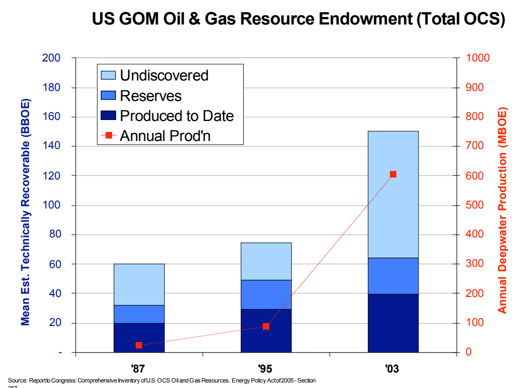

Figure III.3. U.S. GOM oil and gas resource endowment [reference 2].

Globally, the co-evolution and cross-pollination of deepwater technology in the Brazilian Atlantic and the European North Sea have combined not only to enhance the economic growth of U.S. resources, but have opened up further new supply basins in West Africa and SE Asia. Today, roughly 80% of estimated deepwater reserves lie outside the US, with the greatest concentrations in Brazil (25%), Angola (15%), and Nigeria (12%), according to a WoodMackenzie study.[3] Although some may feel the sector is maturing, the evidence suggests that discovery rates per well continue to maintain historical averages (Figure III.4). The WoodMackenzie study concludes that at current discovery rates, global deepwater resources within known basins will take another 20 to 30 years to be found. Development and production are likely to continue for several decades beyond that.

[3] "The Future of Deepwater – Analysis of Possible Scenarios" WoodMackenzie & Fugro Robertson (April 2004). Available at www.woodmacresearch.com/cgi-bin/wmprod/portal/energy/productMicrosite.jsp?searchStr=%22future+of+deepwater%22&productOID=664076&cpSessionID=@@@@0720125341.1164225234@@@@&cpEngineID=ccceaddjglkkgefcflgcegjdffjdgih.0.

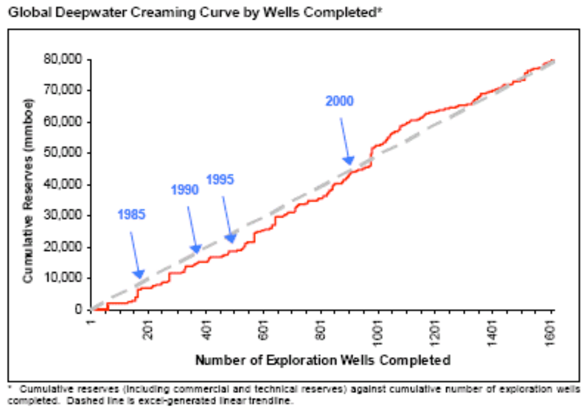

Figure III.4. Global deepwater creaming curve by wells completed [reference 3].

Note that as with the comparable position before the industry first moved offshore, even these projections exclude those areas that either are not open for exploration and development or are beyond the reach of today's economic technology (e.g. offshore arctic). Although no guarantees exist, the trend in deepwater to date has been that the more we find, the more we will see.

For the foreseeable future, the currently interwoven progression of technology and deepwater resource looks like it has a positive outlook. History demonstrates that this industry consistently meets each new challenge with economically competitive technical solutions wherever the resource merits it. In the continuing global progression of technology, we conclude that the solutions to the challenges below have the most potential to unlock the next large rounds of resources for the global markets. Solutions that enable competitive and safe production of the increasingly more difficult resources will ensure that the deepwater regions of the world will continue to be a material part of a secure oil and gas supply mix for decades to come.

IV. Tables of advances

Table IV.1 summarizes top-priority technologies:

Technology	Significance	Brief discussion
Reservoir characterization	Maximizing recovery	Predicting and monitoring the production behavior of increasingly complex reservoirs with fewer but more costly direct well penetrations
Extended system architecture	Enabling economic development	Subsea systems for flow assurance, well control, power distribution, and data communications that improve recovery and extend the reach of production hubs to remote resources
High-pressure and high-temperature completion systems	Safe and reliable development	Materials and equipment to reliably produce the growing number of deepwater resources in corrosive environments with extraordinary pressures and temperatures
Metocean forecasting and systems analysis	Safe and reliable development	Integrated models to predict both above and below surface "weather" and engineering system response

Table IV.1 Summary of technologies in priority order.

