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# ADVANCED COMPOSITES TECHNOLOGY DEVELOPMENT FOR ULTRA DEEPWATER PETROLEUM PRODUCTION IN THE TWENTY-FIRST CENTURY

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## EXECUTIVE SUMMARY

The discovery of large reserves of oil in deepwater Gulf of Mexico (GOM) combined with wells which produce at rates in excess of 10,000 barrels per day has created high interest in the oil industry to develop this valuable United States resource. In response, the Minerals Management Service has opened large blocks of the GOM for leasing including blocks in water depths up to 13,000 feet and the bidding response by both U.S. and foreign oil companies has been very aggressive. Deepwater development poses many new technical and economic challenges, and the oil and oil service industry is aggressively responding to meet these challenges. Although the oil industry is a complex, high-tech industry, it essentially produces a commodity product where the price is controlled by the law of supply and demand. In the first half of 1998, over supply has caused oil prices to be lower than have been typical of recent years. If low oil prices continue, they can be expected to impose a restraining effect on the rate of development of deepwater resources. On the other hand, industry experts indicate the worldwide demand for oil will grow at 2% to 2.5% annually[1] and a strong case can be made that the world is rapidly approaching the point of consuming half the original resource of oil and a supply side deficit is likely to emerge within the next ten years.[2,3]

In spite of price uncertainties, the U.S. oil industry continues to develop deepwater resources with the expectation of improving markets. For the United States, deepwater GOM is the only large new source for petroleum currently available. The United States currently imports approximately 56 percent of the oil consumed internally. Without GOM deepwater development, United States oil production will continue to decline making dependence on imported oil even larger. In the interest of economic and national security, the U.S. government is expected to continue to encourage new oil and gas development to prevent dependence on imported oil from going even higher. The Department of Energy recently published a document called *Comprehensive National Energy Strategy*[4] in which Secretary of Energy Federico F. Pena made the following statement, "Our national security depends on affordable and abundant supply of energy. Under every conceivable scenario projected by energy analysis, natural gas and oil will remain a central part of our Nation's energy future. As the world demand for oil grows, the United States does not want to rely on any particular region of the world for imported oil. Moreover, our own dependence on imported oil is expected to grow from 50 percent today to 60 percent by 2010." [4] One of the five goals of the Department of Energy is to "ensure against energy disruptions by reducing the threat of supply interruption and increasing the security and reliability of our energy infrastructure".[4] One of the DOE strategies to achieve this goal is to stop the decline in domestic oil production by the year 2005. Development of Gulf of Mexico deepwater resources clearly will have a significant role in achievement of this goal.

The technology needed to safely and economically develop deepwater petroleum bearing reservoirs is extremely complex and will require advancements in several different disciplines. Technology is playing a vital role in reducing the cost of finding and producing oil and gas. Important advancements have been made in seismic technology, directional drilling, multiple completions, subsea systems, and production techniques. Composite materials is another technology which could provide important enabling solutions for safe, affordable deepwater development. Floating platforms are the only practical configurations for deepwater and are commonly used in combination with subsea wells. Floating platforms are tied to the ocean floor by moorings or tethers, or for drilling can be dynamically positioned using thrusters. Saving weight is an important design consideration for floating platforms with more cost benefit for some configurations such as Tension Leg Platforms (TLPs) than others and corrosion prevention is also important. Successful introduction of secondary composites on recent GOM TLPs and NIST ATP research programs have positioned the oil industry to be receptive to composite components. Low-cost manufacturing methods and utilization of hybrid materials to minimize cost are two examples of ways composites manufacturers are addressing the cost issue.

The ATP program initiated by NIST in 1995, which focused on composite manufacturing for the oil industry, provided significant stimulus to get composites acceptability within the broader petroleum industry. Products such as composite production risers, drilling risers, and spoolable pipe are being considered in project planning exercises. A significant amount of scientific technology has also been developed under these programs such as complex metal to composite joints, hybrid material design methods, and composite structure reliability analytical methods.

The oil industry is currently developing the deepwater solutions which will be implemented in the 1st decade of the 21st century. Many issues are multi-disciplinary in which a solution for one problem affects the design of many related components. Weight savings fall into this category and if composites are not considered in the early planning stage, the benefits will not be captured and the industry will become entrenched in an alternative inefficient solution. Advanced composites technology needs to be developed now and be ready for application during the introductory window of opportunity which for ultra deepwater GOM will be during the next five years.

NIST sponsored a meeting on January 29, 1998 to assess the oil and civil infrastructure industry needs and their interest for another ATP focus program on composites. A summary of the breakout session discussion of composite applications for the oil industry is presented in Appendix A. Projects were prioritized with regard to the four criteria established by NIST.

1. Potential U.S. Economic Benefit
2. Good Technical Merit
3. Strong Industry Commitment
4. Opportunity for ATP to Make A Difference

A list of the potential candidate projects related to composites for the oil industry which might be appropriate topics for an Advanced Technology Program is presented below. The priority of a fit with ATP criteria was ascribed a value of 1-5 with 1 - low and 5 - high.

## Potential Candidate Projects for NIST ATP Co-Sponsorship

| | | |
|---|---|---|
| 1. | Tubular Tendons for Floating Production Systems | 5 |
| 2. | Other Mooring Systems | 5 |
| 3. | Choke and Kill Lines, 4.5", 7500 - 15,000 psi | 5 |
| 4. | Continuous Tubulars, D>4", Pressure > 4,000 psi | 4 |
| 5. | Thermoplastic, Spoolable, Continuous Tubulars | 4 |
| 6. | Deck Structure for Floating Production Systems. Spacer beams, Main Girders, Fabricated Shapes, Attachment Methods | 3-4 |
| 7. | Analytical Methods for Qualification of Alternative Designs | 3 |
| 8. | Drilling Derricks & Flare Booms | 3 |
| 9. | Fiber Over-Wrapped Steel Pipelines | 3 |
| 10. | Real Time, Performance Monitoring Sensors and Inspection Tools | 2 |
| 11. | NDE Methods for Qualification of Products (Incorporate into 1 & 3) | 2 |
| 12. | Composite Pressure Vessels | 2 |
| 13. | Down Hole Tubulars | 2 |

The January 29 meeting served as background for the current report which provides additional information on these and other applications which could be productive topics for development under NIST ATP joint venture programs. A condensed version of this report was submitted to NIST as a White Paper advocating a new Advanced Technology Program focused on composites for the oil industry[5]. In preparing this document, representatives of the oil, oil service, and composites manufacturing industries were consulted and the report reflects their input. Many of the proposed applications are highly-loaded primary structure with high performance reliability requirements. The user (oil / oil service companies) and composites manufacturer all assume risk in adopting composite materials solutions. The oil company's primary risk is associated with reliability and the expense associated with failure including delays in production should components not meet expectations. The engineering service companies are not experienced in designing or servicing composite components and are skeptical of unknown risks and foresee additional costs in preparing to efficiently design and install composite products. The manufacturer's risks involve being able to precisely understand the requirements and then being able to design and manufacture successful products at a profit. All these risks are formidable barriers to developing composite products, especially without external stimulus such as the NIST ATP program. It was therefore recommended to NIST, that a new ATP program be initiated which would focus on addressing the needs of the oil industry for composite structure solutions for ultra deepwater development.

The benefit to the United States of a new focus program on composites for ultra deepwater petroleum development would be:

1. Provide the technology assistance needed to help make successful the GOM thrust into ultra deepwater.
2. Help increase the domestic production of oil and gas.
3. Improve the international trade balance of payments.
4. Create new U.S. based jobs in the oil service and composites manufacturing industries.
5. Develop composite products for overseas markets.

Such a program is consistent with the November 1997 recommendations of a panel of energy experts appointed by President Clinton which strongly urged the administration to increase funding for energy research by $1 billion over the next five years. The benefit of the program to the petroleum and composites industry will be to provide the stimulus to overcome current technology barriers and reduce economic risks, thus allowing highly-loaded primary structure components to be developed in time to be deployed on the next generation of platforms in ultra deepwater in the GOM and exported to deepwater development in the rest of the world.

## INTRODUCTION:

Approximately 65% of United States energy needs are supplied by petroleum. Domestic oil and gas production, however, is declining and in 1998 the United States will import approximately 4 billion barrels of oil accounting for 56% of consumption and add approximately $63 billion annually to the international trade deficit. In 1972, just prior to the oil embargo, the United States imported 1.7 billion barrels of oil, which was only 29% of total consumption. One promising new source for petroleum in the United States is from reservoirs located beneath deepwater in the Gulf of Mexico (GOM). It will be a significant challenge to produce petroleum from reservoirs located beneath ultra-deepwater (up to13,000 feet of water depth). Lightweight, corrosion-resistant composite materials could provide an important contribution to the safe, economical development of deepwater petroleum resources. In addition, if composite products are developed by U.S. manufacturers rather than overseas, they could be deployed in deepwater basins in other parts of the world to provide a valuable market for U.S. products. The export of composite products for the oil industry will help make U.S. oil and service companies more competitive in international exploration and production services and have a significant positive impact on the U.S. balance of payments.

In January 1994, representative of the petroleum industry submitted a white paper[6] to the National Institute of Standards and Technology (NIST) advocating a program to encourage development of composites technology directed toward petroleum industry applications. Based on the needs and opportunities identified, NIST established a focused program on manufacturing composite structures for the oil industry and six programs addressing oil exploration and production applications were initiated in 1995 (see Table 1). These programs will finish their third year of development in 1998 and several programs have made sufficient progress to move toward commercialization. The technology developed is also being used to develop alternative oil application products based on current market demands. NIST support helped create a critical mass of interested parties involving all the stake holders, the end users (oil companies), technology developers (industry and universities), and potential suppliers (materials and manufacturers). These interdisciplinary teams worked together to define the functional requirements, resolve critical technology barriers, conduct validation tests and establish specifications in preparation for the introduction of new products into service. Without NIST support, the oil industry would be much less prepared to accept and apply composite materials.

