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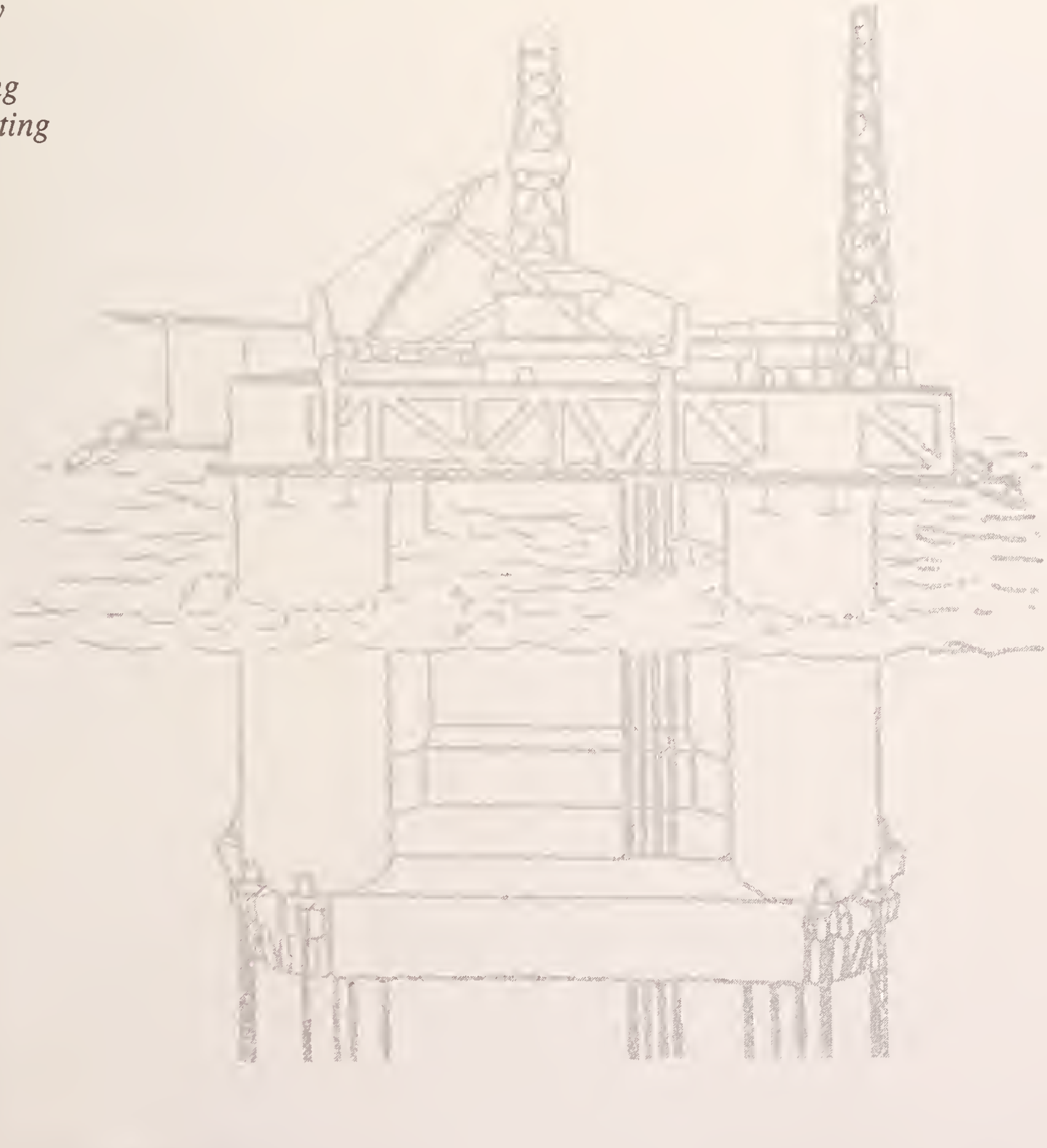
Composite Materials for Offshore Operations: Proceedings of the First International Workshop

Houston, Texas
October 26–28, 1993

Edited by

S.S. Wang
D.W. Fitting



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[1] At Boulder, CO 80303.
[2] Some elements at Boulder, CO 80303.

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Materials Reliability Division
Materials Science and Engineering Laboratory
National Institute of Standards and Technology
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Abstract

The First International Workshop on Composite Materials for Offshore Operations was held on October 26-28, 1993, at the University of Houston, Houston, Texas. This international workshop provided a forum for attendees to review the current state of practice and to assess the current state of the art in using composite materials for offshore petroleum exploration and production operations. It also addressed research issues which might mitigate the gaps between the current practice and the state of composite technology to allow economic and enabling utilization of composites by the petroleum industry. The issues addressed in keynote presentations and working group discussions spanned a broad spectrum of scientific and engineering concerns, including: materials systems; fabrication and construction; material performance; long-term durability and environmental effects; structural design, testing, and reliability; nondestructive evaluation and condition monitoring; flammability and fire safety; nonstructural applications; advanced applications; regulatory concerns; and certification issues. There were over 225 participants in the workshop representing the petroleum industry, manufacturers, design engineers, certification organizations, and academic institutions. This proceedings of the workshop contains 35 invited lectures and papers, discussions, summaries, and recommendations of the 8 working groups, as well as critical assessments and recommendations of needed research and development on advanced composites for deep-water offshore exploration and production operations.

Key Words: advanced materials, certification, composites, construction, damage tolerance, environmental degradation, fabrication, flammability, fire safety, FRP, GRP, maintenance, NDE, nondestructive testing, inspection, offshore platforms, structural design

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Executive Summary

Executive Summary

With ever-increasing challenges in developing deep-water offshore structures for petroleum exploration and production, composite materials technology is expected to play a more important role in meeting the stringent requirements of cost-effective operations and enabling the capability of petroleum technology and its supporting industries. Composite materials offer substantial weight reduction, superior corrosion resistance, long fatigue life, outstanding vibrational damping and energy absorption, and the unlimited potential of innovative material and structural tailoring to meet desired performance requirements. Along with low maintenance, low total-life-cycle costs, and ease of fabrication, construction, and installation, composite materials and structure are ideally suited for immediate and future deep-water challenges. They offer high potential payoffs that are just beginning to be explored and represent a large potential opportunity for U.S. and world industry. Realizing this great potential will require understanding the existing technology and future development of composites, the specific requirements and economic restraints of deep-water offshore applications, and certification and other regulations.

To provide an open forum for leading experts from industry, government, and academia throughout the world to address these issues, the First International Workshop on Composite Materials for Offshore Operations was held 26–28 October 1993 at the University of Houston in Houston, Texas under the joint sponsorship of U.S. Minerals Management Service, the National Institute of Standards and Technology of the U.S. Department of Commerce, and the University of Houston. Other sponsors included American Petroleum Institute, Ameron, Amoco, Brunswick, Canadian National Energy Board, Conoco, DuPont, Exxon, Hercules, Shell, Texas Center for Superconductivity at the University of Houston, and the U.S. Navy. The enthusiasm of the participants (211 from many nations) resulted in a productive meeting.

The goals of the conference were (1) to review the current stat of the art and assess current practice in utilizing composites for offshore operations; (2) to identify gaps between the state of the art and the state of practice; (3) to determine and prioritize research initiatives that might mitigate these gaps and enable safe and economical use of composites by the oil industry; (4) to bring new opportunities to the oil and gas industry through proper and innovative applications of composites; and (5) to provide guidance to petroleum and engineering-service industries for certification of composite offshore structures and components.

The workshop, which lasted two and a half days, consisted of eight working-group sessions and one summary session. More than 45 papers were presented, including 6 invited presentations on the perspectives of government and industry and 6 keynote addresses delivered by world leaders in their respective technical areas. The presentations provided a comprehensive overview of the current status of composites applications in the offshore industry, the state of the art in various areas of petroleum composites technology, and the certification and regulatory agencies' perspectives on the utilization of composites in offshore exploration and production operations.

The eight working group sessions focused on topics selected by the international steering committee of the workshop: (1) fabrication, construction, maintenance, and repair; (2) material performance, damage tolerance, durability, and environmental degradation; (3) structural design, optimization, testing, and reliability; (4) nondestructive evaluation; condition monitoring and inspection; (5) flammability and fire retardation; (6) facilities and secondary structural applications; (7) advanced applications; and (8) certification issues and policy concerns. In each group, leading experts, invited by the steering committee, made presentations and guided and stimulated the discussions.

In the concluding session, the chairmen of the working groups summarized the discussions and reported the recommendations of their respective groups. Representatives of the international steering committee — B. W. Cole of Amoco, K. H. Lo of Shell, J. G. Williams of Conoco, and S. S. Wang of the University of Houston — provided a document that summarized the current status and recommended a comprehensive R and D program for advanced composites offshore.

This proceedings describes the scope, the organization, and the program of the workshop. It contains a summary, recommendations reported by the steering committee representatives, invited lectures, keynote addresses, and most of the papers presented in the working-group sessions. Also included are a list of working-group chairs and panelists and their discussion summaries. A list of registered workshop participants is given at the end of this volume.

S. S. Wang
Workshop Chairman and Coeditor

Summary and Recommendations

SUMMARY AND RECOMMENDATIONS

ADVANCED COMPOSITES OFFSHORE: CURRENT STATUS AND A PROPOSED RESEARCH AND DEVELOPMENT PROGRAM

by

B.W. Cole, Amoco Corporation
K.H. Lo, Shell Development Company
J.G. Williams, Conoco, Inc.
S.S. Wang, University of Houston

1. INTRODUCTION

The petroleum industry is gradually building increased acceptance of fiberglass reinforced plastic (FRP)materials. Some companies make extensive use of FRP pipe for onshore hydrocarbon gathering and transmission lines. A few companies have used FRP downhole tubing products. In offshore applications there is limited use of FRP products in secondary structure such as cable trays, walkways, railing and grating. Recent developments in the North Sea area have resulted in projected increased usage of FRP pipe for various types of low pressure water service offshore.

Industry acceptance of advanced composites, however, is still in the early stages of development. Feasibility work on production risers constructed of carbon/glass fiber laminates was started in 1980. The results of that work have been positive, yet there are no advanced composite systems in service offshore today nor are there any commercial products available.

Studies have shown that some offshore advanced composite applications could greatly reduce capital requirements, decrease maintenance costs or enable operations that are technically or financially infeasible with state of the art materials. The petroleum industry has great interest in these products. However, many are primary structural systems or high pressure hydrocarbon piping systems. the consequence of failure in these systems is very high, involving safety risks, environmental risks, and the financial risk of losing infrastructure.

The investment required to develop reliable commercial products for high risk applications is very large - more than suppliers can afford. The investment is also more than any one petroleum company is likely to commit to at this time. Each offshore platform represents an investment in excess of one billion dollars. The use of new materials systems such as advanced composites in critical systems would be a huge risk - a risk that petroleum companies are not likely to take until it aligns with a strong industry need, offers clearly demonstrated benefits, and is based on technology that is well characterized, and understood.

The need for alternative materials is developing quickly in the petroleum industry. The pressure is growing to reduce the cost of exploration and production and there is strong evidence that advanced composites could reduce costs. There is increased interest in developing deep water leases in the Gulf of Mexico to increase US reserves and advanced composites could be utilized to reduce the cost of deep water facilities. Many undeveloped fields in the Gulf of Mexico and in the North Sea are small. Development of those fields will be feasible only with the development of as well. But advanced composites will be used in these applications only if the work is initiated soon to develop the technology base that is needed to gain industry acceptance.