Additionally, several technologies considered with the scope of other subtask committees are highly valuable to the deepwater but limited discussion will take place here (Table IV.2).

Technology	Significance	Brief discussion
Subsalt imaging	Finding large new resources	Novel seismic processing methods that enable one to accurately image below complex salt layers
Gas liquefaction	Bringing remote gas to market	Technology to convert gas into more easily transportable forms becomes more valuable with both distance from shore and water depth
Arctic	Large untapped offshore regions	Economic development of oil and gas in the offshore arctic oil and gas will likely build on traditional deepwater technologies

Table IV.2 Summary of related technologies in priority order.

Finally, we believe there are two additional issues that are central to the continued progression of successful economic developments in the deepwater technology frontiers (Table IV.3).

Technology	Significance	Brief discussion
Future marine technology leadership	Innovation capability	Reduced centers of excellence in specialized field of marine science and engineering will limit inflow of technical experts required to keep industry moving forward after the "great crew change"
Valuing technology to enable access	Innovation motivation	Access to acreage with potential for economic oil and gas resources is in and of itself a primary, if not the largest, driver which encourages technology development

Table IV.3 Summary of key issues in priority order.

V. Discussion

A. Top Priority Deepwater Technologies

Following is a discussion of each of the technologies that we conclude are most important for the future success of oil and gas resource development in the deepwater regions.

1. Reservoir Characterization

As in any oil and gas play, the largest value driver for both resource holders and business is how much oil can be recovered. With the high cost of deepwater wells and facilities, high per well recoveries are a prerequisite for economics that are competitive with alternative investments. Most deepwater reservoirs are sandstones with prolific local quality but high variability and difficult-to-predict connectivity. With large increments of future capital on the line, there is a compelling requirement to predict more about future reservoir behavior from less data (Figure VA1.1).

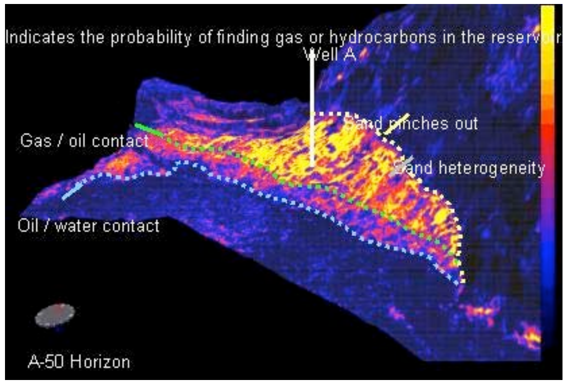

Figure VA1.1. "3D Probability of Hydrocarbon" image derived from processed seismic data.

The biggest challenges are a) predicting and monitoring reservoir properties between well penetrations and b) understanding reservoir compartmentalization. Well-log and core data, quantitative study of geological analogs, well testing and seismic interpretations are all useful in forming an integrated understanding of the reservoir. However, meeting the challenge of accurate prediction in ultradeepwater settings will require, a) measuring methods with greater depth of probing, and b) modeling methods with more quantitative sophistication. Compartmentalization is a particularly difficult challenge as barriers to continuous oil flow are often on a fine scale that is below the resolution of tools even in ideal settings. Understanding and predicting changes in reservoir properties during production (e.g. permeability under compaction) is also key.

Example technology solutions include wide-angle-azimuth seismic acquisition (see Exploration subtask report on Subsalt Seismic) or new inter-well or ocean bottom imaging techniques (e.g. electromagnetic surveys). Such techniques would offer improved fidelity and superior resolution. Deeper-penetrating well tests require longer times and larger volumes creating gas handling challenges that present technical issues. Increasing technical sophistication of quantitative geologic models including depositional systems and geomechanical behavior are also crucial. Progress across all fronts is required to create an integrated prediction of reservoir behavior that maximizes insight for minimal cost.