The Composites Engineering and Applications Center for Petroleum Exploration and Production (CEAC) in October 1997 sponsored an international conference focused on composites for petroleum applications.[7] The conference highlighted progress that had been made in composite applications since a similar International Conference held in October 1994. One of the highlights of the meeting was a presentation by the Mars

Tension Leg Platform (TLP) project manager in which he gave strong endorsement for the numerous secondary composite applications being used on the current class of deepwater TLPs. The Mars TLP was installed in 1996 in 2940 ft. of water. Composite applications include large quantities of low pressure pipe used to transport seawater including fire protection water, as well as secondary structures such as gratings, hand rails, and ladders. Also highlighted in the Conference were research efforts on more advanced composite applications such as drilling and production risers and small diameter spoolable pipe currently under development. These advanced applications are expected to make significant economic and enabling contributions as the oil industry moves into ultra deepwater. More advanced composite applications such as deck structures, synthetic fiber moorings, large-diameter long-length pipe, thick-walled tubulars for ultra high pressure service, extended reach smart drill pipe, corrosion resistant process vessels, and TLP tendons could also contribute to the development of ultra deepwater, but these applications will require significantly more research and development activity to develop the high level of reliability required for highly loaded, safety critical applications.

Several factors have converged in the last few years to make composite materials attractive solutions for primary structural applications on offshore platforms. First, large reserves of oil and gas have been discovered beneath deepwater basins in the GOM and in other parts of the world. World wide, deepwater is estimated to contain over 150 billion barrels of oil of which approximately 18.5 billion barrels are estimated to be located in deepwater GOM.[8] Saving weight on deepwater platforms and the supporting infrastructure could provide significant cost savings and enabling advantages in deepwater developments. Second, the success achieved in applying secondary composites in the last four years in the new generation of deepwater platforms has demonstrated the advantages of composites and opened the door for more challenging applications. For example, high performance components such as high-pressure accumulator vessels used to support riser tensioners were introduced into service on the Mars TLP platform. Successful performance, safety enhancements and significant cost savings for these applications have helped erase industry skepticism and caused a paradigm shift toward accepting broader applications of composite materials offshore. Third, the composites industry has started to mobilize and develop the infrastructure needed to be able to supply products. The NIST ATP focused program on oil industry applications has played a significant role in helping assemble a critical mass of responsible parties focused on development of the required critical technology. Oil operators and service companies are now seriously considering ways to utilize lightweight, corrosion-resistant composites during the planning stage of new projects.

The development cycle for an offshore platform takes about five years from exploratory discovery of oil to development of the necessary infrastructure to allow production. Significant emphasis is being made in new projects to shorten this development time, especially the time from project approval to first oil where expenditures in excess of a billion dollars are typical of deepwater projects. With such large capital expenditures, the time value of money is one of the most important factors impacting the profitability of a project. The long lead-time in developing composites is part of the risk factor that inhibits oil companies from committing to composites. Oil companies are most receptive to consider new ideas during the early planning stage of a field development driven by the goal to lower cost or overcome technology barriers. Project managers are driven to accomplish the project on schedule and in budget and are more comfortable with conventional solutions. In most cases to be seriously considered for a project, the technology must be ready for use or require only minor enhancements. This makes it important to have the technology ready while the window of opportunity is open. The industry is currently very active in addressing the challenge to develop ultra deepwater oil and gas resources and solutions formulated during the next few years will become the standard for the industry for many years to come. The oil industry thinks "metals", but on balance has changed paradigm in the last few years from negative to neutral relative to accepting composites. If composites technology is to be utilized, it is critical that the technology be ready while the window of opportunity is open. This window of opportunity is believed to be the first decade of the 21st century during which the oil industry will develop the framework for exploiting ultra deepwater resources worldwide.

## DEFINITION OF DEEPWATER

The oil industry definition of deepwater continues to escalate. The Minerals Management Service (MMS) defines deepwater as water depths greater than 1312 feet (400 meters). The Ram Powell TLP platform installed in the 1997 is located in 3251 ft. of water and the Ursa platform is scheduled to be installed in 1998 in 3928 ft. of water. The Kings Peak platform is anticipated to begin production in 6800 feet of water in 1999. Exploratory drilling has already taken place in over 7600 ft. of water and companies hold GOM leases at water depths as great as 13,000 ft. For the purposes of this paper, *ultra deepwater* is defined as water depths greater than 4000 ft. Water depths up to 13,000 ft. are believed to hold oil reserves, and it is the greater than 4000 ft. depths where major technical challenges exist and where composite materials are expected to provide significant enabling capabilities

## ECONOMIC INCENTIVE UNCERTAINTIES

Highly successful exploration and production of oil and gas in recent years from deepwater Gulf of Mexico (GOM) resources provided the incentive for the current intense level of activity in leasing, exploring and developing United States deepwater resources. Figure 1 illustrates the rapid growth rate in recent years in leasing deepwater (greater than 2625 feet) GOM tracts.[9] Not only are tracts being leased, but oil and gas are being discovered and production projects are being launched as indicated in Figure 2 which provides a summary of current deepwater development projects in the GOM.[9] The high economic potential for the GOM coupled with restrictions on access to other potential development areas such as the east and west coasts and Alaska have positioned the GOM to be the major region for U.S. oil and gas development for the first part of the 21st century.

It is generally accepted that light-weight, fiber-reinforced, composite materials could play a major role in facilitating the safe, reliable, economical production of oil and gas from deepwater reservoirs; however, significant work needs to be done to make the technology ready. Steel is the primary material used in the construction of offshore platforms and infrastructure and tubulars are the most common structural element. Steel is relatively inexpensive, but heavy and susceptible to corrosion. Low density and corrosion resistance are the primary properties which make composites attractive for offshore developments. In deepwater, the value credited to saving weight increases and composites become more economically attractive.

Unlike the aerospace area, the oil industry does not have a strong sponsor for development work in the materials area, either within oil companies or the oil service industry. In the modern highly competitive commodity market driven by stockholder expectations of ever increasing profits, most oil companies have in the last 5 years reduced or eliminated in-house research in the materials area. Oil companies have downsized or closed materials laboratories with the expectation that the oil service industry and universities would fill the need. The net result is that in the last five years much less research has been sponsored in the materials area. Fortunately for composite materials, the NIST ATP programs have helped keep active a critical level of research and development activity in support of oil E&P applications.

By the time project engineers enter the planning stage to develop the supporting infrastructure of field developments, it is usually too late to develop new technology unless it is impossible to accomplish the objective otherwise. Project teams focus their attention on existing technology, even if it is more expensive or less efficient. The uncertainty of changing development scenarios during such long lead times is a primary concern for product manufacturers and becomes one of the primary reasons government support is needed to help accelerate the pace of development and ensure that products are available when they are needed.

Even though the payoff from using composites offshore can be high, several factors combine to impose a high level of risk on composite manufacturers to develop products. Not only is a substantial investment required to develop reliable commercial products, but also there are numerous unresolved competing development scenarios within the industry, which impact the payoff reward in using composites. Even the type of platform configuration (TLP versus other platform configurations) has an impact. Current thinking is that a TLP is limited to water depths of less than 5000 ft. based on the inefficiencies imposed by the large weight of the tendon and riser systems. Saving weight on a TLP provides more leverage (higher dollar value per pound of weight saved) than saving weight on other types of floating production platforms (FPS). Operators prefer to locate the wellhead on the platform rather than subsea because it permits direct well access from the platform. Frequently during the life of a well, it must be reentered to address production problems and improve the rate of recovery of oil and gas. TLP and Deep Draft Caisson (SPAR) configurations permit the well head to be located on the platform and to employ vertical risers. The heave (vertical) displacement on other types of floating platforms makes it necessary to use shaped or catenary flexible risers to accommodate the large heave displacements and the wellhead is located on the sea bed. Well intervention is then usually accomplished using a separate mobile workover platform rather than directly from the FPS platform. Different field requirements and different company philosophies make it impossible to conclude that one platform concept will always be considered superior to another, so the value associated with saving weight remains a variable. Offshore developments also commonly involve production from subsea wells in which a pipeline is run on the sea bed to a nearby platform or to shore. Sometimes the requirements are not well defined and a significant effort is required to determine all the governing constraints. The composites technology needed for oil industry application frequently are not fully developed and require considerable expense. These combined uncertainties make it difficult for a manufacturer to make bold commitments to develop a product without external stimulus such as from a NIST ATP program.

## GOM DEVELOPMENT IMPORTANCE TO NATIONAL ECONOMY AND REDUCING FOREIGN ENERGY DEPENDENCE

The petroleum industry is a major component of the U.S. economy. During the last decade, U.S. oil production has steadily declined while gas production has shown only a modest increase. At the same time domestic consumption of oil and gas has steadily risen with current oil imports of 10.8 million barrels per day which accounts for over fifty-six percent of consumption. At $16 per barrel, this accounts for a foreign trade deficit of $63 billion. The percent of oil imported when the first NIST white paper[6] was written in 1994 was 49.2%. No major new onshore oil and gas discoveries are expected in the lower forty-eight states, and East and West Coast offshore resources and the Alaskan Naval Petroleum Reserve are currently not available for development. This leaves the development of deepwater GOM resources as the major source of U.S. development for the first part of the 21st century.

Current world oil production is approximately 77 million barrels per day[10] (28 billion barrels per year) as shown on Figure 3. The United States is the second largest producer with 8.5 million barrels per day if OPEC producers are considered as a unit. OPEC produces approximately 32 million barrels per day or 42 % of the total world production. Production of oil from offshore resources is approximately 21.1 million barrels per day (27%) percent of total world production. The geographical distribution of oil production from offshore for 1995 and projected for the year 2000[11] is presented in Figure 4. The North Sea produces the largest quantity of offshore petroleum (approximately 29%) followed by the Persian Gulf and North America. Annual oil production from the GOM annual oil production is currently around 1 to 1.25 billion barrels.[12] This is expected to increase to around 1.7 billion barrels per year over the next decade. Natural gas production from the GOM in this same period is expected to rise from 13.8 to 17.2 BCFD.