2. PROPOSED FOCUS AREA

There is a large advanced composites technology base in this country that has been developed to address the materials needs of the defense, aerospace and commercial aircraft industries. A similar technology base must be developed to use advanced composites products successfully in offshore applications. Some of the needed technology can be transferred from the existing base and adapted to the offshore environment. But a major investment in an expanded technology base is needed to use these materials on a commercial basis.

A large focused program is proposed to assist with this effort. The program could be described as follows:

"Development of the reliability data base, the design methodology and software, the manufacturing technology, the construction technology, and the smart structure sensor technology needed to utilize advanced fiber composites in critical offshore exploration and production (E&P) operations".

3. PROGRAM OBJECTIVES

The technical objective of the proposed program is to identify and resolve each of the barriers that limit the acceptance of advanced composites for critical applications by the petroleum industry. This effort would start with a survey to access in detail the needs of the petroleum companies and engineering firms that design and specify offshore structural systems. Technology development programs would be formulated to address each of the critical needs that limit the acceptance of advanced composite materials for critical systems. The programs will involve multi-disciplinary/ multi-industry teams that include all parties needed for commercialization.

The business objective of the proposed program is to develop a path to commercialization by involving key companies in the development programs from each element of the supply chain and from a broad spectrum of user engineering groups. The development programs would include economic analysis at key junctures to assure that technology development is strategically aligned with industry business needs. Further, market potential will be defined and updated frequently so that companies on the supply side have accurate information. It will be critical that all parties involved have current business opportunity information to maintain a sense of urgency and to minimize the cycle time required to develop each technology element.

The U.S. Air Force sponsored programs in the 60's were successful in developing aircraft applications for advanced composites because they focused on the needs of the engineering groups that design and specify structure. The same strategy is proposed for this program. We intend to build acceptance by first developing applications that are low risk, moderate payoff and can be implemented near term (1995-200) while developing the technology base for high risk, high payoff applications that will be implemented long term (2000 and beyond). Table 1 shows some preliminary projections for usage of composite components over the next ten years. Spoolable pipe for water injection would be an example of a low risk application that can be developed early in the program to develop the experience needed for acceptance of high risk applications, such as hydrocarbon pipelines, late in the program.

4. TECHNICAL BARRIERS

Five technology issues are defined at this time as barriers to utilization. As stated above most applications are in critical systems. The consequence of failure in these systems is very high. The safety of the production platform is at risk should failure occur in a tether and there is environmental and financial risk should failure occur in a riser. So the most important technical barrier is *reliability*. The design of critical components must be based on statistical materials data bases and probabilistic design methodology must be developed to satisfy rigorous risk assessment analysis.

The second barrier is the absence of manufacturing technology needed to produce cost effective offshore structure. For example, most offshore applications require tubular structural elements. Batch process filament winding manufacturers are limited to lengths ranging from 30 to 75 feet, so frequent connections are required. Connections increase the probability of failure and add substantially to the cost of the installation. The proposed program would focus on the development of a *continuous process for manufacture of long composite tubular profiles*. This program will include the development of robust resin cure technology and the use of sensors and process control techniques (intelligent processing) to assure quality and to minimize product variability.

The third barrier that is anticipated is *design methodology and composite structure design software* that is user friendly. The design software that is available is fragmented and not user friendly in the sense of modern software packages. The capability to design complex composites systems lies in the hands of a few experts and the comprehensive software packages are privately owned. It is proposed that funds be used to develop a comprehensive design software package applicable to offshore structural systems. This is a large task that requires characterization work on material systems conditioned in offshore environments and extensive development of design/analysis methodology applicable to offshore types of structures. The objective of this task is to make it relatively easy for knowledgeable structural engineers to design composite structures.

The fourth barrier is the lack of construction techniques, equipment and experience with composites in offshore operations. The proposed program would focus on industry needs for *construction with continuous composite tubulars*. All aspects of offshore construction will be addressed including storage, transport, submersion and installation of continuous tubular goods. Innovative construction techniques will be sought to minimize installation costs which is a large portion of total costs with state-of-the-art carbon steel construction. So it is very important to include installation in the effort to develop positive economics for alternative materials.

The fifth technical barrier relates to the reliability of composite offshore systems during service. *Imbedded sensor technology will be developed for real time monitoring of offshore composite structures* to assure that critical systems are not compromised by unanticipated service conditions.

5. PROPOSED R & D PROGRAMS; SCOPE & FOCUS

To overcome the major technical barriers aforementioned in Section 2, the scope of the proposed program will focus on cutting-edge advanced composites technology R & D with a high degree of technical risk, but would offer significant opportunities to leverage major advances for petroleum E & P operations with high payoff of billions of dollars for several groups or sectors of industries. The proposed program embraces a number of interrelated projects and new critical industrial capabilities. These high-risk, high-payoff projects are critical to successful development of market-driven offshore products and their commercialization, such as composite platform tethers, composite production risers, various composite subsea pipe lines and spoolable composite pipes, for deep sea E & P operations. These interlocking R & D projects will complement each other and provide the synergy that will have the greatest impact not only on the petroleum energy E & P and its supporting technologies but also on the economy of a number of sectors of industries. Also, included in this section are some of the major potential participants from various sectors of relevant industries, national and governmental laboratories, and academic institutions, which can be organized to form a proper team for each of the projects.

5.1 Reliability

The composites offshore reliability technology development will address the most critical technical barrier that prevents the petroleum E & P industry from large-scale utilization of the radically new and different material systems to realizing their fullest potential. The objectives of this project are to establish innovative technology bases for understanding, characterizing and controlling materials, manufacturing and structural reliability of offshore composites and to conduct the proper risk assessment to meet the requirement of regulatory agencies.

a) Material Reliability

Large-scale system studies need to be conducted to determine various optimal combinations of resin and fiber systems suitable for different offshore components and structures. Distinct damage mechanisms and failure modes need to be identified and formulated into material system tailoring and reliability design. The effects of marine environments on mechanical properties of different polymer composites should be determined and documented. The issue of long-term creep and durability of fiber composites on the integrity and safety of offshore components and structures is of critical concern. Model development and a statistical data base are essential to ensure proper evaluation of long-term material performance and associated size effects.

b) Manufacturing Reliability

Offshore composites product variability is governed by manufacturing reliability. Quality assurance is most critical in ensuring the manufacturing reliability. Effects of manufacturing parameters on the product variability should be determined by proper processing modeling of offshore composites. Associated measurement techniques need to be developed, and a data base on the offshore composites manufacturing reliability should be established to provide quantitative information on this issue. Development of proper methodologies and associated techniques to effectively control and optimize offshore composites product variability should be made to ensure the manufacturing reliability.

c) Structural Reliability

Development of acceptable methods (or tools) is needed for performing system reliability analysis of complex or novel composite offshore structural systems. Establishment of analytical methods is required to describe/analyze the joint occurrence of environmental variables and loads in a probabilistic domain to form input to system risk/reliability analysis of composite offshore systems. Research is also needed to quantify the probability of detection and sizing of structural defects and their effects on composite offshore structural failure. Modeling and experimentation should be conducted on crack initiation and growth in complex components, e.g., offshore composite joints and fittings. Of particular interest is development of probability-based analytical methodology to relate the composite offshore component reliability to the overall system reliability.

5.2 Continuous Process for Manufacture of Long Composite Tubulars

Nearly all the major offshore components targeted for advance composites are tubular with thick walls. Significant economical benefits and production advantages can be realized if an automated continuous manufacturing technology can be developed for this class of advanced composite products. The emphasis of this project should be on high-speed intelligent manufacturing technology development, especially for very long length composite tubulars. the development of high-speed continuous processing technology for advanced offshore composites should include the following:

a) *Manufacturing processes:* filament winding, pultrusion, resin transfer molding, braiding, combined filament wind and pultrusion, other innovative methods

b) *Material forms:* dry fibers, hybrid fibers, wet winding, prepreg tape winding, woven fabrics, preforms, other reinforcement forms

c) *Intelligent process control*: curing monitoring and control, fiber placement tension, compaction/consolidation, embedded sensor technology, instrumentation development, process modeling

d) *Product variability*: quality assurance, product variability evaluation & control, effect of product variability on material properties

e) *Manufacturing economics*

5.3 Design Methodology and Composite Structure Design Software

The objectives of this project are to develop analytical methodologies and associated advanced design capabilities for construction of advanced offshore composite components, and establish critical material and component performance criteria for modeling, design and validation. Successful developments of these methods and design capabilities will accelerate large-scale utilization and rapid commercialization of advanced offshore composite products in petroleum E & P, maritime and advanced materials industries. The broad range efforts planned in this project should include:

a) *Advanced Analytic Methodology Development:* Composite lamination theory/analysis for thick-wall cylindric shells, multiaxial failure (strength) for thick wall composite tubular, multiaxial cyclic fatigue degradation and failure, long-term creep and its effect on leakage, life prediction for long-term performance and failure, optimization for material selection, lamination tailoring and structural performance, transportation and installation induced stress and damage, dynamic, environmental and probabilistic loading based reliability analyses.

b) *Integrated computer-aided design tool development and artificial intelligence:*

Based on the above advanced analytic methodology development, an integrated computer-aided design tool or software package development program should be attempted. This effort should include: material system models, multiaxial failure (functional or structural) modes and criteria, environmental effects assessment and probability modeling of damage tolerance and residual properties, 3-D effects involving transverse deformation and bending and torsion economic/cost, analyses and modeling reliability-based design with performance goals and acceptability criteria, design norms and life-cycle optimization.

c) *Associated Critical Performance Characteristics Evaluation:*
The purpose of this effort is to establish critical performance data bases for modeling, design and final validation of offshore composite components in actual service environments. A large-scale, system effort is needed to establish the following critical material and structural performance data bases for design and evaluation.

- damage evolution and tolerance
- multiaxial failure modes and failure criteria
- environmental degradation and failure
- long-term creep and creep failure criteria
- cyclic fatigue and degradation under multiaxial fatigue
- local instability and compressive failure

5.4 Offshore Composite Construction and Installation

The construction project would be used to develop offshore technology for construction with composite components. The proposed program would focus on needs associated with construction with continuous or very long composite tubulars. All aspects of offshore construction will be addressed including storage, transport, submersion and installation of continuous tubular goods. Innovative construction techniques will be sought which will minimize installation costs, a large portion of total costs with state-of-the-art carbon steel construction. An example would be the deployment of a composite tether from a spool.

5.5 Smart Composite Materials and Intelligent Offshore Composite Structures

The objective of this project is to develop offshore composite materials and structures with embedded sensor technologies for real-time interrogation of material damage and degradation in the marine environment and for on-line monitoring of composite offshore structural performance during service. The development of this technology will provide major advances in the industry capability of improving safety of the critical composite systems and expediting commercialization of offshore composite E & P utilization.