Potential for acceleration is only moderate, as the existing industry of operators and service providers see this challenge pretty clearly and are already heavily prioritizing continuous progress. The near-term priorities are a) improving seismic illumination and resolution, and b) increasing model sophistication. The longer term priority is improving the resolution and penetration depth of non-seismic far-field imaging (e.g. EM) techniques currently in early development for exploration.

The commercial industry will very likely spend hundreds of millions of dollars improving the various dimensions of deepwater reservoir characterization in the coming many years.

For further reading, see:

- Albertin U, Kapoor J, Randall R, Smith M, Brown G, Soufleris C, Whitfield P, Dewey F, Farnsworth J, Grubitz G and Kemme M: "The Time for Depth Imaging," *Oilfield Review* 14, no. 1 (Spring 2002): 2–15.
- Shelander D and Dutta N: "Combining Rock Physics Analysis, Full Waveform Prestack Inversion and High-Resolution Seismic Interpretation to Map Lithology Units in Deep Water: A Gulf of Mexico Case Study," *The Leading Edge* (April 2004).
- Pickering S and Waggoner J: "Seismic data helps reservoir management," *Hart's E&P* (January 2004).

2. Extended System Architecture

The deepwater oil and gas industry represents an increasingly complex, interconnected system of gathering and distribution of gasses, liquids, power and data. The differentiation of functions (e.g. separation, compression, processing) in space (e.g. surface, seafloor) is crucial not only to economics but to technical recovery methods. The ability to cost-effectively extend the reach of centralized surface infrastructure to gather oil and gas from more remote fields brings a large number of smaller fields into the economic recovery window. Additionally, within existing reach systems, seafloor pressure boosting enables higher drawdown, which leads to increased recovery in the long term. With riser backpressures as high as 3,000 to 4,000 psi and existing subsea pumps capable of only about a 1,000-psi boost, abandonment pressures in the deepwater are presently limited by water depth. In contrast, abandonment pressures may be as low as 100 to 200 psi in conventional settings. This significantly limits the oil and gas resource that can be recovered economically.

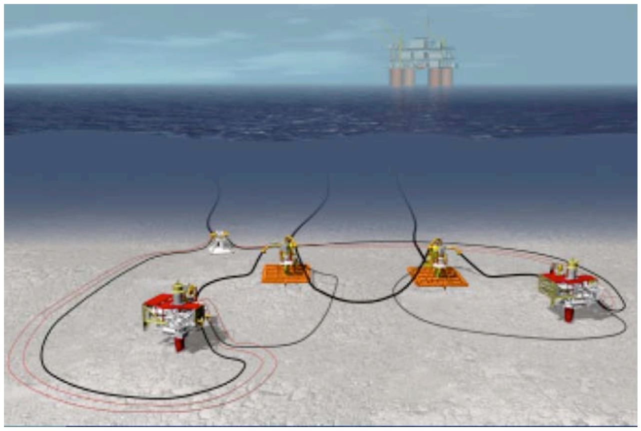

Figure VA2.1 Subsea completion.

Improvements in system-level architecture which are enabled by advanced technology are very likely to have a large impact on long-term ultimate recoveries. For example, subsea boosting, "cold flow" technologies, underwater communications, high voltage subsea power transmission and distribution, and subsea equipment reliability all enable longer lateral distances between subsea equipment and associated hosts (Figure VA2.1). As the system becomes more interconnected, modularization of standardized components will enable more rapid and reliable development. In the very long run, we envision the plausible convergence of sea-floor, well-engineering, and smart-well technologies could enable the gathering system envelop to include the below-mudline region with multilateral wells and pipelines gathering and distributing fluids, power, and data at reservoir depths.

For the gas and liquid system, we see opportunity for seafloor separation, boosting, and compression facilities in the near term. In the long-term, we see this evolving into full-function processing facilities that allow transmission of fluids from the wellhead all the way to land terminals. Near-term flow-assurance challenges are mostly related to the transient conditions associated with startup and shutdown, and low-cost steady-state flow assurance for long offsets. Reliability of mechanical equipment such as motors and pumps are key challenges.