Oil companies have been very active in recent years in leasing deepwater GOM properties from the U.S. government. "There are a total of 4875 active leases issued in all water depths across the US Gulf OCS in the 1992-1997 leasing period, of which 2221 (45%) lie in water depths greater than 1,500 ft. Of the 2221, 1032 (46%) are in water depths greater than 4,999 ft. and 746 (34%) are in water depths ranging between 2,999 ft. and 4,999 ft."[13] "More than 25 percent of new discoveries in the U.S. Gulf are in deepwater. As of January 1998, 104 deepwater prospects have been announced in the GOM of which sixteen are located in water depths ranging from 2,000-2,999 ft., 21 in the 3,000-3,999 ft. depth range, and 18 in 4,000 ft. plus ultra-deepwater."[14] Exploratory drilling activities have been conducted in waters as deep as 7620 ft.[15] The Minerals Management Service estimate of the water depth from which U.S. offshore oil will be produced in future years[15] is presented in Table 2. The data shows a clear government expectation that future offshore production will primarily come from deepwater with 69% coming from water depths greater than 2600 feet by the year 2007 versus only 28% in 1997.

Production from deepwater reservoirs in the GOM can help fill the need for oil from domestic rather than foreign sources. Accelerated production of oil and gas from deepwater reserves will also contribute to the economic growth and prosperity of the United States by creating additional jobs in the oil and gas service industries while federal and state governments will benefit from the growth through lease and royalty payments. In FY 1998, the Minerals Management Service (MMS) expects to collect $5.5 billion in revenue from the Outer Continental Shelf and the amount is expected to grow as production in the GOM expands.

## WORLDWIDE OIL SUPPLY PERSPECTIVE

Worldwide oil production in the first quarter of 1998 was approximately 75 million barrels per day which exceeded consumption by about 1.5 million barrels per day.[16] In response, March 1998 crude oil prices sank to their lowest level in inflation adjusted terms since 1973 and may fall even further this year if global supply and demand are not brought into closer balance. Against this backdrop of oversupply and abundant cheap energy, one may ask why anyone including the oil industry would be concerned about developing new petroleum sources such as deepwater Gulf of Mexico? Oil is a commodity and thus subject to the economic dynamics of supply and demand. The industry tries to plan for up and down cycles, but the factors governing the cycle are most often unpredictable. Large oil field developments from the time of discovery to production require long lead times, on the order of five years, which make long term planning difficult. Last year many oil and oil service companies made record earnings and the economic forecasts looked very promising. World wide oil demands have been rising by 2 percent per year. The Energy Information Administration forecasts that worldwide demand for oil will increase 60 percent to about 110 million barrels per day by 2020.[2]

A recent article in Scientific American by Campbell and Laherrere[2] addressed the energy supply issue and made a strong case for the demand for oil permanently exceeding the supply during the first decade of the 21st Century. According to a model by M. King Hubbert published in 1956 which seems to fit available data, unrestrained extraction of a finite resource rises along a bell-shaped curve that peaks when about half the resource is gone. The oil industry reports about 1,020 billion barrels of oil in proven reserves at the start of 1998 while industry experts indicate that just over 800 billion barrels of oil by 1998 have been extracted from the earth. "About 80 percent of the oil produced today comes from fields that were found before 1973 and the great majority of them are declining."[2] "Even with sophisticated advanced technology for finding oil, oil companies in the 1990s have discovered an average of only 7 billion barrels of oil a year while consumption has exceed more than three times this amount for this period."[2] "There is only so much oil in the world and the oil industry has found about 90 percent of it."[2] "Global discovery peaked in the early 1960s and has been falling steadily ever since."[2] "A number of the largest producers, including Norway and the U.K., will reach their peaks around the turn of the millennium. By 2002 or so, the world will rely on Middle East nations, particularly five countries near the Persian Gulf (Iran, Iraq, Kuwait, Saudi Arabia and the United Arab Emirates), to fill in the gap between dwindling supply and growing demand."[2] Within two years, the Middle East will supply over 30 percent of world consumption and by 2010 the Middle East's share will increase to approximately 50 percent.

Another estimate of the world wide resources of oil and gas (past, present and future) is provided in a recent article by the U.S. Geological Survey[3] and presented in Figure 3. The estimates of reserves present and undiscovered are higher than the estimates of reference 2, but at current rates of consumption still indicate a depletion of the worlds oil and gas energy resource within half a decade.

"Theoretical advancements in geochemistry and geophysics have made it possible to map productive and prospective fields with impressive accuracy."[2] "Exploration has pushed the frontiers back so far that only extremely deep water and polar regions remain to be fully tested and most of the deepwater regions of the world can be condemned as barren." [2] Current expectations for ultra deepwater reservoirs other than the GOM included the West Coast of Africa, the North Sea, west of the Shetland Islands, and Asia.

Accepting the possibility of a permanent decline in the production of oil within 10 years, it becomes prudent for the United States to be positioned so that the main new U.S. prospect, deepwater GOM, can be developed. Composites is one of several technologies which could make a big difference in enabling economical ultra deepwater petroleum production. Lacking a support base like the aerospace industry, manufactures of composite products for the oil industry must assume unusually high risk to develop products. The NIST ATP program could provide the stimulus to the oil industry to unite to support the development of the necessary technology to insure that products are available in time to be applied in the 1st decade of the 21st century window of opportunity.

## COMPOSITE MATERIALS AND PROCESSING

Glass, carbon, aramid, high molecular weight polyethylene, polyamid and polyester are possible candidate fibers for application offshore. Epoxy is the primary class of resin proposed for use offshore, however, resistance to fire has created interest in phenolic and other classes of materials. Thermoplastic resins would be of high interest if a material with a use temperature of 250°F or greater could be supplied at an affordable price (less than $5/lb).

Except for mooring ropes, composite components for the oil industry require a higher stiffness and strength than is provided by polyester, polyamid or polyethylene. Glass fiber is used where the properties are adequate to meet the need, but higher modulus values are frequently required to meet structural requirements. To minimize cost, hybrid construction incorporating combinations of glass and carbon is commonly used. Aramid may also be used in hybrid construction to improve damage tolerance. For water depths around 4000 feet, polyester is the primary material being considered for FPS and MODU mooring rope applications. Further study of moorings for ultra deepwater may show that higher stiffness properties are needed and drive the design toward the use of aramid fiber ropes or even carbon/matrix materials.

Commercial grade, large strand tow, carbon fiber appears to be coming down in price to a range which would make it affordable to more applications in the oil industry.[17] One company projects a price of $5/lb by the year 2000 for commercial grade carbon and pitch carbon fiber may become available at even lower prices. New manufacturers of low cost carbon fibers are also entering the market. Sufficiently large quantities of carbon fiber should be available in the time period of the first decade of the 21st century to supply the large need should oil applications for composites described herein develop. One hundred seven million pounds of carbon fiber are forecast to be produced by the year 2000 of which 59 million would be lower cost commercial grade.[17]

Although the design allowables associated with commercial grade, large strand tow, carbon fibers are not well established, such fibers are compatible with some of the low-cost manufacturing processes such as filament winding and pultrusion. Wet filament winding and pultrusion are standard processes used to make products directed toward the oil industry. By uniting the resin and matrix materials during manufacturing, rather than using prepreg or fabric material, significant cost savings can be achieved. There are also other manufacturing processes which show promise for low cost manufacturing which should be investigated in developing new products. Unexplored processes which may have merit include SCRIMP, resin transfer molding, and the use of rapid cure processes such as electron beam curing, to name a few. The combinations of new materials and processes introduce further financial risk to the developer and requires process as well as design and fabrication development.

## PROMISING NEW COMPOSITE APPLICATIONS

In preparation for this paper, representatives of the oil and composites industries were contacted to identify potential new applications for composites and to determine if there was sufficient technical merit and interest to form project teams to conduct the necessary development. A positive response was received and the ideas expressed below reflect the topics around which projects could be expected to be formulated. The production of oil and gas in ultra deepwater demands creative thinking and the topics expressed below capture some of the solutions being considered utilizing composite materials and structures.

A listing of some of the components which could provide significant enabling capabilities if constructed of composites rather than steel is provided in Table 3. In addition, an estimate is provided of the quantity and market value of projected utilization of these composite components during the first decade of the 21st century. The last column highlights the advantages of using composites as seen from the perspective of the oil company end user. Large quantities of composites are forecast to be used if the technology can be demonstrated to meet the requirements at an affordable price and are developed in time to be applied when needed. This includes approximately one-half billion pounds of composite materials with estimated value over $5 billion. This scenario is for new composite products currently not available and does not include the use of composite products such as low-pressure fiberglass pipe, gratings and other products already baselined on new TLPs designed for the GOM. Even though additional work will be required to extend the capabilities of composite production and drilling risers to meet ultra deepwater requirements, the technology developed under the current NIST ATP program is believed to be adequate to permit the development of new products. It is not anticipated that additional ATP programs would be requested in these two areas.

The values in Table 3 assume a total of 40 field developments in the time period 2000-2010 utilizing bottom anchored platforms including 10 TLPs and 30 Floating Production Systems (FPS). In addition, it is assumed 10 Mobil Offshore Drilling Units (MODU) will be outfitted with drilling risers and 20 MODUs with drilling riser support lines (choke and kill, hydraulic, and mud boost lines). It is assumed that the 40 field developments will make the indicated utilization of composites. In addition, existing composite products such as low-pressure fiberglass pipe, composite gratings, etc. deployed on current generation deepwater platforms will continue to be utilized. However, these applications are not included in the total because the table is intended to reflect the impact a new NIST ATP program might have on composites utilization.

One could argue that 40 field developments are too many for this period or by other measures even too few. There are currently eighteen undeveloped discoveries in the GOM at water depths greater than 4000 ft. including one at 7620 ft.[14] and the industry is just beginning to mobilize to develop ultra deepwater. The number of new discoveries in future years will depend on many factors including the price of oil, whether there is really as much oil in place as predicted, and other technical and economic factors. Because ultra deepwater developments take time to materialize, the growth of composites utilization will develop progressively in concert with discoveries.