Advanced composite materials and structures integrated with embedded optical fiber or other sensors represent new and exciting technologies that may revolutionize the development, design and operations of offshore composite structures and related machineries and equipment. They will lead to future offshore systems that are safer and easier to maintain and monitor their integrity, and can sense and correct their structural and environmental anomalies. More advanced intelligent offshore composite structures may be able to control their stiffness, dynamic configuration, orientation, rotation and acceleration, etc. In this project, the following areas of research and technology developments should be considered:

a) Fiber optics and other sensor technology development, including
Optical fibers sensors, including intensity based, polarization and various interferometric sensors
Optical time and frequency optical domain reflectometries
Demodulation techniques for fiber optical sensors
Other sensor and instruments, such as miniature GC.

b) Smart material technology development
Advanced fiber composites with built-in fiber optic monitoring system (e.g., acoustic emission, opto-acoustic sounding, etc.)
Material integrity monitoring with optic fiber sensors (e.g., damage growth evaluation)
Potential opto-control systems for offshore composite damage

c) Intelligent offshore composite structure development
Offshore composite structural measurements with fiber optic sensors, including deformation and vibration and motion, and control.
Active dynamic control of large composite tubulars, including benefits of embedded/bounded sensors and actuators.
Piezoelectric dynamic control application
Mechanical modeling of piezoelectric substructure coupling
Impedance matching of actuators for various functions and offshore composite structural systems
Active offshore composite structural acoustic control with induced strain actuation

6. ECONOMIC IMPACT

Domestic oil reserves are declining and without further discoveries and development, proven U.S. reserves at current rates of production will last only another 10 years. Approximately 65% of United States energy needs are supplied by petroleum while at the same time U.S. oil production in 1993 was the lowest in 35 years. The United States will import approximately 3.1 billion barrels of oil in 1993, 49.2% of consumption and 53% of the negative balance in international trade.

One promising source for new petroleum production is from deep water (over 2000-feet) in the Gulf of Mexico. Composite materials could provide a very important contribution to the development of deep water reserves in the Gulf of Mexico as well as in other parts of the world such as the North Sea and the west coast of Africa. If composite components are developed and built by U.S. companies; they could be used to support oil industry needs worldwide, help make U.S. oil and service companies more competitive in international exploration and production services and provide significant improvements in the balance of payments.

Some of the potential offshore composite applications are shown in Table 1. Estimates are included for worldwide usage over the next 10 years in terms of product length, material usage in total pounds, and cost of manufactured components. It should be recognized in this scenario that the development cycle for an offshore platform takes at least five years. So the applications associated with deep water platforms would not occur before year 2000. The projections in Table 1 assume just 6 floating platforms with composite tethers and risers from year 2000 to 2005, a conservative estimate considering there are more than 10 deep water platforms under study for the Gulf alone that could go into production during that time period.

The 184-million pounds of composite weight utilization forecast in Table 1 includes composites constructed of carbon, aramid and glass fibers. Stiffness constraints which govern the design of some of the components such as the tether drive the design toward the use of carbon fiber while other components having less demanding requirements normally use glass fiber or hybrids of glass and carbon. If one assumes that half the projected weight is for fiber and half the fiber weight is carbon, the carbon fiber consumption in the 10-year period would be 41 million pounds. This would indicate an $8.2 MM annual market for carbon by year 2005 assuming linear development of the market. The $2.7 billion value forecast in Table 1 for composite components is based on offshore needs including subsea, but does not include additional expected onshore utilization of new composites technology.

This is the estimated value of manufactured components and does not include the cost of installation. Offshore installation costs can be very high ranging from 2 to 8 times the cost of material in the case of steel construction. We have not tried to estimate installed costs here because new construction techniques are expected to reduce the cost of composite parts as compared to that of in the installation of steel.

To summarize, we anticipate positive economic effects throughout the supply sector, the utilization sector, and the entire US economy. The supply sector gains a new market that will replace the loss of projected defense and aircraft sales. The US offshore engineering firms, the construction companies and the service companies will develop capabilities with a new technology that will greatly improve their competitiveness in the world market for petroleum services. The petroleum companies will reduce the cost of E&P operations generally. More specifically, they can reduce the investment needed to develop the deep water reserves in the Gulf. As indicated above we badly need new US reserves. This is an issue that impacts many economic factors, cost of energy, international trade balance, etc.

7. INDUSTRY COMMITMENT

The petroleum E&P industry uses new technology routinely and generally has high commitment to technologies that meet industry needs. The E&P industry has shown interest in composites as alternatives to metals to solve several different materials needs. As mentioned in the introduction, the acceptance of FRP piping for offshore service has increased dramatically over the last two years in the North Sea area. There are several active joint industry research programs in Norway and in the UKOOA formed by the petroleum industry to develop the technology base for utilization of FRP composites on the topside of offshore platforms. Those programs are very active now and they receive extensive government support. The North Sea programs help, however, they do not address the use of advanced composites for offshore operations.

The technology base for advanced composites resides primarily in the US. The first US joint industry program involving the application of advanced composites to petroleum operations was initiated this year. Several petroleum companies and supporting industries are supporting Hydril in the development of coiled tubing. This is a demanding but noncritical application where carbon/glass hybrid composites hold promise for extending the capability and the life of small diameter tubing utilized in downhole operations.

A core group of representatives from the petroleum industry announced at the workshop that they plan to form a consortia of petroleum companies and supporting industries for the purpose of developing composite material applications for petroleum E&P operations. The response and the enthusiasm resulting from the announcement have been very encouraging. The consortia will corroborate with the formation of the Composites Engineering and Applications Center (CEAC) at the University of Houston. The CEAC is expected to start operation 3/1/94. The first task is to administrate a survey and design study to better define the materials needs of the industry and the markets for alternative materials.

The activities described above all point to a strong interest and commitment by the industry to pursue the development of alternative materials. The petroleum companies have also shown a strong commitment in recent years to joint industry development of new technology that benefits the industry as a whole. That commitment extends to cooperative efforts that involve government laboratories and government agencies.

The materials suppliers and the manufactures are also quite interested in cooperative programs that will result in new markets. Markets for advanced composites are depressed and the development of new markets is essential for the survival for many companies. The petroleum E&P industry may represent one of the few remaining market opportunities for the advanced composites supply industry.

The development of good information on industry needs and time based markets for alternative materials will be essential. Current activities on the design of platforms for deep water reserves in the Gulf of Mexico will be very useful in the development of accurate forecasts. We do not anticipate a problem in finding participants for projects requiring matching funds.

8. IMPORTANCE OF THE PROGRAM

The DOD has funded the development of advanced composites technology applicable to thin panel structure used in aircraft. Design methodology, manufacturing technology, materials characterization and reliability have been addressed as required for aircraft structure. However, that technology is not applicable to the thick wall cylindrical structure and the environments that are typical of offshore applications.

The summary below compares the existing DOD manufacturing technology to that proposed for offshore components.

Manufacturing Technology

	DOD/Aircraft Skins	DOD/Missile	Offshore
Materials	Carbon/epoxy	Carbon/epoxy Kevlar/epoxy	Hybrids Carbon/Glass/aramide/epoxy
Geometry	Thin panels	Thin wall tubulars	Thick wall tubulars
Process	Autoclave	Filament Wind (batch)	Filament Wind/Pultrude (continuous)
Quantities	2000 lb/AV-8B Plane		2.5MM lb/platform
Size	12' x 20"	8'D x 20'L x 0.100"T	12"D x 0.75"T x continuous
Cost **Mfg** **Structure**	200-750 $/lb	50-150 $/lb	15-25 $/lb

The aircraft skin technology is included because it constitutes most of the DOD inventory. That technology does not translate at all to the needs for offshore structure. Rocket motor case/missile/launch tube technology is tubular, but those structures had totally different performance criteria: light weight/low stress/single mission vs. thick wall/long life/sustained loading. So, very little of that technology will meet the requirements of offshore structure. In manufacturing technology, the key difference is cost. Industry studies show that composites start to offer significant systems cost savings at 25$/lb. Manufactures contend they are close to that figure with 75 feet batch processing of hybrid fiber composite production risers. Hybrid structures of glass, aramide, and carbon fiber are used to reduce the material costs as much as possible.

The timing is ideal for an industry-government cooperative initiative in this area. As mentioned in the introduction, the use of FRP composites offshore has received a great deal of attention in the last two years. We expect to see very significant increases in the use of FRP materials offshore in the near future, including piping systems for the upcoming TLP's for deep-water GOM production. The FRP experience will provide the basis for acceptance of advanced composites offshore when the technology base is available.

Deep water production in the Gulf will start with the Auger platform in 1994. The Mars platform and the Ram Powell platforms are scheduled to go into production in '96 and '98, respectively. These platforms will not use advanced composites because of the technology barriers described above. The initiative would provide the technology needed for the use of advanced composites on the deep water platforms projected for year 2000 and beyond. Industry experts have projected that six deep water platforms will be constructed from 2000 to 2010.

Federal funding could make the difference. The supply industry has little capital to invest in new product development. Experts project significant cost savings in deepwater platforms by using advanced composites, but reliability is a concern and the technology base is not in place. A very large investment would be required to develop that technology base. So the industry is proceeding with metals technology. Advanced composites offshore represents an opportunity that may go unfilled unless a major initiative is developed to address it. A federal program would provide the means for that initiative.

Table 1 - Offshore Oil Industry Composite Applications, Estimated Potential Usage and Earliest Application over the next Ten Years.

Composite Component	Quantity	Composite Weight, Million lb	Component Cost, Million$	Earliest Application
Tether	Six TLP's	15	430	2000
Riser	in 3000-ft water	9	180	1998
Tubing Inside Riser	16 tethers, 40 risers per TLP	6	90	1998
Spoolable Pipe	20-million ft 1"-4"	20	300	1996
Drill Pipe	0.5 million ft	5	125	1996
Drilling Riser	0.1 million ft	1	.25	1995
Subsea Structure		5	70	1995
Subsea Pipe Line	3000 mile	50	800	1996 [1] 2000 [2]
Mooring Rope	12 Floating Production Storage Facilities	3	60	1996
GRP Facilities		20	200	1993
Platform Structure		50	600	1998
	TOTAL	184	2880	

[1] Water Injection flowlines

[2] Hydrocarbon flowlines

1. Introduction

1. INTRODUCTION

Composite materials are increasingly being considered for use in offshore petroleum production engineering operations. This is particularly true for deep-water offshore platform and drilling technologies. Composite materials are recognized to offer substantial weight reduction, superior fatigue and corrosion resistance, outstanding acoustic, vibration damping and energy absorption, and unlimited potential of innovative material and structural tailoring to desired stiffness and strength. Coupled with low maintenance and low total life-cycle costs and ease of fabrication and construction, composite materials are an enabling technology ideally suited for both immediate and future deep-water challenges and offer the highest payoff potential in the offshore operations. Success in realizing this great potential will require understanding the existing composites technology base and its future development, unique structural requirements of deep-water offshore operations, and economic and reliability constraints in the use of composites.

1.1 Workshop Objectives

To review the current state of the art in composite materials for offshore use, and to assess the current state of practice for offshore operations;

To identify gaps between the state of the art and state of practice;

To determine and prioritize research initiatives which might mitigate these gaps to allow safe and economical utilization of composites by the oil industry;

To bring out new opportunities to oil and gas industries through using composite materials and structures; and

To provide guidance to petroleum and related industries for certification of offshore composite structures and components.

1.2 Issues Addressed and the Program

The topics covered in the workshop will focus on offshore structural, nonstructural and advanced applications, including: structural components, mooring systems, risers and tubing, platform (water and oil) piping, coiled tubing, drilling equipment, completion equipment, and logging and MWD tools. The issues to be addressed will span a broad spectrum of scientific and engineering concerns, including: material systems, fabrication and construction; material performance, long-term durability and environmental effects; structural design, testing and reliability; NDE and condition monitoring/inspection; flammability and fire safety; GRP applications; advanced applications; regulatory concerns and certification issues.