For the power system, present technology requires large, expensive umbilicals with high power losses. Possibly, segmentation of the power system, or components (e.g. motors) which operate at high voltages could simplify requirements (e.g. avoid transformers and variable frequency drives). Low-loss or superconducting cables would enable transmission and distribution over longer distances. In the long term, we see potential for localized power generation (e.g. fuel cells) on the seafloor as being a significant enabler to a distributed deepwater infrastructure.

For the data communication system, wired systems work fine, where we have them. For unwired interaction, today's technologies do reasonably well at handling low-bandwidth data transmission in the vertical plane. High bandwidth and lateral distances are remaining challenges. Future systems are likely to be hybrids of long-range, high-bandwidth, wired systems and short-range lower-bandwidth, wireless technologies.

An integral part of the system architecture will be the design of flexible intervention systems to inspect and maintain the submarine equipment. Tethered or autonomous, work-class, underwater robotics systems area a likely part of the workable solutions.

The greatest challenge for the system architecture is aligning developments in one component area with developments in another. For example, advances in pressure-boosting technologies are interdependent with progress in power-distribution technologies and require consideration of intervention systems.

System gathering architecture is and will remain a priority for deepwater engineers working for both operators and service suppliers. As the system is complex and involves sophisticated engineering, advances are likely to carry price tags in the hundreds of millions of dollars.

For further reading, see:

- GRI-03/0126 Reservoir Applications of New Multilateral Field Drainage Architectures and Related Technologies
- SPE 57472: "Managing Risks Using Integrated Production Models: Process Description"

- OTC 13235: "Extending Tieback Distances: Wet-Mate Connectors, Enabling Technologies for Critical Systems Developments – Ocean Design" (2001).
- OTRC PROJECT: "Investigation of Factors Affecting Ultimate Recovery from Subsea Wells" (2003)
- OTC: "Innovative Approaches to Gathering Systems for Producing Wells in Deep Water," INTEC (2005).
- SPE 83976: "Enhanced Oil Recovery by Retrofitting Subsea Processing"
- SPE 71549: "Deepwater Separation: What Could Be the Use of It?"
- SPE 84045: "An Assessment of Subsea Production Systems"
- Akyildiz I, Pompili D, and Melodia T: "Underwater acoustic sensor networks: Research challenges," *Ad Hoc Networks Journal* 3, issue 3, Elsevier (March 2005): 257–279.

3. High Pressure and Temperature Completions

With up to the first 10,000' as water, the absolute depth below the rig floor of deepwater reservoirs is often up to twice as deep as was typical just 20 years ago. This creates conditions where seafloor equipment must operate reliably in an external environment of 4,500 psi and 34°F and withstand internal pressures up to 20,000 or 25,000 psi and 400–450°F. Such equipment must also withstand and contain a harsh and corrosive chemical environment including H_2S (Figure VA3.1).

Figure VA3.1. Existing HPHT subsea tree rated to 15,000 psi and 350°F.

This requires at least new engineering designs and likely new types of materials. These include: titanium and/or composite materials, novel elastomers/seals, and high-temperature electronics and motors. Design targets are 20,000 psi and 400°F in the near term and 30,000 psi and 500°F in the long term—in both cases suitable for sour and corrosive service. Materials and designs must be both identified and qualified for HPHT service.

Accelerating progress in this technology domain is likely to cost hundreds of millions of dollars and take many years. We believe there is excellent potential for transfer or co-development of fundamental materials science and engineering technologies across industry boundaries—most notably aerospace and military (e.g. navy). Thus although a domain of intentional industry pursuit, we believe there is compelling scope for collaborative research in academia and government labs.

4. Metocean Forecasting and Systems Analysis

The safe and efficient development of deepwater resources requires a robust understanding of the ocean environment and its interaction with our productions systems and operations. Gaps in this understanding lead to uncertainty that introduces cost, risk, and impedes effective decisions.