The 485-million pounds of composite weight utilization forecast in Table 3 includes composites constructed of carbon, aramid and glass fibers. Large portions of the material will be carbon to meet the high performance requirements of strength and stiffness for primary structure. As indicated above, the demand for advanced composite components will be greater at the end of ten years than at the beginning while fiberglass components will show an earlier growth history. The values forecast in Table 3 for composite components are based on offshore needs for the Gulf of Mexico including subsea pipelines, but do not include additional markets expected from deepwater developments in other parts of the world which could be even larger. Exploration in ultra deepwater with discovers is also taking place in the North Sea, off the West Coast of Africa and in Asia.

A brief description is presented below of some of the needs and opportunities to use composite components in deepwater oil and gas developments. If a NIST ATP program focused on deepwater oil needs is advertised, these are the topics on which proposals for support could be expected.

### *Composite TLP Tendon*

A TLP tendon represents an ideal way to utilize composite materials because the design requirements are predominately axial tension loads which best utilize composite materials high unidirectional strength and stiffness. The potential economic benefits anticipated from using carbon fiber tendons are associated with composites low density which reduces the need for buoyancy, the availability of low-cost manufacturing processes, and the expected availability in the near future of low-cost carbon fibers.[17] Neutrally buoyant steel tubular TLP tendons currently used in deepwater are considerably more expensive in ultra deepwater due the need to resist collapse from higher external pressure loading. There are several options to resist collapse of steel tubular tendons in deepwater. The tubular can be stiffened with rings and stiffeners, the tube can be internally pressurized, or the diameter-to-thickness ratio can be reduced below 30 thus making the tendon heavier than water. The wet weight of the tendon must be carried by the buoyancy of the hull or by externally mounted buoyancy modules.

A discussion of the advantages provided by a composite tendon compared to steel is presented in reference 18. Two configurations have been proposed, a composite tube similar to steel tendons and a rod rope or ribbon tendon constructed as an assembly of numerous small diameter pultruded unidirectional rods.[19,20] To achieve neutral buoyancy in seawater, a diameter-to-thickness ratio of 30 is required for a steel tube and a ratio of 5 for a carbon/resin tube. Deepwater TLP tendons are primarily stiffness driven rather than strength driven. Steel tendons are also limited by fatigue loading whereas a composite tendon designed to meet stiffness requirements is relatively insensitive to fatigue. A composite tube designed to resist hydrostatic collapse requires that a large percent of the fibers be oriented at an angle other than axial which significantly reduces the axial stiffness. A composite tube, therefore, is structurally less efficient for the tendon application than a rope constructed of unidirectional carbon rods.

A third or more of the cost of a TLP tendon system is associated with installation. A composite rod rope or ribbon constructed of unidirectional fibers has the potential to lower the cost of installation by deployment from a large spool. Carbon rod tendons can be spooled since the individual rods can be bent without damage and slide one relative to the other in a rope assembly. For example, the strain imposed on a 5 mm diameter composite rod bent to a 2 meter radius is only 0.25 percent. Although carbon fibers are available with modulus values as high as four times the modulus of steel, high modulus carbon fibers are more expensive and exhibit low strain to failure. Based on current economics, a composite rod constructed of carbon fiber encapsulated in a vinyl ester or epoxy resin binder will have an axial modulus of elasticity around two-thirds the modulus of steel. To match the stiffness of the steel, additional cross-sectional area must be provided to the composite tendon. However, the areal profile to ocean currents and associated loads will still be less for the smaller composite rope than for an equivalent stiffness neutrally buoyant steel tubular supported by buoyancy modules.

The total dry weight of composite tendons for 10 TLPs located in Gulf of Mexico at water depths from 4000 to 7000 feet is estimated to be 127 million pounds of which 76 million pounds is carbon fiber. This is a substantial market for carbon fiber which has a current annual production of approximately 52-million pounds of which 18.5 million pounds is the lower cost large tow commercial grade[17]. The estimated value of the composite tendons excluding installation, engineering, or top and bottom terminations is $1 billion. With successful demonstration of the economic merit of the technology, additional sales could be expected from overseas markets. There are also expected to be other infrastructure markets for carbon rod tendon elements such as suspension bridges, towlines and support lines. Carbon rod ropes might also find opportunities in other marine applications which require predominately unidirectional strength such as seismic tow lines or as mooring lines for floating civil structures.

### *Synthetic Fiber Moorings*

Steel mooring systems for floating production platforms (FPSs) become very expensive in deep water because of the need to provide extensive buoyancy to support the weight of the mooring and due to related operational complexities such as an extended footprint which may interfere with adjacent operations or extend outside the operators lease. Lightweight, synthetic fiber moorings ropes constructed of polyester or other high-strength, low-density fibers appear to be an attractive alternative to conventional steel wire rope and chain systems currently deployed. Petrobras (Brazil) pioneered the introduction of polyester fiber mooring ropes into deep water service and currently has floating platforms moored with polyester rope in water depths exceeding 3000 feet of water.[21] There are currently no deepwater floating platforms in United States waters moored with synthetic fiber ropes, however, oil company operators in the GOM are seriously evaluating their use in future developments.

The GOM marine environment is much more severe than waters off the coast of Brazil including deep high velocity loop currents and strong hurricane conditions. Therefore, United States regulatory agencies can be expected to take a much more conservative approach to the design of moored platforms installed in the GOM. At the request of the

Minerals Management Service, the Composites Engineering and Applications Center on January 23, 1998 sponsored a workshop on synthetic fiber moorings. This meeting highlighted the keen interest of U.S. oil companies to use synthetic fiber moorings as well as the need for a more scientific verified methodology to reliably predict the performance and life of synthetic fiber moorings.

The need for weight savings is the primary driver encouraging operators to use synthetic fiber moorings. The choices available for ultra deepwater developments are to use synthetic fiber moorings for drilling and production platforms, to accept the large penalty of providing buoyancy to support steel wire rope, or to use dynamic positioning. The general industry consensus is that synthetic fiber mooring ropes could provide cost savings on the order of 50% compared to conventional steel mooring systems. For water depths on the order of 3000-4000 feet, polyester is the most economical material which meets typical mooring requirements. Greater axial stiffness and strength requirements for ultra deepwater may drive the designer to use higher performance materials such as aramid for the mooring material. Carbon rod ropes developed for tendons might also have merit for the ultra deepwater application. More study is needed to better scope the needs and different system characteristics for the ultra deepwater scenario. Both FPS production platforms and MODU drilling platforms are potential users of synthetic fiber mooring ropes. Dynamically positioning is the current method used to hold drill ships on location during ultra deepwater drilling operations. If synthetic fiber moorings could be deployed for ultra deepwater drilling, additional savings could be expected. In the example listed in Table 3, 30 FPS platforms were predicted to use approximately 97 million pounds of polyester fiber at an estimated cost of $485 million. There should also be substantial capital expense cost savings to the operator for the mooring rope application, but more study is needed to accurately assess the value.

Several technical and operational advancements were identified in the CEAC workshop as being needed to improve the performance and reliability of synthetic fiber rope moorings for deepwater developments. One major problem is the ability to deploy fiber ropes without damaging them. Polyester fiber ropes are larger in diameter than steel wire ropes of equal load capacity and are bulky to handle. Tougher rope covers and more friendly deployment equipment and installation procedures are needed. The eye splice is the current industry standard for terminating synthetic fiber ropes. Improved terminations are needed including the development of reliable potted terminations. Efficient and reliable inspection methods are needed to evaluate the effects of damage and re-certify rope for service. There is a need for an improved facility to test full-scale ropes. The test facility should have a long test bed (over 100 feet) with a long stroke (10% of specimen length), a rapid displacement rate to simulate in-service dynamic loading, and a large load capacity (2 million pounds). Accurate analysis and design methods are needed to predict the mechanical response of synthetic fiber ropes, life expectancy in the marine environment, and ultimate strength. Safety factors being used for synthetic fiber ropes are greater than steel wire ropes by 10 to 25 percent; however, there is controversy as to what is adequate. A serious barrier to accelerating the deployment of synthetic fiber moorings in the GOM is the lack of standards.

Synthetic fibers are viscoelastic polymers and experience creep and nonlinear time dependent load-deformation response. Current methods used to design mooring systems assume the material to be linear elastic with different modulus values at different load histories. The technology to introduce a more scientific viscoelastic analytical basis currently exists within the scientific community and should be introduced into the design of mooring ropes. In addition, the load-deformation behavior of ropes is also complex and needs to be better characterized to allow analytical predictions of deformation and failure. The current method is to test full-scale ropes. Different rope constructions require additional tests. A methodology is needed to predict the nonlinear viscoelastic behavior of ropes. Such a method would be used not only to predict the long-term behavior of ropes, but also would be a valuable tool to predict the behavior of different rope constructions as well as different rope sizes. Such a method would provide a significant cost savings by eliminating the need for the large numbers of expensive full-scale tests. In summary, even though synthetic fiber moorings are being aggressively pursued, a fundamental need exists to bring more science into the technology.

### *Thick-Walled Tubular for Ultra High Pressure*

Production operations involve the transport of large amount of fluid over long lengths and steel pipe is the primary structural element used in the oil industry. The corrosion resistant and lighter weight properties of composites have allowed fiberglass pipe to replace steel as the material of choice for low-pressure water transport applications on deepwater platforms. Small diameter spoolable pipe is currently being developed for moderate pressure (7500 psi) applications including coiled tubing.[22,23] The next level of application needed is moderate diameter (4-in to 8-in) composite pipe products which can operate at very high pressures (10,000 to 15,000 psi) and transport hydrocarbons. Four possible applications are listed in Table 3. The component value estimated for these four applications is $1.24 billion.