The workshop was conducted with a two and one-half day program. The first day's program consisted of a series of invited lectures given by internationally recognized experts. Working group sessions followed the invited lectures and continued to the second day. Findings from each working group were presented and discussed in the third day sessions.

1.3 Working Group

Each working group was led by a chairperson and a co-chair, with the assistance of a recording secretary to facilitate and document the discussions. Working group chairs, co-chairs, recording secretaries, and panelists are listed in Section 6 (Working Groups and Discussion Summary Reports). Attendees of the workshop participated in the discussion sessions, in one of the following eight working groups:

1. Fabrication, Construction, Maintenance and Repair
2. Material Performance, Damage Tolerance, Durability and Environmental Degradation
3. Structural Design, Optimization, Testing and Reliability
4. NDE and Condition Monitoring/Inspection
5. Flammability and Fire Safety
6. GRP Applications
7. Advanced Applications
8. Policy Concerns and Certification Issues

2. Workshop Program and International Steering Committee

2.1 WORKSHOP PROGRAM

Tuesday, 26 October 1993

7:30 a.m.	Registration opens
8:30 a.m.	Welcome and Introduction — *S.S. Wang,* University of Houston
	1. GOVERNMENTAL and INDUSTRIAL PERSPECTIVES
8:40 a.m.	Minerals Management Service (USA) — *H.G. Bartholomew*
8:50 a.m.	National Energy Board (Canada) — *G. Yunblut*
9:00 a.m.	Health & Safety Executive (U.K.) — *M. Bishop*
9:10 a.m.	Norwegian Petroleum Directorate (Norway) — *Per Endresen*
9:20 a.m.	UKOOA (U.K.) — *C. Houghton*
9:35 a.m.	OLF (Norway) — *J. Helge Jenssen*
9:50 a.m.	Coffee Break
	2. CRITICAL ISSUES, EXPERIENCE LEARNED, AND FORECAST
10:05 a.m.	Keynote Address #1 — Oil and Gas Industry Perspective *B.W. Cole,* AMOCO
10:35 a.m.	Keynote Address #2 — Oil and Gas Industry Perspective *J.G. Williams,* CONOCO
10:05 a.m.	Keynote Address #3 — Composites Industry Perspective *G. Robertson,* Ameron
11:35 a.m.	Keynote Address #3 — U.S. Navy Experience *I. Caplan,* U.S. Navy DTRC
Noon	Lunch
1:30 p.m.	Introduction to the Working Group Format for Discussions — *S.S. Wang*
1:45 p.m.	Move to Working Group Meeting Rooms
2:00 p.m.	Presentations by Working Group Chairmen
3:15 p.m.	Coffee Break

3:30 p.m.	Working Group Sessions
5:00 p.m.	Adjourn
6:00 p.m.	Reception and Texas Barbecue

Wednesday, 27 October 1993

8:00 a.m.	Registration opens
	4. CRITICAL ISSUES, EXPERIENCE LEARNED AND FORECAST
8:30 a.m.	Keynote Address #5 — Challenges and the Future *J.M. Bowman,* Du Pont
	5. WORKING GROUP DISCUSSIONS
9:00 a.m.	Working Group Sessions
10:15 a.m.	Coffee Break
10:45 a.m.	Working Group Sessions
Noon	Lunch
1:30 p.m.	Working Group Sessions
3:00 p.m.	Coffee Break
3:30 p.m.	Working Group Sessions

5:00 p.m. Adjourn

Thursday, 28 October 1993

	6. WORKING GROUP PRESENTATIONS AND DISCUSSION
8:30 a.m.	Presentations by Working Groups #1–4 and General Discussion
10:00 a.m.	Coffee Break
10:20 a.m.	Presentations by Working Groups #5–8 and General Discussion
11:50 a.m.	Concluding Remarks — *S.S. Wang* and *C.S. Smith*
12:10	Workshop Adjourns

2.2 WORKSHOP CHAIRMAN, SECRETARY, AND INTERNATIONAL STEERING COMMITTEE

Workshop Chairman

Su Su Wang, University of Houston

Secretary

Dale W. Fitting, National Institute of Standards and Technology

International Steering Committee

U.S. Minerals Management Service	*Charles E. Smith* and *Maurice Stewart*
Canadian National Energy Board	*Ibrahim Konuk*
U.K. Health and Safety Executive	*M. Bishopp*
Norweigian Petroeleum Directorate	*K. Nilsson*
National Institute of Standards and Tech.	*Dale W. Fitting*
U.S. Navy	*Rembert F. Jones, Jr.*
U.S. Coast Guard	*Paul Cojeen*
ABS Americas	*J.S. Spencer*
American Petroleum Institute	*George G. Huntoon*

Major Oil and Gas Companies

Amoco	*Bill Cole*
BP	*H.J. Choi*
Chevron	*Steve Turnipseed*
Conoco	*Jerry G. Williams*
Exxon	*Jemei Chang*
Philips Petroleum	*Alex Lou*
Shell	*W.G. Gottenburg*

International Steering Committee (cont'd)

Composite Materials Industry

DuPont	*M. Monib*
Brunswick	*Douglas Johnson*
Hercules	*Mark Courtney*
Ameron	*Ram Ananthataman*
AMAT	*Tore Lundh*
SpyroTech	*Chris Lundberg*

Machinery, Tool, and Equipment Industry

Schlumberger	*Bart Thomeer*
Halliburton	*Don Hushbeck*

Energy Engineering Service Company

McDermott	*Richard Lopushansky*

Academic Institutions

University of Houston	*Su Su Wang*

3. Invited Presentations — Government and Industrial

U. S. MINERALS MANAGEMENTS SERVICE'S PERSPECTIVE

ON

COMPOSITES FOR OFFSHORE OPERATIONS

AND SAFETY MANAGEMENT

By
H.G. Bartholomew
Deputy Associate Director
Offshore Operations & Safety Management
U.S. Minerals Management Service
Herndon, VA 22070

Introduction and Welcome

On behalf of the U.S. Minerals Management Service, I want to add my welcome to all of you to this first international workshop on composite materials for offshore operations.

I want to extend a special welcome to our colleagues from Canada, Norway, the United Kingdom, and elsewhere outside the United States, whose participation truly makes this an international event.

A number of *Thank You's* also are in order:

- First, thanks to the organizers and co-sponsors of the workshop, Dr. Su Su Wang, University of Houston, and Dr. Dale Fitting, National Institute of Standards and Technology.
- Also, thanks to the University of Houston for hosting this event and for the generous use of their facilities.
- And special thanks to the members of the joint government-industry steering committee for preparing the workshop program.
- And lastly, a special word of appreciation to the many other co-sponsors, whose names you'll find listed on the front of the workshop program.

The Minerals Management Service

As most of you may know, my agency, the Minerals Management Service, or MMS, regulates oil and gas exploration, development, and production in the offshore waters of the United States.

Not as well known is that MMS also collects lease bonuses, rents, and royalties due to the U.S. Government for minerals production from Federal and Indian lands, both offshore and onshore. Last year, MMS collected more than $2 billion, making us the second or third largest revenue collecting agency in the U.S. Government.

And of course MMS conducts a technology assessment and research program aimed at promoting the use of the *best and safest technologies* in offshore operations.

Workshop Objectives

It is in furtherance of this mission that we are pleased to join with NIST, the University of Houston, and the dozen other government agencies and companies who have made this workshop possible.

Our purpose in co-sponsoring this workshop is to facilitate an exchange of information on composite materials for offshore applications among regulatory agencies, oil companies, material suppliers, composite manufacturers, certification organizations, design engineers, and academic institutions worldwide.

This workshop should also serve to:

- First, review the current state-of-the-art in composite materials for offshore use;
- Second, assess the current state-of-practice for offshore operations;
- Third, identify gaps between the state-of-the-art and state-of-practice, and to suggest and prioritize research initiatives that might mitigate these gaps to allow safe and economical use of composites by the offshore industry;
- Fourth, identify new opportunities for the use of composite materials; and
- Fifth, to provide guidance to industry and regulatory agencies on the use of composite materials offshore.

Importance of Composites

At the outset, I want to stipulate that, while I have an engineering background, I am not an expert in either structural engineering or the use of composites. In these areas, I rely on experts such as Charles Smith, who manages MMS's safety technology program, and Felix Dyhrkopp, the manager of our platform verification program.

The experts tell me that composites are characterized by high stregth-to-weight ratios and resistance to corrosion and fatigue.

These characteristics allow offshore facilities designers to tailor structural and mechanical responses to a degree unachievable with conventional materials. In turn, this will produce safer structures and lower maintenance costs.

Technical and Regulatory Issues

Before the full potential for composites can be realized, however, we need to address a number of technical and regulatory issues. To this end, we need an organized effort to identify critical issues and to assess those actions that will enable the use of composite materials in the offshore environment. Which brings us to this workshop.

Before closing, I'd like to pose some issues for consideration by you, the experts:

- First, MMS's interests regarding the use of composites are wide-ranging and go from installation, maintenance, repair, testing, inspection, and certification issues to concerns over fire safety, durability, damage tolerance, and environmental degradation.
- Next, while API RP-14G addresses the relative merits of reinforced fiberglass plastics (RFPs) in deluge and firewater systems and <u>other</u> API documents address the use of RFPS in storage

tanks, MMS has no regulations that address acceptance or inspection of composite materials in offshore applications.

I'm told that we would consider the results of performance tests in reviewing applications for the use of composites--for example, flame, toxicity, and smoke tests--provided that such tests are conducted in an environment that closely resembles offshore conditions.

- Moreover, MMS has no regulations on the use of composite materials offshore, although requests to use composites have been considered and approved by MMS on a case-by-case basis.

For example, based on proven long term use in the North Sea, *coflex*, which is flexible pipe fabricated from sheets of steel molded into a rubber jacket, has been approved in the U.S. for deep water risers and pipeline segments in mudslide areas.

RFPs and other non-traditional materials have been approved for use in offshore galleys, living quarters, open atmospheric drain systems, and produced water systems. In addition, RFPs have been approved for chemical and non-hydrocarbon storage tanks.

Conclusion

In closing, I again want to thank Dr. Wang and Dr. Fitting for organizing this workshop and the steering committee and co-sponsors for their support. And I thank all of you for participating in this important undertaking.

Approach of National Energy Board on the Use of Composites in Petroleum Industry

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Canada

Introduction

Innuit (Eskimos) living in the Canadian Arctic make ingenious use of a "composite" material in constructing their dwellings[1]. The most readily available material in their environment is naturally ice which is a crystalline material. We know from our research programs that ice is typically a brittle material. The cracks in an ice sheet can sometimes propagate miles. Inuit has found that by freezing moss into a block of ice, one can obtain a quite a different material that is comparatively ductile. We know that there are many other examples of earlier use of composite materials going back as early as 1500BC such as armour plates, Samurai swords. There are also many examples of composites in nature such as wood which is a cohesive combination of cellulose fibers and lignin and bone which is composed of compact tissues and slender fibers made from cancellous tissue[2].

Although modern composites are also based on the same principle of mixing different materials to obtain a material that possesses the best qualities of the individual constituents, they are usually designed and developed to obtain a precise set of properties. I am sure that during the workshop, we will be exposed to various types of composites: fibrous (plastic reinforced with glass fibre or carbon fibre or metals reinforced with boron fibre), laminated (cladded metals, laminated glass, plastic-impregnated cloths), and particulate (concrete, ceramics, acrylonitrile butadiene styrene (ABS) polymers). The purpose of this presentation is to describe, in general, how we are handling the approval and certification of these materials and also to describe our research and development efforts in this area rather than providing a survey of such materials or their applications.