The ocean is a complex "weather" environment much like the atmosphere. While waves are the first image one associates with the ocean, the full "weather" picture encompasses conditions in the atmosphere, on the ocean surface, and below the surface of the water (Figure VA4.1). Many of these conditions are dynamic in nature and require characterization in terms of physical and actuarial properties. Wind, tides, waves, and currents are the most common examples. Conditions such as water depth, temperature, sea floor topography, and geotechnical characteristics and activity also drive decisions for deepwater production.

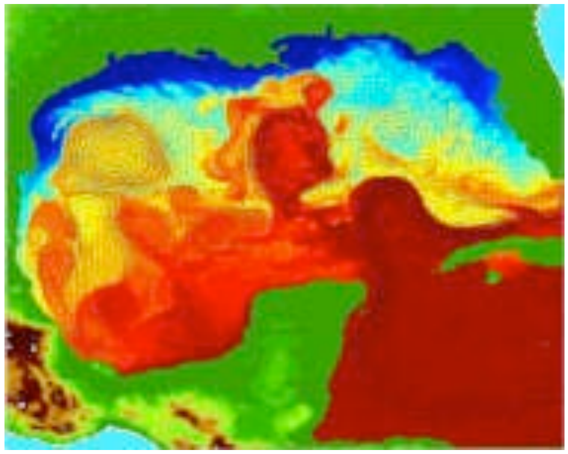

Figure VA4.1 Snapshot of map of GOM currents.

Marine weather conditions have an especially large impact on the oil and gas industry, which operates not just on the surface, but miles below it. Expected conditions impact all phases of oil and gas operations from design to operations. Increased completeness and accuracy lead to safer and more efficient designs and operations.

However, deepwater "weather" being remote and intrinsically more costly to measure, capabilities to establish complete information on real-time conditions and reliable forecasts of future marine conditions are still immature. The engineering precision required for deepwater systems remains heavily dependent on site-specific observation. Technologies such as remote sensing and numerical ocean models that are emerging to support scientific work on climate and earth processes appear promising. However, they have yet to demonstrate the accuracy necessary to overcome our dependence on site-specific measurement. Furthermore, the user communities sponsoring the development of these technologies do not appear to require the levels of accuracy necessary for offshore engineering.

New technologies that enable more comprehensive acquisition of high-quality ocean data, and more reliable forecasts for operations and design, can significantly benefit future deepwater development. Beyond the potential to enhance safe and efficient operations, the availability of such capabilities could accelerate the development of resources in new deepwater areas where the information for design is inadequate. For example, as industry moves into much deeper waters (i.e. up to

10,000’), it is moving into the domain of higher and more volatile currents with more impact on operations, but poorer data—especially below the sea surface.

Furthermore, new technologies that provide operators and regulators a more comprehensive picture of the conditions can mitigate surprises and enhance security of production supply.

Efforts to advance such technologies have significant synergistic benefit for other purposes of interest to the U.S. and the scientific community. For example, industry efforts to characterize loop and eddy currents of the deep Gulf of Mexico have enabled researchers to correlate these deep warm currents with hurricane intensity, a development that U.S. hurricane forecasters are now incorporating into their predictions.

Additionally, engineering systems-analysis models that predict the impact of marine conditions on system designs are not always available to handle the increasing complexity associated with some of the new, innovative concepts. For example, the forces acting on systems that use a combination of blunt and slender geometric shapes are intrinsically difficult to model with traditional scaling rules. New models that can account for the multi-scale nature of system configurations as they interact with the deepwater “weather” are required for safe and economic designs. Thus, technical progress designing safe and efficient deepwater infrastructure requires coupled progress in both weather forecasting and engineering-systems modeling.

We believe this is an area with significant potential for cross-industry and government, and academic cooperation. Global climate-modeling sciences face similar challenges in progressing accurate ocean models. The data and forecasts themselves are something with a clear common good, much like land weather to the agricultural industry. We see potential for the evolution of data-acquisition technologies that operate on regional scales and that can be integrated and dynamically reconfigured with existing data-gathering systems that tap both fixed and mobile assets. Model development should focus on predictive capabilities for support forecasting for real-time operations and long-term design. Over time, we see an increasing demand for higher-fidelity predictive models with uncertainty quantification. In the long term, maturation may support linking the interfaces with global climate, ocean, coastal, and arctic dynamics.