Operation at high pressure requires the pipe to be thick-walled which introduces complexities in design and manufacturing. Related technology gained extensive advancement from U.S. Navy research programs in support of deep submersibles. Unclassified technology from these programs could be a valuable resource in designing and manufacturing high performance tubes for the oil industry. There are a number of safety issues which must be addressed in the design of high-pressure pipe for hydrocarbon service on a platform. A multidisciplinary program is needed to develop the capability to supply safe reliable high-pressure, thick-walled, tubular products to the oil industry. The program should include definition of the critical issues, development of design methodology, application of cost-effective manufacturing processes and addressing certification issues.

Production tubing is an important application for composites in combination with production risers because it addresses the thermal mismatch between a composite riser and steel tubing which occur during changes in temperature when hot oil flows and the well is shut in. In addition to matching the thermal coefficient of expansion, significant weight can be saved using composite tubing. The wellhead on wells supported by an FPS are on the sea bed and since control of the well is subsea and not on the platform, single tubular risers without internal tubing can be used to transport produced fluids to the platform. However, because of large heave displacements, vertical risers cannot be used on FPS vessels. Instead non-vertical S-shaped risers are used to accommodate the large displacements. Composite flexible risers are a promising application, particularly if non-vertical riser could be made in long lengths and a reliable cost-effective method of installation developed.

Drilling operations are also prime candidates for thick-walled composite tubulars. Such applications include the support and control lines located on the outside of a drilling riser i.e., the choke and kill, hydraulic, and mud boost lines. The weight savings provided by composite support lines are sufficiently large to enable extending the drilling operations water depth range of existing MODU and might for this reason be introduced into service earlier than composite drilling risers.

A recent innovation proposed for drilling is to use a separate line for return of the mud to the MODU rather than circulation back up through the drilling riser[24]. The drilling riser is thus eliminated and replaced by the riserless drilling mud return line. Composites are being considered for the application but work has been performed to develop a solution. In addition, the riserless drilling mud return line bundle which includes control lines as well as pipe might incorporate a high strength composite rod rope tendon to help reduce the tension loads on these components.

### *Drilling Riser*

Significant progress has been made in developing the technology for a drilling riser under joint sponsorship of the first NIST ATP program. Although ultra deepwater imposes new design requirements on the drilling riser applications, it is not anticipated that additional support will be requested from NIST for this development.

### *Double-Wall Insulated Subsea Pipe*

Petroleum coming from deep reservoirs is hot and contains hydrate, paraffin and asphaltine in solution. If the produced fluids are not kept at an elevated temperature and pressure, these materials precipitate out of solution in the pipe line and restrict or even arrest the flow. Flow restriction constitutes the number one production problem with deep subsea pipelines and has been the subject of intense study in recent years. A solution to this problem would provide considerable value. The lower heat conductivity of single walled composite pipe provides some but not enough advantage to solve the problem. Needed is a double-wall insulated pipe with very low heat conductivity from the surface exposed to seawater to the inside of the pipe. The inner pipe might be steel or composite since the net heat transfer is the critical parameter and the space between the inner and outer walls might be filled with insulation material. In addition, it is technically feasible to integrate into the wall electrical heaters or even small diameter tubulars through which hot fluid could be circulated. The problem with thermal energy input is how to physically and cost-effectively supply the energy. A successful insulated composite pipe is conservatively estimated to be worth $546 million of product potential plus a significant enabling value to the oil operators by providing a solution to the pipeline flow disruption problem.

### *Long-Length, Large-Diameter Pipe*

Several oil field applications appear attractive for the use of lightweight, large-diameter (up to 10-inch), long length (several hundred feet), composite pipe. Such a product could be used for subsea pipelines carrying oil and gas to shore or to offshore terminal facilities. These lines would not normally require insulation. New processing techniques are needed for making large diameter, lightweight, long-length tubulars. The processes used to make smaller diameter (3-in) spoolable tubulars places several circular winding machines in series. It becomes impractical to scale this process up to large diameter pipe because the number of machines required is too large, perhaps hundreds. At question, is whether processes can be developed which could fabricate a high quality component by making multiple passes of long length pipe through the fabrication equipment. It is also important to determine whether large tow can be utilized without compromising the mechanical properties. In addition to logistics issues, it is difficult to achieve good bonding at the interface in successively cured elements. New processes such as electron beam curing might be used to accelerate the production and reduce residual thermal stresses. A significant challenge would also be the development of methods for joining one piece of high-pressure pipe to the next. The physical process of joining long lengths of steel pipe has been developed and was used to assemble 250-ft long, 28-inch diameter steel tubulars using mechanical couplings on the Mars TLP tendons. The finished long length composite pipe would be transported by barge or if very long lengths could be made, they would be transported by towing similar to the way the steel tendons on the Jolliet and Heidrun TLPs were installed. This application is estimated to have about a $494 million dollar market value as well as to provide an undetermined high value to the oil industry.

### *Extended Reach Smart Drill Pipe*

Composite drill pipe was the subject of a NIST ATP joint venture from the first theme focus announcement. Considerable progress was made under this program, but the program terminated prior to solving all the important issues. Additional work is needed to make the technology ready to progress into products. The risks are to high to expect manufactures to proceed without additional external support. In addition, there are several new dimensions which the research should take to make a product that provides even greater enabling capabilities. First, there is a need to develop drilling capability to extend the range of horizontal drilling. Lightweight, near neutrally buoyant composite pipe provides a significant enabling capability. Second, modern drilling procedures seek to obtain real-time information about the reservoir during the drilling operation to help make decisions about how to achieve the most productive well. Integrating fiber optics and information sensors into the body of the composite drill pipe could provide significant enabling capability. Another related, but different application is to integrate sonic sensors into the wall of logging lines to conduct downhole seismic surveys. Composite materials transparency to these frequencies provides an enabling capability. Downhole sensor related applications are high-tech development areas and potentially could be worth hundreds of millions of dollars to U.S. companies.

### *Linerless, High-Performance Fiber-Reinforced Thermoplastic Pipe*

Many of the pipe applications designed for the oil industry such as spoolable pipe and risers have been found to require an internal and often an external liner because the matrix cracks during cure or field application. Liners are usually thermoplastic materials and difficulty is experienced in bonding the liner to the thermoset composite body. For high external pressure loading, permeation through the pipe wall will eventually lead to collapse of the liner. Extruded thermoplastic liners are also expensive, particularly those constructed of fluoropolymer needed for high temperature and chemical resistance, and constitute a significant part of the cost of the product.

It is anticipated that a thermoplastic material could be used as the tube matrix material and eliminate the need for a separate liner. This would require that the large strains imposed during spooling the pipe could be accommodated without cracking the matrix.

There is also the possibility to use lower modulus rubber type materials for the matrix of composite tubes not subjected to significant external pressure loads. This is a generic type solution and no specific applications are highlighted. If the technology could be developed, spoolable pipe and some of the applications described above would be candidates for applications.

### *Primary Platform Structure*

Excluding the risers and mooring system, the biggest targets for weight reduction on floating platforms are the large structural components including the hull, deck, drilling derrick, accommodation module and flare boom. In May 1997, CEAC sponsored a Workshop on "Load-Bearing Composite Structures for Offshore Platform Topside Applications" to examine the technical and economic barriers inhibiting the development of this class of promising application. There appears to be a large payoff for large structural components, but there is a need for a concerted effort to develop the requirements, address certain critical barriers such as joining and fire resistance, and demonstrate the cost competitiveness of making components using low-cost manufacturing processes such as pultrusion, SCRIMP, and RTM.

The value of weight saved on a platform is impacted by the location of the component on the platform. In general; topside facilities, risers and tendons provide the highest value for weight savings because their weight must be transferred by other supporting structure into the component providing buoyancy. For example, the weight of the riser is transferred by the deck into the hull and the deck must be strengthened to perform this function. Extending this explanation, it can be seen that saving weight on the hull has the least impact in saving weight on other components. Saving weight on the deck structure is slightly less important than saving weight on the topside facilities or riser, but it is still important because the deck is such a large component and because it is anticipated that the manufacturing processes available to make large integrated structure will help reduce the relative cost per pound of produced structure.

One of the most promising large structure applications for development would be an integrated deck structure which might be on the order of 30 ft. by 40 ft. in size. Subsequent applications could be scaled to even larger sizes. Such a structural module would be prefabricated in a composite shop, possibly as a single unit and integrated into the platform in the final assembly yard. Part of the merit of the concept would be to work with the fabricator to help speed the assembly and fabrication process. Other large structure applications might also be considered such as the living quarters, drilling derrick and flare boom.

### *Pressure Vessels and Tanks*

Although pressure vessels and tanks have already been used on offshore platforms, there is the potential for much greater utilization. A program focused on addressing the barriers and deficiencies of existing technology and developing new application opportunities would do much toward making greater utilization a reality. Both weight savings and corrosion resistance are primary drivers to use composite tanks and vessels. The CEAC sponsored a workshop "On Composite Tanks and Vessels for Use On Offshore Platforms" in June 1997 to help define the barriers for tanks and vessels. One of the problems identified is leakage and damage at and near nozzles and flanges which allow penetration of the tank. Repair methods and procedures are also needed.

Improved fire resistant resins need to be evaluated for applications involving hydrocarbon storage or processing. Hybrid construction including combinations of reinforcement fibers and with metal or polymeric liners need to be investigated. Abrasion and erosion are issues associated with some high flow process applications such as a mud gas separator. Design methods and design allowables need to be established to allow reliable but not overly conservative design safety factors. Also, there is a need to work closely with regulatory agencies to develop acceptable standards.

Several reasons can be given as to why such a program is needed. First, there is an expected economic and safety enhancement payoff. Second, tank and vessel manufacturers are generally small businesses and lack the resources to support an extensive inhouse development program. In addition, manufacturers have been reluctant to pursue the offshore market because of uncertainty about the size of the market, the burden of qualifying components for use offshore and the need for additional engineering and technology development to meet the demands of the users.