Regulatory Responsibilities of the National Energy Board

The National Energy Board (NEB) has regulatory responsibility for all oil and gas exploration, drilling and production facilities, and activities, in the Northern Territories including offshore Arctic Ocean. NEB is also responsible for regulating the construction and operation of pipelines that cross provincial or international borders.

The principle objective in regulating exploration, drilling, development, and production activities is:

(a) To ensure the safety of the workers on the site or facility;

(b) To ensure that all reasonable steps are taken to protect the environment; and,

(c) To ensure that the production practices do not result in the oil and gas resources being lost or wasted.

These objectives are achieved through ensuring that proper design and operating criteria are used. In fulfilling its responsibilities, NEB develops, administers and enforces a number of sets of regulations which establish the approval process and prescribes standards that must be met in order to obtain an approval. Generally, these standards are selected or developed in consultation with technical experts in the oil companies.

NEB also cooperates with industry in the development of new design codes and standards which may be referred in the regulations.

NEB also manages an extensive research program to develop new design and analysis methods to improve effectiveness of the regulation to make the Canadian oil and gas project cost effective. We also sponsor research to develop new materials and structures and new construction techniques to keep the Canadian industry competitive.

Acceptance and Certification Procedures

Before any approval is given, a careful study is made of the equipment, materials and procedures that will be used to determine if the regulations are being met and if the environment will be adequately protected at the particular site or area.

During the approval of drilling and production systems approvals, most of this study role can be delegated to recognized certifying authorities. However, in the case that a new material is being proposed that is not clearly covered by the regulations and the standards referred in the regulations, the company would be expected to demonstrate that the use of new materials would provide a level of safety higher or equivalent to engineering performance specifications that are the prescribed or intended by the regulations.

This can be accomplished by presenting documentation and data on the performance of the new materials obtained in a laboratory environment or during the application of the material under similar conditions. We know that there are continuing efforts to rationalize and standardize this process in various countries. One of the major efforts in this area is taking place in Europe under the term of "Performance Based Materials Selection" (PBMS)[3]. In NEB, we are keeping an open mind towards such developments and would consider including references to these standards in our regulations or may decide to sponsor the development of Canadian standards to cover the unique conditions in Canada.

Research and Development

We have a number of unique problems in Canadian offshore. The main challenge in designing structures is to overcome high loads induced by ice-structure interactions. NEB has sponsored research and testing program to develop high strength composite steel-concrete-steel sandwich walls.

Other problems related to ice stems from the low temperature properties of conventional materials such as carbon steel. Canadian government is sponsoring research towards the development of high toughness alloys.

In pipeline area, we have been experiencing problems since the mid 1980's due to a phenomena called stress corrosion cracking (SCC). The term SCC is used to describe a crack initiation and propagation process which results from the interaction of tensile stress and corrosion. In pipelines, SCC cracks are usually initiated at locations where the coating is separated from the pipe and bare metal contacts a corrosive fluid.

Composite materials have been proposed to address these kinds of problems. Recent literature contains many such developments[4,5,6]. However, as discussed in [3], the use of composites in offshore is not always economical or straightforward. We also have to understand the long-term behaviour of composites and overcome some of the difficulties associated with the long-term behaviour of these materials under given environmental and thermal conditions[7].

At NEB, we are prepared to work with industry to develop standards for design, fabrication and selection of the composites. We would also welcome opportunity to join research efforts in this area initiated in other countries.

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UK GOVERNMENTAL PERSPECTIVE

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Health and Safety Executive
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The UK legislative regime for the offshore industry is currently in the process of being reformed. This reform is a consequence of the Cullen Report into the Piper Alpha disaster which made a number of criticisms of the old legislative regime. The major criticisms were that the Regulations were too prescriptive, were not in line with modern thinking on safety legislation and were constraining technological development. The Cullen Report made a number of wide ranging recommendations for reform, all of which were accepted by the UK Government, the Health and Safety Executive (HSE) is in the process of turning these recommendations into legislation.

The old system, much of which has yet to be reformed, consists of a number of Acts and Regulations which are prescriptive in nature. These Regulations make requirements that certain precautions be provided, regardless of whether there was a need for them, and often the standard to which they would be provided is specified regardless of the actual situation. The Regulations were backed up by formal guidance, perhaps the best known of which is the guidance to the Construction and Survey Regulations, usually called the Green Book or the 4th. Edition Guidance. This guidance is primarily targeted at designers and the Certifying Authorities and, had, partly due to the lack of anything better, become regarded as equivalent to the Regulations themselves.

This prescriptive style has certain advantages, for the designer it gives a clear set of rules which must be complied with, and does not require the provision to be based on the results of a risk or hazard analysis. For the Regulator the advantages are that it is easy to demonstrate fairness in the treatment of all operators because the rules are exactly the same, and at the enforcement stage these same prescriptive rules give a clear go/no go decision.

The downside is of course that there is no connection between the actual hazards present and the precautions required by the Regulations. This inhibits innovation and the development of alternative methods of ensuring safety as there is no mechanism to provide a credit for such a developments.

The inflexibility of this legislation was also shown by the need to grant around 400 requests a year for exemptions from certain provisions of the legislation.

The first element of the reform process is now in place, with the Safety Case Regulations, which came into force on the 31 May 1993. In essence these require that for existing installations the operator must submit a "Safety Case" to the Health and Safety Executive (HSE) by the end of November this year. This Safety Case must identify the hazards and show how these hazards will be managed and controlled throughout the lifetime of the installation, and demonstrate that the risks to personnel have been reduced to "As low as reasonably practicable" (ALARP). These precautions will be a combination of a installed precautions such as active and passive fire protection, and a Safety Management System. They emphasise the need to design out the hazard ie inherent safety and prevention rather than control and mitigation

The next phase is the review and reform of offshore legislation. The first of the new regulations will be the Prevention of Fire and Explosions, and Emergency Response Regulations, (PFEER Regulations), the consultative draft of which has recently been published for formal public consultation. There has already been substantial informal consultation with all parties in the industry on these draft Regulations. The consultation phase will close on 3rd December and it is intended to have these Regulations in place by the Summer of 1994. These Regulations will be accompanied by an Approved Code of Practice (ACoP) which will be issued by the HSE. We also see the need for technical guidance on Fire and Explosion Hazard management and on Emergency Response, one way of taking this forward would be for guidance in specific areas to be prepared by the Industry Associations. The hierarchy of this is that the Regulations are at the top of the tree, then comes the Approved Code of Practice which gives practical guidance on the ways in which the safety goals set by the Regulations can be met, below this is the Technical Guidance and the various Standards that can be adopted, International, National, Industry (eg API standards) and internal company standards.

The Regulations make a number of requirements:-

- Regulation 5 (1) (a) The duty holder shall perform, and so far as is reasonably practicable, complete, and repeat as often as may be appropriate, a sufficient fire and explosion analysis in relation to the installation.
- Regulation 5 (3) In this regulation "fire and explosion analysis" means a process consisting of -
  (a) identification of the various events which could give rise to a major accident involving a fire or explosion;
  (b) evaluation of the likelihood and consequences of such events;
  (c) the identification of suitable arrangements to prevent, detect, control and mitigate the effect of major accidents referred to in (a), other than arrangements for evacuation escape and rescue of persons; and
  (d) establishment of suitable and sufficient performance standards in relation to such arrangements and the structures and plant they involve.
- Regulation 9(1) The duty holder shall make suitable and sufficient arrangements to prevent fire and explosion, including such arrangements to -
  (a) minimise quantities of hydrocarbons on the installation;
  (b) prevent the uncontrolled release of hydrocarbons;
  (c) prevent the accumulations of explosive atmospheres; and
  (d) prevent the leakage of flammable liquids;
  and to prevent their ignition.

The Regulations emphasise the need for an integrated approach to fire and explosion hazard management, with the priority being given to eliminating hazards by design, ie inherent safety, then prevention, minimisation, control and mitigation. The recommended approach in the Regulations is derived from the Safety Lifecycle approach developed for programmable electronic systems, whereby the overall safety requirements are determined as a result of the hazard and risk analysis, these requirements are allocated to the various safety systems. The performance standards for the various systems are therefore set by the hazard analysis.

Following the PFEER Regulations there will be the Management and Administration regulations, which it is planned to have in place by late 1994, and the Design and Construction Regulations which it is intended to have in place by Summer 1995. These Regulations will reform a large number of the existing prescriptive requirements which will be revoked. This will achieve a simplification and rationalisation of the existing legislation, and will complement the Safety Case Regulations by setting minimum standards applicable to all installations.

Application to Composites

The current Construction and Survey Regulations says very little about the use of composite materials. Part VI which deals with materials states: in paragraph 1 *"....All such material, so far as is consistent with its function, shall be incombustible."*, Paragraph 3 of this Section indicates that steel, concrete and aluminium should be selected from grades conforming to a recognised standard. For other structural materials it simply states that they should be suitable for use in a marine environment.

The guidance to these Regulations indicates for example that A and H rated fire walls should be constructed of steel or other equivalent material, and that all materials should be non-combustible. The guidance had extensive sections on steel, but virtually nothing on composite materials. With many composite materials failing the standard tests for combustibility, designers had the option therefore of going the safe conventional route and using steel based materials or preparing a fairly detailed justification for the use of composites, often with few generally acceptable standards to use as a basis and accepting the possibility that this justification would not be acceptable to the Regulator. With the tight timescale of many offshore projects it is not surprising that few designers were prepared to take that risk.

One of the criticisms of the Cullen Report of the old legislation was that it inhibited technological development. As a consequence, one of the objectives of the new legislation is to remove such artificial barriers to development, and I therefore believe that many new applications for alternative materials such as composites will be proposed in the future. UKOOA has developed a series of guidance documents on the use of composite materials offshore which will give potential users the basis for demonstrating that their proposed use is acceptable, I am sure that Chris Houghton who is speaking shortly will expand on this subject. I welcome such industry initiatives.

Norwegian Authorities' Perspectives on Composite Materials for Offshore Operations

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Introduction

The Norwegian Petroleum Directorate (NPD) is the governmental agency vested with the task to supervise the offshore licensees' performance regards regulatory compliance. The scope of the NPD supervision comprise the licensees' performance regards safety and working environment, as well as the management of the petroleum resources.

The petroleum activity offshore Norway started in the mid 60'ies, and fairly quickly a number of major oil and gas discoveries were made. The development in the 70–ies and 80–ies was characterised by huge, integrated installations, including the development and use of gravity base structures.

Towards the end of 1993, a total of approx. 5 billion tons oil equivalents (toe) has been produced, are being produced, or is decided to be produced. Future discoveries are combined with a relatively high uncertainty, with scenarios ranging from 3 to 12 billions toe additional discoveries for the entire Norwegian Continental Shelf. There is also a potential for enhanced recovery from existing or planned developments which may add approx. 0,5 billion toe to the above figures.

Future development scenarios are characterised by a high number of relatively small fields. The scenarios indicates as many as 200 – 300 developments within the next decades, against around 40 per today. This means that the majority of future developments will consist of relatively small fields with a marginal profitability. Based on today's technology, many of these field will not be profitable, unless there will be a significant increase in the oil price.