In the area of systems analysis models, we see the need to develop multi-scale models for the impact of surface and submarine weather on engineering systems. These models must be calibrated and validated with real physical performance. A shared understanding of models would aid both industry and government oversight agencies in ensuring a safe operating environment and reliable energy supply.

We believe theoretical developments for both the weather and engineering systems could be accelerated with a few million dollars. Development and operation of regional data-acquisition technologies and associated predictive capabilities will like cost in the range of tens to hundreds of millions of dollars.

For further reading, see:

- Haidvogel DB et al: "Model Evaluation Experiments in the North Atlantic Basin: Simulations in Nonlinear Terrain-Following Coordinates," *Dynamic Atmospheres and Oceans* 32 (2000): 239–281.
- Michalakes JS et al: "Development of a Next Generation Regional Weather Research and Forecast Model," in *Developments in Teracomputing*: *Proceedings of the Ninth ECMWF Workshop on the Use of High Performance Computing in Meteorology,* Zwieflhofer W and Kreitz N (eds), World Scientific, Singapore (2001): 269–276.

5. Special Note - Safety & Environmental Performance

The U.S. offshore industry has a proud track record of improvement in safely and cleanly developing U.S. offshore oil and gas resources (Figure VA5.1). As the industry moves into deeper waters, the challenge to continue this record of improvement grows with infrastructure that is further from shore, and the ocean environment that is more challenging. Sustaining this progress requires overcoming equipment and skilled-labor shortages, developing industry standards in a timely manner, resolving the above and other technical challenges through research programs, and applying comprehensive safety management programs.

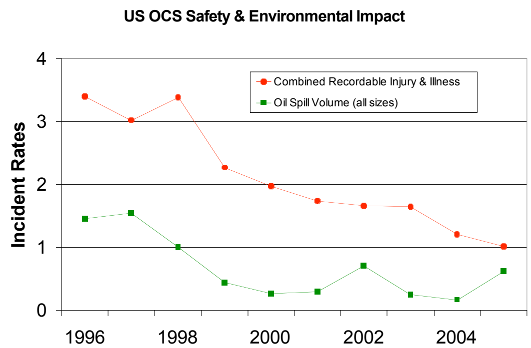

Figure VA5.1. U.S. OCS safety and environmental impact.

We believe it will remain a high priority for industry, academia, and government to continue to work together to simultaneously enable access to important economic resources while ensuring adequate conservation and protection of the marine environment. Of particular note are the challenges to ensure effective emergency response for increasingly remote facilities, and early assurance of suitability and integrity for novel development concepts.

Quality scientific information on environmental issues and their sensitivity to hydrocarbon production operations will be mutually important in making decisions regarding resource access and development options. Improved understanding of deepwater biological processes and habitats and both the short and long term effects of seismic survey activity on marine mammals are areas worthy of additional study.

Thus, although perhaps not a distinct technology area in its own right, we believe safety and environmental performance improvement has been and will continue to be critical to the future of deepwater.

For further reading see…

Godec M and Johnson N: "Quantifying Environmental Benefits of Improved Oil and Gas Exploration and Production Technology," paper SPE 94388 (2005).

"Environmental Benefits of Advanced Oil and Gas Exploration and Production Technology," U.S. Department of Energy (1999). Available at www.fossil.energy.gov/programs/oilgas/publications/environ_benefits/Environmental_Benefits_Report.html.

OCS Incident Data, see http://www.mms.gov/incidents/index.htm.

6. Other Deepwater Technologies Considered

Below are examples of other technologies discussed but judged to be of lower priority than those listed above.

Infrastructure life extension – For the present, deepwater infrastructure is young and of high quality. However, the day will come when deepwater structures and pipelines will become old like any other infrastructure. Solutions to inspect, remediate, redeploy or decommission physical assets will become increasingly valuable. This process is already underway in the oldest deepwater developments in the North Sea.