A NIST program could provide the support needed to develop the design and materials technology required to define and expand the pressure/temperature operating envelope of composite tanks and vessels so that they can be used safely offshore. Composite tanks and vessels could provide investment savings due to weight reduction and long term operational cost savings by lowering maintenance costs. A NIST program would help encourage offshore oil companies to participate in a program oriented toward developing advanced composite tanks and vessels technology. It is unlikely that a significant advancement will be made without a joint industry effort.

### *Buoyancy Modules*

Buoyancy modules are applied to help support the weight of numerous components used in the oil industry including drilling risers, production risers and mooring ropes. Buoyancy modules are currently made from syntactic foam or as steel spherical pressure vessels. To prevent collapse due to the ocean hydrostatic pressure, the density of the syntactic foam increases significantly as a function of water depth and steel buoyancy vessels must be stiffened. Large light-weight composite pressure vessels with internal bulkheads and stiffening, constructed using low-cost manufacturing methods, may be able to compete with syntactic foam and steel vessels on the basis of cost per pound of buoyancy provided. The cost of providing buoyancy with syntactic foam is estimated at $5.50/lb of buoyancy for 350 meter and $8.50/lb at 1400 meter. More prestudy of the opportunity is needed, but it appears to be a good application for composites.

### *Metal/Composite Hybrid Structures*

Several companies in the survey indicated an interest in developing metal/composite hybrid structures. Metal liners have been used to provide a sealing function for composite pressure vessels while recent efforts have been directed toward study of metal/composite hybrid structure involving significant load sharing by both the composite and the metal. Commonly used composite materials have a lower modulus but a higher elastic working strain than metals. An innovative concept described by at the Second International Conference On Composite Materials for Offshore Operations involves compression prestressing a steel tube by circumferentially winding an outer composite layer of aramid fiber in a thermoplastic matrix applied under tension[25]. Another concept described at the 2nd International Conference involves integrating a spiral band of high tensile steel into the composite laminate to provide a high-pressure pipe[26]. NASA has also conducted research on metal/composite hybrid structures. The merits claimed for metal/composite hybrids are reduced weight and corrosion resistance with more efficient utilization of the metal. If NIST elects to make composites an ATP theme, at least two companies could be expected to submit proposals in this area.

## APPLIED TECHNOLOGY ADVANCEMENT AND TECHNOLOGY TRANSFER

Although composites technology applied to the oil industry has much in common with aerospace, infrastructure and automotive, it also is driven by unique requirements, both technical and economic. Some applications will benefit significantly from technology transfer while other applications or issues require unique new developments to succeed. NASA has provided valuable technology support to one of the current NIST programs and future programs should be aligned to take fuller advantage of available government resources. In addition, technology transfer can propagate in two directions. Research conducted in support of oil industry applications has generated several advanced capabilities which could be helpful to other industries. Examples of frontier areas of research conducted for the oil industry include understanding of the mechanics of hybrid structures, design of ultra high strain components, and design of thick-walled tubulars. In addition, very advanced failure prediction analytical methods have been developed in support of NIST ATP composite production riser and spoolable tubing projects. Although it is the policy of NIST not to sponsor basic research, an ideal model for ATP programs is to encourage participation by the academic community to ensure that good engineering principles are applied and advanced technology capabilities are developed as needed.

There are several areas in which more research is needed to advance the state of understanding to support the design of future oil industry applications. More work needs to be done on hybrid structures. Most of the advanced applications will rely on combinations of carbon and glass to meet high performance requirements at minimum cost. The availability of low cost carbon will move toward greater carbon utilization. Another interesting area which has surfaced in the development of certain applications is the requirement to resist ultra high impact loads. The hull of a TLP, for example, must resist impact by 2500 kJ and the drilling riser must resist a 250 kJ impact. These are extremely large energies and work needs to be done to be able to survive this level of impact load safely. Sensor technology is rapidly advancing in drilling and logging operations. It is not only possible to integrate fiber optics into the wall of composite tubes as transmission lines, but to better use the sensors themselves in a composite component. The area of damage tolerance and repair are important as well as inspection and non destructive test methods. The use of new materials and combinations of materials means that design allowables are not well established and safety factors have not been well defined. In addition, much work remains to be done to develop and translate advanced analytical methods into more automated design procedures. All of these technical areas are important and should selectively be given support either in a focused technology program or as elements of individual projects.

## IMPORTANCE OF ATP FOCUSED PROGRAM

How important are composites to the development of Gulf of Mexico petroleum resources and how important is NIST ATP funding to help make the technology ready for use in the first decade of the 21st century?

Perhaps an answer to the first half of the question is by analogy. Could you fly a steel aircraft or put a man in space without aluminum? The answer is yes, but why would you want to and certainly you couldn't fly as many passengers for the same energy costs. Likewise for ultra deepwater developments, oil will be produced with or without composites. Probably not as much oil because marginal fields may be uneconomical and also with less efficiency. For example, producing a field for 30 years from a dynamically positioned platform would appear to be very inefficient, but it could be done.

The answer to the second half of the question concerning the need for another focused NIST ATP program and whether it would make a difference contain two elements. First, are there sufficient good technical ideas to warrant a program? The discussion of problems and potential composite solutions provided above is believed to support an affirmative answer. The second question to ask is, would a NIST ATP program be subscribed with good proposals? This question is more difficult to answer. If a NIST ATP focus program is offered, it is anticipated that proposals would be submitted on at least six of the topics described above and maybe all. However, some preparatory coordination work would be required to assemble the right skill mix to ensure that good projects with high probability of success were formulated. Composite manufacturers have the highest invested interest, but oil and oil service company participation is essential to insure that the requirements are completely defined with buy-in for their utilization, and a place needs to be reserved for university participation to develop and coordinate the supporting advanced technology.

A successful development program spurred by a NIST ATP initiative will have a significant impact on the economic development of ultra deepwater in the GOM. The increased utilization of composites will have an extensive impact on the composites supply and manufacturing industries. An expansion of the composites industry will result in a large net increase in needs for skilled labor in the U.S. to supply materials and products. A new market for composite materials will be developed. The increase in the market for carbon fiber over the next ten years, for example, could be on the order of 250 million pounds. This market will also consume large quantities of aramid fiber, glass fiber, matrix resins and other associated materials used in the manufacture of composite structure. The potential market for new components for the GOM offshore market over the next ten years could exceed $5 billion. The global market could be even larger.

Realistically, however, the composites industry has little capital to invest in new product development and oil companies allocate little resources to the materials development area. Without a NIST ATP or other external stimulus, only a portion of the needed development will occur and such efforts will not be at the pace needed to meet the window of opportunity concurrent with the early development of ultra deepwater resources.

## CONCLUDING REMARKS

The results of this survey on opportunities to use composites in ultra deepwater petroleum field development suggest that the timing is right for a new NIST ATP focus program. NIST support for the program will benefit the United States in the following ways.

1. The U.S. needs the oil expected from ultra deepwater resources in the GOM to help reduce the financial burden of imported oil and maintain an acceptable level of energy independence.

2. Composites technology is needed for efficient development of future ultra deepwater Gulf of Mexico petroleum resources.

3. NIST ATP financial support would enable U.S. composites industry manufacturers to reduce their financial risk and accelerate the pace of development to meet the upcoming window of opportunity to use composite products in ultra deepwater developments.

4. Once composite products are demonstrated in the GOM, significant overseas sales could be expected to support ultra deepwater developments overseas thus helping the international trade balance of payments.

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## TABLE 1. - NATIONAL INSTITUTE OF STANDARDS & TECHNOLOGY ADVANCED TECHNOLOGY PROGRAMS CONDUCTED WITH EMPHASIS ON OIL INDUSTRY EXPLORATION AND PRODUCTION.

| Program | Goal | Manufacturing Sponsor | Supporting Sponsors | Funding, $ | Start / years |
|---|---|---|---|---|---|
| Composite Production Riser | R & D program to design, analyze, manufacture and test composite production riser for floating production platform. | Lincoln Composites Inc. | NIST, Brown and Root USA Inc., Conoco Inc., Hercules Inc., Hydril Company, Shell Development Company, Stress Engineering Services Inc., University of Houston. | $7,168,000 | 1995 / 5 |
| Manufacturing Composite Structures for Offshore Oil Industry | Develop cost-effective manufacturing methods with emphasis on a composite drilling riser. | Westinghouse Electric Corporation, Marine Division | NIST, ABB Vetco Gray Inc., Hercules Inc., Offshore Technology Research Center, Reading & Bates Development Company, Texaco Inc./Deepstar Project. | $4,814,000 | 1995 / 5 |
| Spoolable Composite Tubing | Develop long continuous lengths of composite tubulars for oil production operations including coiled tubing and flowlines. | Hydril Company | NIST, Amoco Corp., Dowell Schlumberger Inc., Elf Atochem North America Inc., Mobil E&P Service, Phillips Petroleum Co., Shell Chemical Co., Shell Development Co., Dow Chemical Co., University of Houston. | $5,015,000 | 1995 / 5 |
| Innovative Joining/Fitting Technology for Advanced Composite Piping | Develop innovative composite joining and fitting technologies to enable and stimulate the use of composites in offshore oil/gas production pipelines. | Specialty Plastics, Inc. | NIST, NASA | $2,867,000 | 1995 / 3 |
| Light-Weight /High Strength Composite Intelligent Flexible Pipe | Develop and validate flexible composite pipe with built-in performance monitoring for use in oil /gas production. | Wellstream Inc. | NIST | $5,760,000 | 1995 / 2 |
| Composite Drill Pipe | Design, manufacture, test, and demonstrate affordable composite drill pipes for use in offshore oil drilling. | Spyro Tech Corporation | NIST, Phillips Petroleum Company, Amoco Exploration and Production Technology Group, University of Houston. | $2,770,000 | 1995 / 4 |
| Development of Innovative Manuf. Techniques to Prod. A Large Phenolic Composite Shape. | Optimize a 36-inch deep composite structural beam element using phenolic resin and glass/carbon fiber which has a modulus of 6 million psi | Strongwell | NIST, Georgia Tech<br>Note: This project has application to the oil industry but was funded under the infrastructure program. | $2,000,000 | 1995 / 3 |