Norwegian offshore safety regime

Norwegian petroleum legislation emphasises the sharing of roles; the licensed companies to be fully responsible for prudent activities, and the authorities to supervise that the licensees comply with the given framework. The NPD has been greatly concerned that the regulations and the supervisory functions should fully reflect this basic principle. Hence, the NPD has gradually changed the profile of the supervisory function towards an increased focus on the internal control systems in the licensees' organisations.

The Norwegian offshore safety regime rests on the principle of self–regulation (Norwegian: "Internkontroll"). The main feature of this regime is the requirement for a systematic organisation of the internal management systems that shall ensure compliance with rules and regulations. It also implies that the NPD does not issue any kind of approvals concerning installations, equipment, components, personnel etc., neither directly, nor by delegation to a certifying body. The basic philosophy behind, is the perception that approvals imply a transfer of responsibility from the licensees to the authorities.

Safety regulations

The NPD has recently completed a major restructuring of the safety regulations pertaining to the offshore activities. The revision was deemed necessary mainly because the legislation during the initial period of the offshore petroleum activity had gradually developed into comprehensive, detailed instructions related to technical solutions, procedures etc. In view of the change in supervisory profile to approach the control systems rather than undertaking detailed inspections etc., the specific requirements in the regulations were an obvious anachronism. Besides appearing as a hindrance to the industry's need and wish to be innovative, it implied a transfer of responsibilities from the licensees to the authorities, thus conflicting with the basic principle in the regulatory regime.

The new regulations are, as far as practicable, expressed in terms of goal–setting requirements, i.e. they state the *purpose* of the requirement rather than specifying the technical solution. One significant effect of this type of regulations, is the freedom it offers the licensees to choose solutions which are optimal to the specific projects and compatible with corporate philosophies. In addition it promotes the search for new and cost–effective solutions.

Supervisory strategies

The NPD has paid great attention to the development of supervisory strategies and methodologies which reflect the basic principles in a regime based on self–regulation. The initial approach based on detailed inspection, approval of procedures, drawings and documents, etc., had the contrary effect, in the sense that it resulted in a transfer of responsibilities from the operator to the authorities.

The current strategy implies that the operators' self–regulation systems are evaluated by means of system audits and verifications. System audits are well planned and systematic examinations of the self–regulation systems in order to ensure that these have been established, complied with and maintained as specified. Verifications are spot checks which aim to ensure that the systems actually give the expected output.

This approach implies that the NPD does not give safety related approvals to the operating companies, neither for plans, nor for the use of installations, equipment or components. Again, the reason is that approval implies a transfer of responsibility. As a further consequence, the NPD's supervision does not make use of a certifying body, as such arrangements can be seen as a kind of delegation of approval authority.

A central tool in the NPD supervisory activities is the *consent system.* In brief, this system requires the operators to apply for an NPD consent prior to starting the activity at certain pre–defined milestones throughout the various phases in the field development, production phase and removal. Application for a consent shall contain a self declaration as to the status of the relevant parts of the self–regulation system, identified deviations between the planned activity and the pertaining legislation, the safety impact of such deviations, and a plan for the removal of or compensation for such deviation.

Based on this declaration, and with a view to previous experience with the company in question, the NPD will initiate the actions that are deemed necessary in order to remain confident with the company's capability of carrying out the activity in a satisfactory manner. A consent is activity oriented, i.e. it is concerned with the activity to be executed, hence not implying any kind of approval of installations, equipment etc.

The consent milestones have been carefully chosen as appropriate for the operators to review their accumulated experience with the project so far, and to assess the plans for the planned activity. Also, these milestones provide the authorities with the opportunity to have an impact on crucial decisions in the project development.

The potential for composite materials

From a Norwegian point of view, a continuous search for more cost–effective solutions are therefore highly needed. Use of composite materials for various applications may prove to be one important contribution to such a development. Substitution of steel with composite materials may have positive effects both with respect to investments and to operational costs. Concerning the investments, there is a close connection between the total weight and the cost of an offshore installation. Any contribution to weight reduction will therefore have an impact on the total investments. In the operational phase, the cost saving potential is obviously tied to the volume of maintenance.

There is, however, all reason to have a cautious attitude to the introduction of composite materials on offshore petroleum installations, both for technical and for safety reasons. In all human enterprise, technological improvements have been achieved by some degree of trial and error. The offshore industry, however, is to sensitive to serve as a experimental scene. Norwegian experience indicates that an typical offshore modification, e.g. changing of a piping system, can cost as much as ten times more than a similar operation in an onshore plant. In addition, the lay–out characteristics of an offshore installation imply certain accidental scenarios which can not be tolerated. Great concern must thereforebe paid to the methods and systems that shall assure the quality of composite materials for offshore application with regards to the physical properties. These include technical strength and durability as well as fire properties.

A great challenge is connected with testing and inspection. As conventional methods do not apply to composite materials, new methods will probably have to be developed. However, there will also be a need to change of attitudes towards reliance in quality assurance activities that ensure that a product will meet the required standard.

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An Engineering Documentation Scheme for GRP in the Oil Industry

by

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Presented at OMAE, June 1993, Glasgow, Scotland

ABSTRACT

The absence of adequate engineering documentation has been a major inhibition to the use of GRP in offshore oil industry projects. Increasing dialogue with Regulatory and Certifying Authorities has emphasised the importance of thorough performance based documentation in gaining their approval. This paper describes the work of the UKOOA FRP Workgroup (with collaboration from other industry groups) in developing a framework for common industry documents for the use of FRP materials offshore, initially focusing on piping applications. It is intended that these documents be submitted to ISO for future adoption as international standards. (A short postscript has been added at the end of the paper, to describe the progress since this paper was originally presented)

BACKGROUND

The use of glass reinforced plastics (GRP) on offshore installations in the UK Sector of the North Sea, requires that any documentation scheme must address the existing legislative requirements. Due account must be taken of the Offshore Installations (Construction and Survey) Regulations 1974 and of any guidance issued by the relevant Government Departments in support of the Regulations. In respect of materials of construction, the Regulations (Ref 1) stipulate that:

> "Every part of an offshore installation shall be composed of material which is suitable having regard to the nature of the forces and the environmental factors to which that part may be forseeably subjected. <u>All material, so far as is consistent with its function, shall be incombustible."</u>

In 1986, the Government supported Offshore Energy Technology Board, identified weight and cost savings as one of the priority areas for study. To this end they identified the use of lightweight materials (GRP and aluminium alloys) as a possible way of achieving substantial savings. As a result, a conceptual study was commissioned by the Offshore Supply Office of the U.K. Department of Energy. This study, published in 1987, supported the perception that the introduction of lightweight materials into the offshore oil industry could generate significant weight and cost savings, at a time when the advent of lower oil prices necessitated cost-effective engineering. More importantly, however, the Piper Alpha disaster in July 1988 demanded that safe engineering was a paramount requirement.

The offshore use of a combustible material such as GRP, need not conflict with the objectives of safe and cost effective engineering provided that relevant factors are taken into account when its use is proposed. This was recognised by the Department of Energy in 1988, when they wrote to industry bodies and the Certifying Authorities advising of their intent "to develop guidance on performance requirements for composite materials", emphasising the importance of fire safety. They also proposed the establishment of an ad-hoc working group of interested parties to provide input to the preparation of such guidance. This proactive stance was further reflected in the issue of the Fourth Edition of their Guidance Notes on Offshore Installation: Guidance of Design, Construction and Certification. Section 24 of the Notes covering "Materials other than steel or concrete", states that "non-combustible materials should be used except where any required property or use of a material precludes non-combustibility". Specific factors that need to be taken into account, when the use of GRP was proposed, were listed as follows:-

- Fire risk in the location of use and likely fire exposure (intensity and duration);
- Consequences of failure in fire (e.g. for pipes or tanks containing combustible liquids or gases, or structures supporting such);
- Fire endurance to provide the necessary fire integrity of the structure or piping system;
- Combustibility;
- Ignitability;
- Surface spread of flame;
- Emission of smoke and toxic combustion products, especially for applications within enclosed spaces likely to be occupied by personnel.

A UKOOA (United Kingdom Offshore Operators Association) Workgroup was formed in 1989, whose objective was to further the use of GRP materials offshore, especially in seawater piping applications. Against the above background, a meeting was convened, in London, in early 1992 by the UKOOA FRP (Fibre Reinforced Plastics) Workgroup. The selection of FRP rather than GRP in the Workgroup title, is to signify recognition that fibres of different types other than glass may be used where appropriate. This meeting was part of a continuing liaison between UKOOA and the Health and Safety Executive (HSE), who had taken over responsibilities for offshore safety matters from the Department of Energy. The meeting addressed:

a) the current level of industry knowledge on GRP piping applications and in particular a recent project in the Norwegian sector of the North Sea, where a successful programme of system development and testing had resulted in approval for the retrofit of GRE piping with a fire protective coating, as firewater system deluge piping, in place of carbon steel (Ref 2);

b) an action plan building on the Norwegian work,to permit wider approval of GRP use in the UK sector.

It was suggested that the use of "performance based materials selection" (PBMS) against appropriate application performance requirements reflected the goal-setting objective approach within safety assessments as recommended by the Cullen report, after the Piper Alpha disaster. This approach could permit exemption from SI 289, pending the

introduction of new legislation recommended by Cullen. The meeting agreed that a workgroup forum comprising HSE, Certifying Authorities (C.A's) and UKOOA should be established to pursue action plans. These plans included the listing of concerns and definition of documentation requirements for proposed applications, eg. a Code of Practice (later to be re-named, Guidelines).
What follows in this paper should be viewed in context of the above "background".

THE BENEFITS OF FRP OFFSHORE

The motivation within the North Sea offshore industry to obtain wider approval for the useof GRP materials, in particular piping, is linked to the historical problems that have been encountered with metallic materials in seawater service and the need to improve safety and cost efficiency in both existing producing fields and new projects.

The first generation of North Sea platforms used carbon steel, either bare, galvanised or internally lined with concrete for the range of seawater piping services from utility to cooling water and firewater systems. Although there are some cases of reasonable lifetime performance of carbon steel, the majority of experience has been that major maintenance costs have been incurred as a result of corrosion, mostly internal. In particular, firewater deluge systems have been prone to plugging of the deluge nozzles from corrosion product scales, often rendering these critical systems ineffective.

During the late 70's and early 80's, there was a major shift away from carbon steels to copper-nickel alloys (90/10 Cu-Ni) for seawater and other water service piping. On the whole this material has performed reasonably due to its inherent seawater corrosion resistance. However, over a number of years several limitations became apparent which in total have caused many operators to move towards high alloy stainless steels as an alternate. These were, velocity limitations, which necessitated the use of larger diameter piping sizes in design (with the associated weight and cost penalties), a history of localised erosion failures in continuous flowing service, despite the best efforts of designers to limit velocities below 3m/s in design, corrosion failures when used in produced water service and exposed to hot slightly acidic fluids often containing sulphides and a general susceptibility to mechanical damage during installation and in operation.

The mid 80's saw a move towards high alloy stainless steels, 22% Cr duplex, 25% Cr super-duplex and super austenitic 6% Mo grades. These materials, despite their significant cost and early availability problems have been used extensively throughout the North Sea. Their main advantage over copper-nickel is their high strength and effectively unlimited erosion resistance, which has permitted designers to reduce pipe diameters while retaining thin wall thicknesses (typically schedule 10S). However, these materials have also shown some limitations in use. One problem area has been the fabrication controls for welding of thin walled piping and another has been the recently reported crevice corrosion failures in threaded and flanged connections of 6% Mo grades, at service temperatures between 10-45 C, in as short a period as 8 months from the Norwegian Sector (Ref 3).