Virtual prototyping – All companies heavily utilize computer models to predict system behavior before costly construction begins. However, as an industry, there is not yet an emergent approach to fully model the whole system using component inputs from an array of vendors and participants. Development of standards and tools that allow fully integrated models could be increasingly valuable as the industry architecture becomes more complex and integrated.

Unconventional options – Deepwater today is primarily about light oil in high quality reservoirs. Some heavy or poorer quality oils do exist (e.g. Brazil) but are a small part of the current mix. Enhanced oil recovery is not yet a significant factor even in the shallower regions of offshore. However, as the "easier oil" is developed over the next few decades, we see the potential for the emergence of new technology to enable the economic development of more difficult hydrocarbons in deepwater regions. This could include not only heavier oils, but wholly unconventional hydrocarbons such as hydrates. However, we believe that offshore hydrates will remain more costly than less exotic alternatives for the foreseeable future.

Subsea drilling – The general long-term trend in the offshore is for functions (e.g. processing) to move from fixed structures to floating structures to the sea bottom. Possibilities for relocating drilling functions to the sea floor have been proposed in the past, but with high costs and absent a compelling advantage over today's advanced floaters, have never matured. Although not a high priority, we hold out the possibility that some or all drilling function could move to the sea floor in the very long term.

For those interested in a broader array of technologies discussed that could be enabling in deepwater should read the RPSEA ultra-deepwater workshop report.[4]

B. Related Priority Deepwater Technologies

Several technologies are deemed to be important to deepwater, but are discussed elsewhere in the Technology Subtask report due to their broader context.

1. Subsalt Imaging

Commercial oil and gas deposits are found in geological settings with "working petroleum systems"—or areas with a) a plentiful source to generate oil or gas, b) porous reservoirs to store it, and c) sealing layers to trap it. However, some working petroleum systems are hidden in settings that make potential reservoirs and traps difficult to "see" with conventional seismic technology. The U.S. Gulf of Mexico and some other basins around the world (e.g. Angola, Egypt) contain working petroleum systems below thick layers of salt. Seeing through an undulating layer of salt with seismic imaging is like trying to see through textured glass—the bending of the rays makes it difficult to recover a clear image of what's on the other side. The advance of leading-edge seismic technologies which can "see through" salt are likely to have the most significant impact of all on the development of deepwater oil and gas resources. This technology is discussed in the Exploration Technology subtask team report.

2. Gas Liquefaction

Gas is more expensive than oil to transport very long distances. Gas-to-liquids and liquefied natural gas are discussed elsewhere in the work of the Supply

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[4] "Ultra-Deepwater Oil and Gas Technology Workshop Report: A Report on the Ultra-Deepwater Technology Workshop Held at the Houston Hilton Post Oak," University of Houston, Texas A&M University, Louisiana State University, RPSEA. Final Report (Nov 29, 2005). Available at http://www.ultradeepwater.org/pdf/Ultradeep_report_final.pdf.

committee. We only note here that continued progress on these technologies is also of benefit to deepwater developments. This is because as fields are developed in deeper and deeper waters, not only are they farther from existing land infrastructure, but the cost of building new ultra-deepwater alternative infrastructure (e.g. pipelines, reinjection) goes up significantly. Breakthroughs that enable utilization of such technologies in smaller footprints and on floating vessels are thus a significant enhancer to the global deepwater industry.

3. Offshore Arctic

The arctic oil and gas industry has yet to move significantly offshore like the industry in more temperate climates did in the 1960s. With the increased challenges of the harsh arctic surface environment (i.e. ice and cold), there will be an increased drive for advanced technology even in shallower water depths. Although many technologies will be optimized for arctic specifics, we believe they will often be founded upon or derived from their deepwater cousins (e.g. subsea processing). As such, development of traditional deepwater technologies should be seen as a forerunner of offshore arctic technology in the same way the shallow activity was a forerunner of the deep. Long range deepwater technologies (e.g. subsea drilling) could become even more important in the arctic.