Table 2. - MMS Estimate of Future Offshore Oil Production.

| Water Depth, ft | 1997 % | 2002 % | 2007 % |
|---|---|---|---|
| 0 - 650 | 59 | 39 | 17 |
| 650 - 2600 | 13 | 14 | 14 |
| > 2600 | 28 | 47 | 69 |

## TABLE 3.- GULF OF MEXICO DEEPWATER OFFSHORE OIL INDUSTRY ESTIMATED COMPOSITE APPLICATIONS YEARS 2000-2010.

| COMPOSITE COMPONENT | QUANTITY | COMPOSITE WEIGHT, MILLION LB | COMPONENT COST, $MILLION | ADVANTAGE COMPARED TO STEEL, $MILLION |
|---|---|---|---|---|
| TLP Tendon | 10 TLPs[1]<br>18 Risers<br>Per TLP | 127 (composite) including 76 (carbon) | 1,000 | Large Cost Savings Enabling[5] |
| TLP Production Riser | | 29 (composite) | 286 | $98 Cost Savings |
| FPS Mooring Rope | 30 FPSs[2]<br>16 Lines Each | 97 (polyester) | 485 | Large Cost Savings Enabling[6] |
| Thick-Walled Tubulars for Ultra High Pressure[3] | Tubing Inside 180 TLP Risers | 7 | 147 | Enabling[7] |
| | Non-Vertical Risers On FPSs 18 each FPS | 40 | 888 | Cost Saving[8] |
| | Choke & Kill, Hydraulic, Mud Boost Lines, On 20 MODU | 7 | 100 | Enabling[9] |
| | Riserless Drilling Mud Return Lines[4] | 5 | 106 | Enabling[10] |
| Drilling Riser | 10 MODU | 6 | 128 | Enabling[11] |
| Double-Wall Insulated Subsea Pipe | 300 Miles<br>6"-8" I.D. | 31 | 546 | Enabling[12] |
| Long Length, Large Diameter Tubulars | 400 Miles<br>10" I.D. | 25 | 494 | Cost Savings |
| Extended Reach Smart Drill Pipe | 300,000 ft | 2 | 63 | Enabling[13] |
| Linerless High Performance Thermoplastic Pipe | Special Products Including CoiledTubing | | | Enabling[14] |
| Platform Primary Structure | Topside, Hull | 100 | 800 | Cost Savings |
| Process Vessels and Tanks | Storage, Processing | 8 | 64 | Cost Savings |
| Buoyancy Modules | Large Number | | | Cost Savings |
| Metal/Composite Hybrid Structures | Pipe, Tanks, Primary Structure | | | Cost Savings |
| | **TOTAL** | **485 million lbs** | **$5,107 million** | |

**Estimated economic impact of oil produced from 10 TLPs and 30 FPSs utilizing advanced composite enabling technology is $525 billion.[15]**

## Table 3 Footnotes:

[1] 3 TLPs - 4000 ft, 3 TLPs - 5000 ft, 2 TLPs - 6000 ft, 2 TLPs - 7000 ft

[2] 6 FPS - 4000 ft, 6 FPS - 5000 ft, 6 FPS - 6000 ft, 5 FPS - 7000 ft, 3 PFS 8000 ft, 2 FPS - 9000 ft, 2 FPS - 10,000 ft

[3] High operating pressure (15,000 psi), 6-inch I.D.

[4] 30 systems, 10,000 ft, 6-in I.D. , 2 lines per MODU

[5] Enabling. TLP permits direct wellhead access from the platform providing immediate capability for remediation workover of wells and eliminates the need for support from expensive workover rigs.

[6] Enabling. Synthetic fiber moorings save significant weight versus steel which allows existing drill ships to work in deeper water. In ultra deepwater, steel is too heavy to be used and synthetic fiber ropes become the only alternative for mooring FPS platforms.

[7] Enabling. Light-weight composite risers provide significant advantage. Composite tubing will provide additional weight savings, but more importantly, composite tubing can be designed to match the thermal expansion coefficient of the riser to eliminate thermal expansion problems coming from the change in temperature of the hot oil.

[8] Cost Savings. It is believed that composite flexible risers could be constructed at significant cost savings to current flexible risers constructed with steel armor.

[9] Enabling. The drilling riser system includes lines for control of the well should high gas pockets be discovered. The choke and kill, hydraulic and mud boost lines, if made of composite, would provide significant weight advantage.

[10] Enabling. Riserless drilling is a new concept being explored in which there is no riser outside the drill pipe for circulation of the mud. The mud return is a separate line which would is an ideal application for composites because of the difficulty in using a heavy steel line.

[11] Enabling. A light weight drilling riser opens new possibilities for cost efficient drilling operations through elimination of buoyancy material, corrosion resistance, storage volume reduction, and fatigue tolerance.

[12] Enabling. A common problem in deepwater is hydrate and paraffin depositing our of the produced fluid as temperature drops and plugging the line. By using a double-wall insulated pipe this significantly expensive event can be mitigated. In addition heaters can be integrated into the pipe wall.

[13] Enabling. A composite drill pipe with integral communication and reservoir testing lines opens new possibilities in exploration.

[14] Enabling: Availability of thermoplastic pipe would open the door to several applications and holds the possibility for making spoolable pipe without a liner.

[15] $525 billion is the estimated value of oil produced over 20 year life at $18/barrel, 100,000 barrel/day from 40 fields supported by 10 TLPs and 30 FPSs.

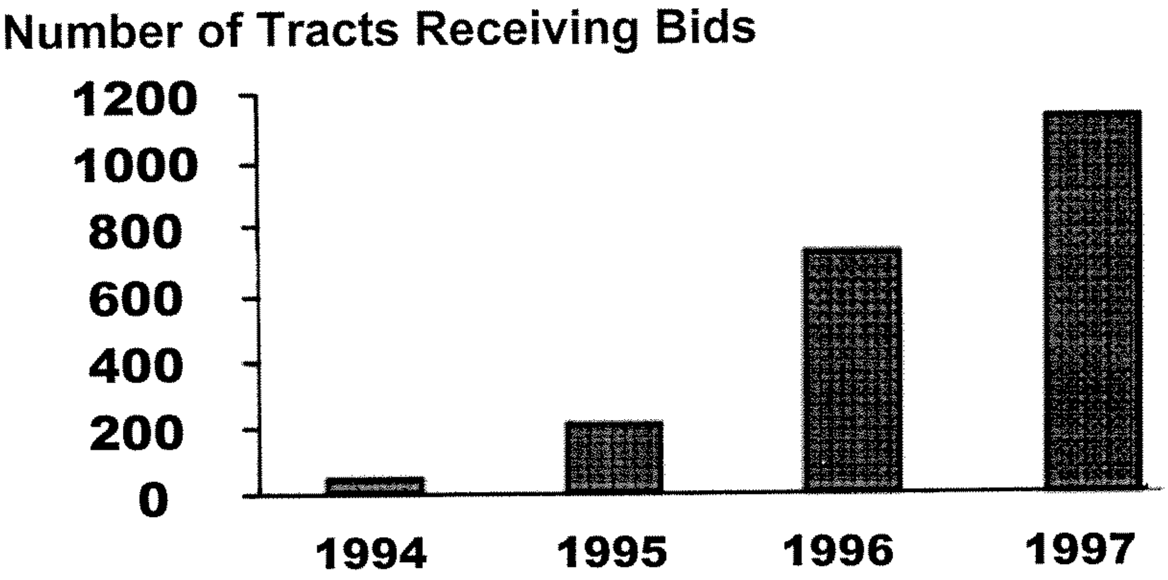

Figure 1. - Bids received by MMS for deepwater leases in Central and Western Gulf of Mexico regions in water deeper than 2650 feet.

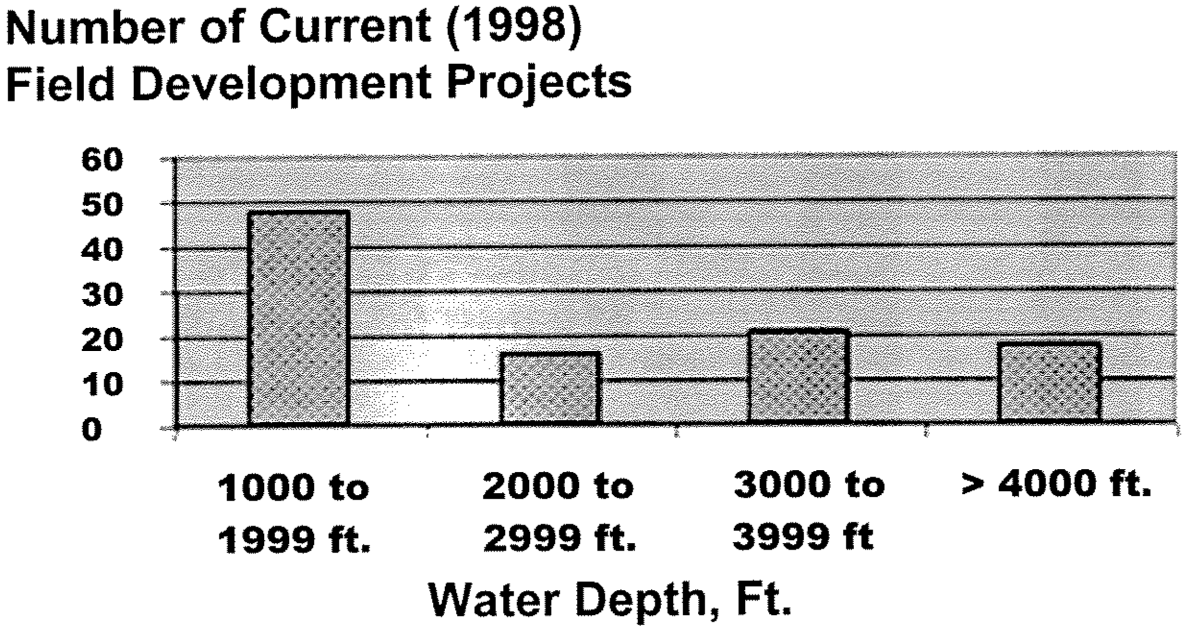

Figure 2. - Oil and gas projects currently under development in Gulf of Mexico at selected water depths.