Many of the benefits of GRP are obvious in the context of the above background, i.e. a natural corrosion resistance to seawater and to a wide range of typically used chemicals offshore, over a temperature range which adequately covers that normally found offshore, with the possible exception of produced water systems.
The fabrication related benefits of light weight (i.e. ease of handling) and use of adhesive bonding instead of welding, thus minimizing "hot work", are especially important in the case of retrofit projects to existing offshore installations, where the offshore labour costs are usually the major project cost component.

Further less obvious benefits include, an erosion resistance high enough (typically in the range 5-10 m/s) to ensure equivalent pipe sizing with stainless steels, when taking account of overall process design limitations of pump sizing and acceptable system pressure losses, etc. (in the author's opinion there is still considerable conservatism in this area. Reliable flow loop testing and field experience indicates that velocities of 10 m/s and higher should cause no problem with due design consideration of cavitation and water hammer effects). Essentially "maintenance free" life-cycle operation should be achievable if properly designed, installed and with due care for its limited physical robustness in service.

All of the above benefits are in addition to the often cited material cost benefits. This aspect should be treated with caution for a number of reasons. Although GRP piping is unquestionably cheaper by a significant margin (from 0.5 to 0.2 times that of stainless steels and copper nickel, the larger the pipe diameter the bigger the saving), for complex piping systems offshore with large numbers of fittings, i.e. bends, elbows, tees and flanges etc, the overall installed cost benefit ratio is often reduced to a range of 0.5 to equivalent cost, again dependant on the system pipe sizes. For example, a cost comparison exercise for a piping system covering 1" to 3" diameters will show little to no cost saving over stainless steels, or even as recently reported from Norway, against titanium.
One would expect to show large fabrication manhour savings for GRP systems over all metals, however, with increasing use of cold bending technology, the cost advantage in small diameter ranges is also marginal. For size ranges above 3-4" diameter, significant savings can be expected, of the order of 50%, although this has not been well documented for any large North Sea projects to date. Other factors influencing fabrication cost savings will be the location (i.e. whether carried out on or offshore) and the degree of spool pre-fabrication possible to minimize site bonding.
A paper from J.D.Winkel of Phillips Petroleum Company Norway (Ref 4), also being presented at this conference, provides a detailed economic review of several GRP retrofit projects in the Ekofisk field over the last 4 years. One conclusion was that the project engineering design costs were too high due to lack of training, poor product standardization and a general lack of experience feedback from completed projects.
Another unfortunate trend in recent major North Sea projects, is that of design conservatism, two examples being the use of "heavy duty" flanges throughout and the use of electrically conductive piping for seawater systems, both of which reduce the economic benefits to the project. Although at this stage in the use of GRP offshore in the North Sea, a conservative design approach is understandable, the author hopes that the PBMS approach within the document suite under preparation, will allow designers to aim more confidently for "fitness-for- purpose".

All of the above comments regarding costs have been based upon the use of bare GRP piping. For critical applications, where extended fire endurance is a performance requirement (i.e. deluge systems), the use of GRP in conjunction with fire retardant coatings, such as intumescents, must be considered. It has been demonstrated under normal hydrocarbon and full scale jet fire tests (Ref 5), that this combination can provide a technically viable material alternative to metallic piping systems. In fact, it should be stated that some of the commonly used metallic materials for deluge systems have not been subjected to these rigorous proving tests, their performance capability has been "assumed". However, in relation to cost-effectiveness, the use of currently available fire retardant coatings with GRP has the effect of approximately doubling the material cost and therefore making the economics of a direct comparison on materials marginal for new projects. This area of application should continue to be attractive for offshore retrofits and promising industry sponsored research in Norway, evaluating "thin film" intumescents could result in improved "system" cost-effectiveness in the future.

In summary, significant cost benefits can be achieved with GRP piping systems, in both new development projects and particularly with offshore retrofit projects. However, it is not wise to generalise on the level of installed cost saving as this will vary with, location of installation (on or offshore), the degree of spool prefabrication, system complexity, system pipe sizes, the comparative metallic materials and current market costs and the level of design completeness and conservatism. Therefore, until the use of the material becomes more widespread, project specific lifecycle cost evaluations are recommended.

REVIEW OF CODES AND STANDARDS

The following is a brief review of the principal codes and Standards, currently in use, related to GRP piping applications in the marine, petrochemical and offshore industries. The three public domain Codes and Standards documents of most use in providing guidance for the use of GRP piping offshore are:

* OLF Recommended Guidelines on Specifications for Composite Piping Offshore, November 1991.
* IMO Guidelines for the Application of Plastic Pipes on Ships, Dec 1992.
* ASME B 31.3 Chemical Plant and Petroleum Refinery Piping.

(OLF is the Norwegian counterpart to UKOOA, and has had an established GRP Workgroup since the late 1980's).
The OLF document was written specifically for GRP piping applications on offshore platforms and represents an important first step in providing standardised engineering guidance for the use of GRP offshore. There are four main sections:

- Qualification Testing and Manufacturing Requirements
- Design of Piping Systems
- Handling, Storage and Installation
- Inspection, Maintenance and Repair

On the face of it this should provide sufficient guidance to meet the needs of the offshore oil industry. However, it was felt that the OLF document structure did not lend itself readily to adoption into an internationally accepted standards format, i.e. API or ISO, allowing ease of future revisions, nor did it use a performance based methodology allowing the user to demonstrate "fitness-for-purpose" to the Certifying Authorities. It was also considered that the important aspect of fire safety was inadequately covered. Despite the above comments, it was widely accepted and agreed that this document would be a major reference for the required suite of industry standard documents sought.

The IMO (International Maritime Organisation) document, aimed at shipboard applications, gives good guidance on the issues and concerns which need to be addressed but provides only limited detailed information about GRP piping design, procurement and installation. Most significantly it prescribes fire endurance requirements and means of demonstrating performance against three standard test procedures of increasing severity. These provide a necessary basis but may require modification before being applied to offshore structures.

The ASME Code, being written predominantly for metals, places the requirements for GRP (and other non-metallics) into a separate Chapter VII, thereby allowing exceptions to the corresponding paragraphs of the base code given in the previous chapters. The main areas addressed by the Code are the consideration of the different material properties, pressure design rules and bonding requirements. While the Code identifies many of the important issues and concerns there is little supportive guidance.

All the above documents make reference to National Standards/Specifications which provide the means of defining acceptance criteria, most of which cover component specifications. Significant references include:

API Spec 15LR Specifications for Low Pressure Fibreglass Line Pipe.
ASTM D 1599 Standard Test Method for Short Time Hydraulic Failure Pressure of Plastic Pipe, Tubing and Fittings.
ASTM D 2992 Standard practice for Obtaining Hydrostatic or Pressure Design Basis for "Fiberglass" (Glass-Fiber Reinforced Thermo-setting Resin) Pipe and Fittings.
ASTM D 2563 Standard Practice for Classifying Visual Defects in Glass-Reinforced Thermo-Setting Resin Pipe and Tube.
BS 5958 Control of Undesirable Static Electricity
ISO DP 5658 Reaction to Fire Test - Spread of Flame Test

One area not well addressed in the OLF, IMO and ASME documents is material anisotropy and its effect on stress analysis. A standard which provides a much greater depth of information about system design is BS 7159 "Design and Construction of Glass Reinforced Plastics (GRP) Piping Systems for Individual Plants or Sites". Of particular note are recommendations given for flexibility and stress analyses factors. As it stands BS 7159 is not immediately applicable for use within the offshore industry because it was written primarily for the chemical industry for applications up to 10 bar and where greater emphasis is placed on corrosion resistance than structural efficiency. Also the design qualification procedure is different to that in ASTM D2992, usually referenced by manufacturers supplying to the oil industry.

None of the above documents is sufficiently complete to meet the needs of the oil industry within their own right. All have some facet of information which is missing and very often redress must be made to more than one document. This introduces potential for conflict. For example the ASME bonding qualification tests requires that the test assembly should be subjected to a hydrostatic test pressure of four times the design pressure for not less than one hour with no leakage or separation of joints. This conflicts with some of the manufacturers' products which have been qualified according to API 15LR to meet the long term design basis requirement but which will leak at less than four times the design pressure (this has recently been drawn to the attention of the B31.3 review committee, and a revision is anticipated).

There are gaps still to be filled which are not well covered by the above documents. The most important are perceived to be:

(i) Lack of procurement specification of sufficient rigor to ensure all components and variants meet a defined specification.

(ii) Lack of guidelines for fire performance.

(iii) Uncertainties in definition of appropriate limits for less tangible design parameters such as erosion limits and water hammer effects.

PERFORMANCE BASED MATERIALS SELECTION

It is not the intention within this paper to repeat the content of another paper being presented at this conference (Ref 6). Rather, the intention here is to outline the concept of the PBMS approach within a total documentation framework and to demonstrate that this approach is compatible with the safe use of GRP (piping) offshore.

The documentation framework proposes three tiers of documents. Tier 1 is the Guidelines that has been drafted by the UKOOA FRP Workgroup in consultation with the Regulatory and Certifying Authorities. The scope of the Guidelines covers identification of factors that have to be addressed when engineering with FRP materials, while also defining what constitutes FRP. The Tier 2 documents are Specifications and Recommended Practices covering system performance requirements and their achievement through all project phases from design, procurement and construction, through to operations and maintenance to decommissioning. Tier 3 documents define standards and procedures for specific test methods.

The hierarchy of the documentation framework is illustrated in Figure 1, hence, the Tier 1 document, ie the Guidelines, is essentially philosophical in nature. It is the " what issues must be addressed" document. Tier 2 documents are application-specific and address "what performance is required and how do we get it?". The Tier 3 documents underpin the Tier 2 documents via the definition of standards and procedures by which attainment of the required performance is confirmed.

PBMS is at the heart of the documentation framework. This affords a common methodology in which material selection reflects true functional needs and keeps abreast of technological advances. Prescriptive approaches cannot keep pace with such advances, and designing with FRP by seeking "equivalence" to traditional (steel) options is technically ill-founded. The PBMS concept, described below, provides a means of establishing common performance bases from which technically equivalent competitor materials and designs may be assessed for safety and cost effectiveness.

The PBMS Concept

In the PBMS approach, acceptance of a material depends on demonstration that it (or the system constructed of it) complies with a performance specification, the requirements of which are based on an assessment of the functional requirements of the system but are material-independent. The aim of introducing the PBMS approach is not to promote GRP per se but to base selection on a material's technical merits and to avoid excluding fully satisfactory materials for arbitrary reasons.

The price of PBMS is better upfront definition of what is expected from systems - i.e. performance requirements - than may have been customary or necessary when material options were more limited. The prize, however, is improved quality or material performance arising from a quantified, standardised and auditable approach.

There are four key steps in implementing PBMS:

i) **Identify and document key functional needs**

These should be based on an assessment of all key aspects of a system's desired function during all operational phases. For example, for an off-shore firewater piping system both standby and emergency situations should be considered. In the emergency case, the fire exposure survival duration required should reflect the firefighting and abandonment philosophies of the installation, its layout, firewater system design and control, and the nature of credible fire insults (fire type, heat flux and duration).

ii) **Develop performance requirements to meet functional needs**

Performance requirements should provide a workable means of assessing whether a material or system is capable of achieving its intended function. the assessment may be made by test/measurement or, where adequate predictive analyses exist, by calculation.