C. Deepwater Technology Development Issues

1. Future Marine Technology Leadership

Marine sciences and engineering is a specialty field where many disciplines (e.g. mechanical and civil engineering) can be taught to apply known techniques. However, the few, small centers of excellence that have historically trained the leading marine thinkers, shapers, and innovators are disappearing due to university competition for research in information-, nano-, and bio-technologies (MIT, Michigan, Berkeley). As this continues, the intellectual capital responsible for driving our industry to push the leading-edge solutions for ever more challenging environments is shrinking, while the challenges we face grow increasingly more difficult.

This is a concern of national importance and has been recognized by the U.S. Navy as well. This development is positive. However, while the goals are similar, the scale of the impact is too modest to meet broader U.S. interests inclusive of oil and gas applications.

We conclude that the U.S. must maintain critical mass for deep specialization in the marine sciences by providing balanced funding to U.S. research universities for physical sciences, engineering mechanics, and marine system design on par with other U.S. technical priorities. Options to address could include

1) research grants to promote graduate and post-doctoral studies that focus on crucial ocean energy issues
2) initiatives to re-energize university collaboration with national research centers and industry
3) incentives to elevate university priorities or delivery of research and continuing professional education
4) taking advantage of the stunningly impressive accomplishments that have come from deepwater development to promote public and university pull for physical sciences and technologies.

Improving the current situation is likely to cost tens of millions of dollars for top tier universities in ocean sciences and marine engineering.

For further reading, see:

- SPECIAL REPORT 266 - Naval Engineering Alternative Approaches for Organizing Cooperative Research – Transportation Research Board of the National Academies
- "An Ocean Blueprint for the 21st Century," Final Report, U.S. Commission of Ocean Policy, Washington DC (2004).
- SPE 99898.

2. Valuing Technology to Enable Access

Policies about access to acreage for the purposes of oil and gas exploration and development are a complex matter. However, access to acreage with potential for economic oil and gas resources is in and of itself a primary, if not the largest, driver that encourages technology development. The onset of area-wide leasing for the U.S. GOM in the early 1980s led to significant acceleration of interest in deepwater regions.

However, when viewed from the community perspective, governments generally are not favorable to opening acreage for access until they are confident that the resources can be developed safely and cleanly. The norm is thus to wait for proven answers before opening doors.

Although we realize this is a complex issue, we believe there is at least theoretical advantage to a "necessary solutions" approach to the dialogue process associated with acreage access. By this we mean that the better governments are able to articulate primary concerns that drive them to limit access, the more likely that this itself would be stimulating to both technology and resource development.

The Atlantic, Pacific and Arctic offshore coasts are estimated to contain roughly 74 billion barrels of oil (equivalent) of undeveloped resource.[5] However, we feel compelled to note that even in the GOM, the actual resource that could be developed was not known until after exploration and development began. We therefore conclude that the amount these basins could contribute to U.S. domestic energy supply remains highly uncertain.

We thus propose that a) the better key concerns regarding restriction of access are articulated within a common dialogue, the better the industry will be able to bring forth technical solutions that satisfy broader social needs, and b) the act of granting access will in and of itself be *a*, if not *the* primary technology development driver.

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[5] "Report to Congress," reference 2.

VI. Conclusion

Finding and developing oil and gas anywhere offshore was once a significant challenge, itself. The industry followed the opportunity first into shallow waters, and then into the deep waters. Each challenge along the way has been met and conquered safely and effectively.

Although continuing challenges for moving into ultra-deep waters loom large, to the extent the resource endowment itself continues to be present, technology is unlikely to become the barrier that inhibits ultimate progress. We conclude that the top priority challenges that would enable progress are:

1) Reservoir characterization
2) Extended system architecture
3) High-pressure and -temperature completions
4) Metocean forecasting and systems analysis.

With these and other challenges, we believe the track record of the industry should give confidence that wherever the opportunity presents itself, safe, economical and environmentally friendly technology will be developed that allows the development and recovery of accessible resources.