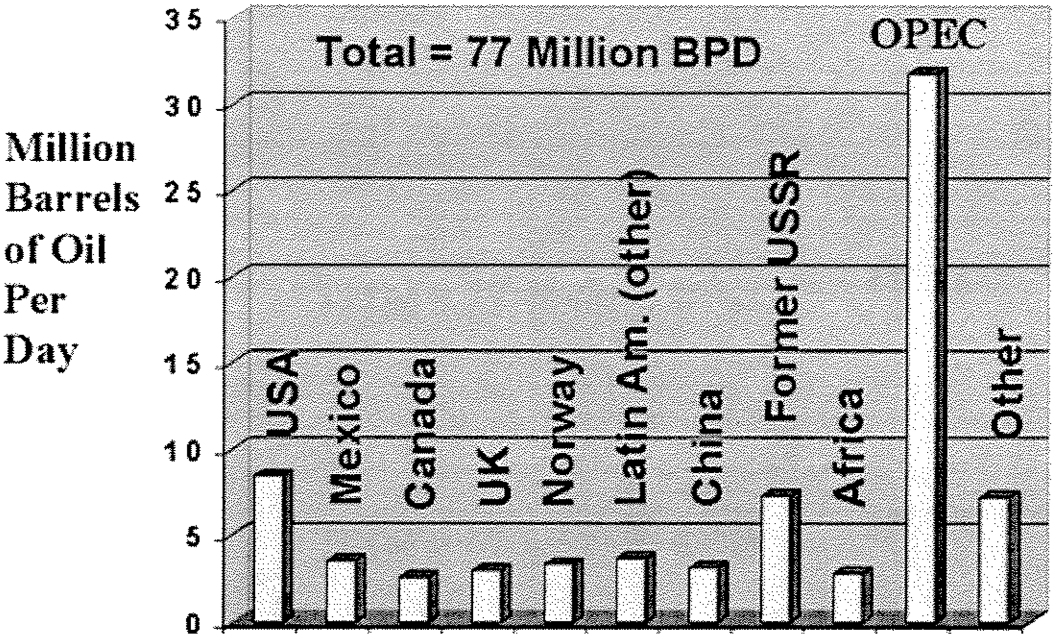

Figure 3. - Current world oil production.
Source - Petroleum Engineer, April 1998.

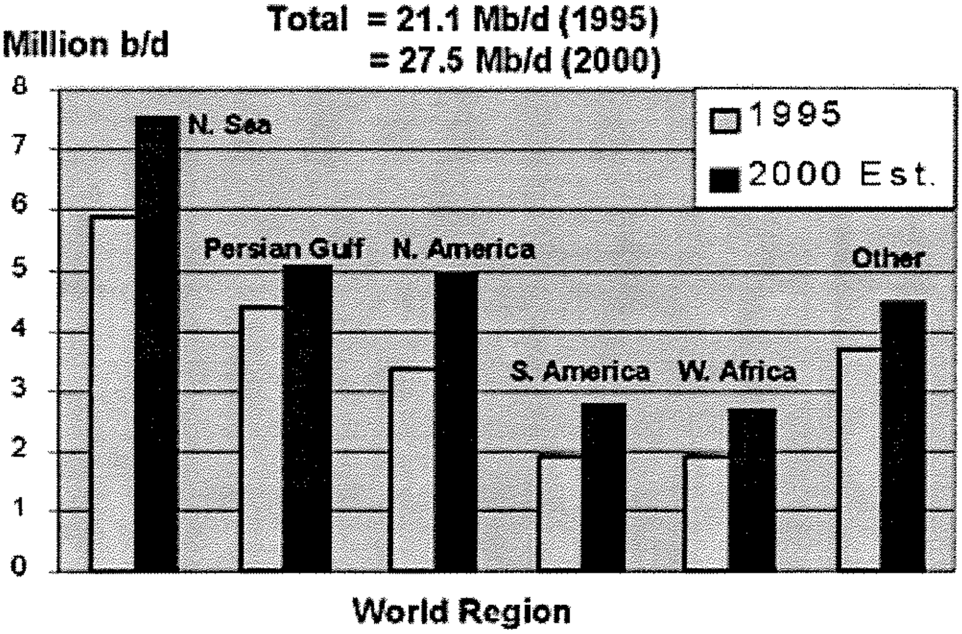

Figure 4. - Geographical distribution of worldwide production of oil from offshore.
Source - Offshore May 1997. IAE

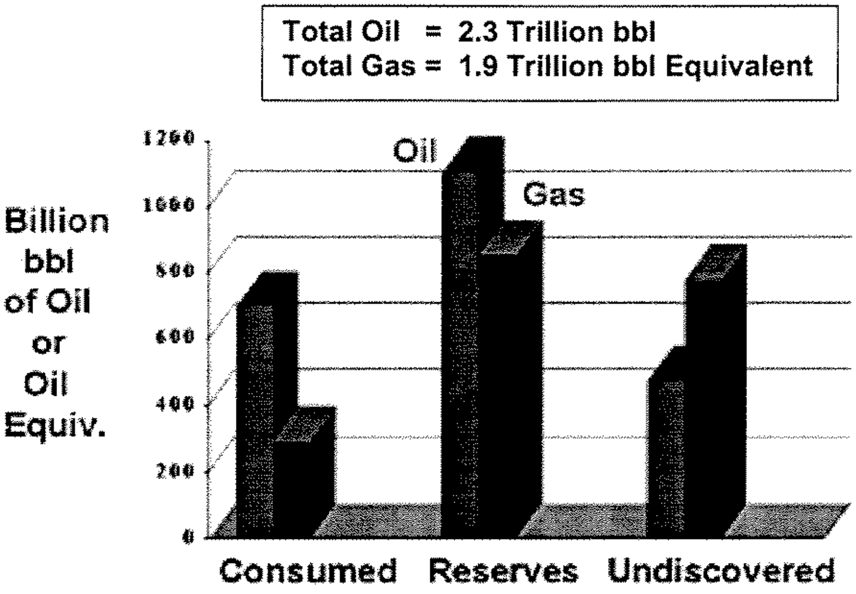

Figure 5. - Estimates of oil and gas total resources: already consumed, discovered reserves and expectations for future discovery. Source - U.S. Geological Survey. Oil & Gas Journal. Feb. 1998.

## APPENDIX A - SUMMARY OF PETROLEUM OFFSHORE E&P BREAKOUT SESSION

To: Felix Wu, NIST

From: Bill Cole, Amoco

Date: 2/4/98

Subject: NIST/ATP “Composites Infrastructure” Planning Meeting, 1/29/98
Summary of Petroleum Offshore E&P Breakout session

I. The group reviewed the criteria for NIST/ATP projects

1. Potential US Economic Benefit
2. Good technical merit
3. Strong industry commitment
4. Opportunity for ATP to make a difference

II. The group reviewed the barriers to more extensive use of composites in our industry. Most comments relate back to the barriers cited in the 1994 white paper: reliability, cost and complexity. However some of the specific barriers cited are listed below:

1 Long term durability (reliability)
2. Accelerated testing ( “ )
3. Scaling from small sample test data to full scale structure performance ( “ )
4. Materials availability ( cost )
5. Manufacturing limitations ( “ )
6. Installation of composite structure ( complexity )
7. Products are not standard from alternate manufacturers ( “ )
8. Complex design process ( “ )
9. Extensive testing required to qualify new designs ( “ )

| III. Candidate Projects (proposals) | Fit with ATP Criteria (5 - high, 1 - low) |
|---|---|
| 1. Tubular Tendons for floating production systems | 5 |
| 2. Other mooring systems | 5 |
| 3. Continuous tubulars, D > 4”, Pressure > 4,000 psi | 4 |
| 4. Analytical methods for qualification of alternative designs | 3 |
| 5. Real time, performance monitoring sensors<br>Inspection tools | 2 |
| 6. Deck structure for floating production systems.<br>Spacer beams, main girders, fabricated shapes, attachment methods | 3-4 |
| 7. NDE methods for qualification of products (incorporate into 1. & 3) | 2 |

| | |
|---|---|
| 8. Composite pressure vessels | 2 |
| 9. Down hole tubulars | 2 |
| 10. Drilling derricks & flare booms | 3 |
| 11. Choke and kill lines, 4.5", 7500 - 15,000 psi | 5 |
| 12. Fiber overwrapped steel pipelines | 3 |
| 13. Thermoplastic, spoolable, continuous tubulars | 4 |

| IV. Proposals in response to a solicitation | Probability |
|---|---|
| 1. Composite tendons, tubular design | High |
| 2. Composite choke & kill lines, continuous tubulars | High |
| 3. Composite tendons, strap design | High |
| 4. Composite deck structure | Medium |
| 5. Composite pressure vessels | Medium to low |
| 6. Down hole tubulars | Medium to low |
| 7. Fiber overwrapped steel piplines, onshore & offshore | High |

## V. Comments

There are several project ideas that have considerable merit, but do not align with the four four criteria for good ATP projects. Some have strong technical merit, but it is difficult to show benefit to the US economy. Others would have economic impact but are not as strong in technical merit. Some projects will probably occur with or without ATP funding.

A third solicitation under the existing focus program would result in several additional strong proposals.

A new focus program would also result in several new proposals if the existing focus program is not continued. The members of the planning group were able to identify four proposals that have high probability of occuring, and three additional proposals that might be developed. Additional participation can be expected from industry members that were not present.

In summary we see continued interest in the ATP program and would expect several additional strong proposals under the existing composites manufacturing program or with the proposed composites in infrastructure program. In fact industry would probably propose the same projects under either focus program.