Requirements for any particular performance feature may differ for different operational phases of the system under consideration. For example, firewater piping may be required to be leaktight during standby, but during emergency operation minor leakage is unimportant so long as design water delivery rates can be achieved.

The use of defined performance requirements will avoid the problem of carrying over into designs in new materials any feature of traditional designs which are incidental or arbitrary rather than functionally necessary.

iii) <u>Screen candidate materials for technical acceptability</u>

Simplification in screening methods should be sought so far as rigour is not compromised. For example, although predictive models are being developed for the fire response of even quite complex materials, at present performance requirements for fire resistance often still require testing, although in some cases samples may be substituted for full structures. In other examples compliance with a functional requirement may be demonstrated by a simplified material characterisation test, e.g. heat gain limitations to a structure may be assessed by thermal conductivity measurements on samples of fire protection materials and appropriate analysis. For established technologies sufficient data is often available to demonstrate compliance with defined performance requirements.

(iv) <u>Make final selection from technically acceptable options based on other criteria e.g. cost, availability</u>

Completion of steps i/ to iii/ above will ensure that final selection can be made based on commercial criteria from a short list of technically acceptable solutions.

To summarise, PBMS uses standardised acceptance tests or performance predictions to vet all candidate materials against performance requirements derived from an assessment of functional needs. The approach gives, and is seen to give, a "level playing field" for competitor options and improves the quality of the material selection and design processes, at the cost of improved design definition in a project's early stages. By contrast, traditional prescriptive approaches specify materials but do not necessarily ensure satisfactory performance.

From the foregoing it is argued that the PBMS approach is compatible with the Regulatory objective that the engineering design will comprise materials of construction that are consistent with their function.

THE UKOOA WORKGROUP APPROACH AND TIMETABLE

As a result of the meeting in February 1992 with the HSE and CA's, the UKOOA FRP Workgroup focused its resources on two main objectives, the preparation of Guidelines covering all offshore FRP applications and a piping specific suite of documents in the form of Specifications and Recommended Practices, underpinned by existing standard test methods. The latter objective also involved the consideration of a fire testing requirements for GRP piping. Underlying the whole activity was a "performance based material selection" approach that is compatible with a legislative regime that presumes the use of any material to be consistent with its function.

It was clearly understood from the beginning that any guidance documentation, either Specifications or Recommended Practices, to come out from the Workgroup would be submitted to an appropriate internationally recognized standards body for incorporation. This would ensure the widest possible use and value for any documents. Because of the strong links with API 15 Committee for Plastic Pipe through some of the active Workgroup member companies, this was considered initially, to be the most suitable body. However, further debate on this subject, including discussion with API 15 Committee representatives, concluded that ISO standards would be the preferred final format to ensure the widest use and acceptance.

The Guidelines

After some early debate it was decided to write the Guidelines to cover all FRP applications offshore, rather than restrict it to GRP materials or specific applications. It was also agreed that it was essential to gain a wider technical review and input than was available within the Workgroup members (who comprise materials engineers, composites specialists, piping engineers and general offshore project engineers).

A small sub-group was established to write an initial draft. Major source documents were the OLF Guidelines document, the IMO document (both referenced above), and a draft guidelines document (specific to piping) that had been prepared under contract for the Dept of Energy in late 1990, and made available to the Workgroup.

The Table of Contents is shown in Figure 2 and one of two appended summary guidance tables, modelled from the IMO document, in Figure 3.

From the preface, "The Guidelines identify factors which should be addressed when considering the application of FRP materials on offshore oil and gas facilities. The document is intended to be a common check list for design engineers, end users and approval authorities, to ensure that all relevant factors relating to specific applications of FRP in the offshore environment have been considered".

It is worth making the point that, following the PBMS approach, a large part of the Guidelines will be applicable to ALL materials evaluation, not just composites and therefore is of wider value to design engineers.

The initial timetable was to complete the Guidelines by 1st April, 1993. This timescale permitted more time for input from key industry groups such as the OLF GRP Workgroup, API 15 Committee and the Industry Advisory Group (IAG), established for the preparation of the piping related documentation suite (see below), as well as the Certifying Authorities and the HSE.

The 4th draft (14th April, 1993) was formally submitted to the HSE for their final review and endorsement in May, with the intention being to submit it to ISO along with the piping specific documentation suite in September 1993.

Industry Standard Documentation for GRP Piping Use Offshore

The second objective for the Workgroup was the preparation of industry standard documentation for piping. Although numerous specifications and other engineering documents have been developed for GRP piping, the development has been rather ad-hoc resulting in overlap and inconsistencies between documents.

The UKOOA members increasingly recognize the benefit of using industry standard

documents, thus minimizing their own in-house requirements and providing a common basis for the supply industry. GRP piping applications, predominantly for low to medium pressure seawater, cooling water and firewater services had been identified as an area where significant benefits could be obtained, working from the large body of information already in existence.
It was decided that the preparation of a suite of documents, which would address design, procurement, fabrication, operation and maintenance and could be adopted by an international standards body was the goal.
The planned approach involved the following stages:-

- Preparing an outline document structure and a preliminary bid document.
- Pre-qualify potential contractors to carry out the work and obtain budget quotations.
- Submit a request for funds and obtain UKOOA Council approval for the work.
- Obtain bids from pre-qualified companies and devise an auditable technical evaluation process.
- Establish a steering group from the UKOOA FRP Workgroup.
- Establish an Industry Advisory Group, comprising representatives from manufacturers, engineering design companies, GRP fabricators, Regulatory Authorities, Certifying Authorities and key researchers.
- Award a contract and complete the work on schedule and within budget.

The above process was commenced in July 1992, and in mid-November a contract was placed covering a project duration of eight months, commencing December 1992. To aid project control, the scope of work was divided into eight principal CTR's (the project schedule is shown in Figure 4).
The IAG established has 24 members and will meet three times at key stages in the project to provide technical input to and comments on the documents under preparation. At present, the work is proceeding to schedule with the first draft of the documentation suite issued for comment.
The document suite structure is following that proposed by the Workgroup, with five sections (intended to be stand alone documents) comprising:-

* Philosophy and Scope
* Procurement Specification
* Recommended Practice for Design
* Recommended Practice for Fabrication and Installation
* Recommended Practice for Operations and Maintenance

A third area that the Workgroup has been addressing over the last year, is that of fire testing requirements for FRP materials. A performance based strategy document is under development to provide guidance on the fire endurance properties that may be required dependant on the material application, its criticality to the facility and safety of personnel onboard, its location and the consequences of failure. The current version of the "decision flow chart" is shown in Figure 5.
The strategy may, after a full industry wide review, propose a number of standard fire tests (similar to the IMO approach) to allow qualification testing of components or systems against differing levels of hydrocarbon fire severity, up to and including jet fires.

THE FUTURE

The use of GRP or FRP has many other potential beneficial application areas besides low pressure piping. Some of the more important of these include:

* Fire and Blast Protection Panels and Enclosures
* Module Panels, i.e. living quarters
* Downhole Tubing
* Low Pressure Tanks and Vessels
* Caissons and Deep Water Risers
* Secondary structural applications, i.e walkways, ladders, access platforms and cable trays

The use of composites for fire and blast protection has attracted much attention in recent years and is fast becoming an accepted and often preferred material for this application. Ease of handling and its lightweight compared to metal based alternatives are the main reasons for this success. Most structures have been qualified for service by full scale testing. This is expensive and time consuming and further work is needed to qualify design procedures. This shortcoming is not specific to FRP, it also applies to metal based structures. Joint Industry Programmes such as Marinetech North West ("The Cost Effective Use of Fibre Reinforced Composites Offshore, Phases 1 and 2, 1988 - 93) and the Steel Construction Institute ("Blast and Fire Engineering Project for Topsides Structures, May 1990 and ongoing), can provide valuable input here.

A recently completed joint industry study managed by ODE and BMT ("Development of Guidelines for the Application of Fibre Reinforced Plastic Materials to Topsides and Superstructures in a Marine Environment, 1989 - 92") demonstrated how a complete module in GRP (on a portal steel frame) could be designed and built to meet previously prescribed load and fire performance criteria. This culminated in the issue of design guide engineering documentation. Although quite different in application, similar technology is being developed for use as subsea protection structures.

GRP downhole tubing has provided cost effective service for many years in North America and the Middle East as an alternative to corrosion resistant alloys. While it is reported to have been used offshore in the Gulf of Mexico its use offshore is restricted by the high design pressure and temperature usually encountered and high deviation angles at which there is no operational experience of GRP. Nevertheless there are opportunities where the reservoir shut-in pressure is or has diminished below about 3000 psi which makes the use of GRP tubing technically feasible. The challenge is to upgrade the technology to meet the higher temperature requirements likely to be more frequently encountered in the future. New developments taking place in Norway and USA is enabling thermoplastic line FRP tubing to be produced in a continuous length for use as subsea umbilicals and coiled tubing. This raises the possibility that similar technology, when applied to downhole production/injection tubing, could provide the benefit of reduced drag and increased reliability, particularly of value in extended reach drilling. Recent trials in the USA are reported to have demonstrated the capability of flexible drillpipe made from composites to drill small radius bends for re-entrant drilling applications.

GRP tanks have been in use for many years offshore but problems still arise. This is often due to poor identification of all design loads (eg lifting) and failure to identify/comply with a suitable design code. The use of BS4994:1987 ("Design and Construction of Vessels and Tanks in Reinforced Plastics") should ensure a sound basis for the design of tanks and vessels. One area of increasing interest, especially in Norway, is the proposed use of GRP for hydrocarbon separators.

GRP walkways, cable trays and access platforms have been used offshore particularly in the Gulf of Mexico. There are niche applications where the benefits of ease of handling, lightweight, low installation cost and corrosion resistance make the use of these attractive despite the material cost being more expensive than galvanised carbon steel. The main concern is fire and tests suggest that this material should not be used on primary escape routes where there is risk from hydrocarbon fire engulfment. A recent British Standard, BS 4592 Part 4, 1992, addresses the use of GRP's for flooring, walkways and stair treads. One area of particular benefit would be access walkways below steel jacket cellar deck levels, often exposed to storm wave action.

Looking much further ahead a potentially very attractive use of composites is as a production riser of a Deep Water Facility particularly at depths beyond 1500 m. Here the benefit is derived from the material's lightweight and high fatigue strain.

The above list is not exhaustive and work is in progress on other applications including subsea flowlines and topside process piping. However, the widespread use of many of these applications will be inhibited by a lack of structured industry standard design and fabrication documentation. We hope that the approach taken by the UKOOA FRP Workgroup will provide a "blueprint" that can be used to minimize the time frame required to develop the necessary documentation to permit future composite applications offshore.

POSTCRIPT

Since the content of this paper was reviewed at the 1st International Conference on the Use of Composites Offshore, in Houston, the following progress has been made.
In March 1994, at a special meeting in Aberdeen, Scotland, the Tier 1 Guidelines document and the Tier 2 piping specific documentation suite were formally issued to industry under the UKOOA cover. Also, the Fire Testing Strategy document was released for wider industry comment. Further, in September of 1994, the ISO TC67/SC6 Committee approved a new work programme to take the UKOOA "Specification and Recommneded Practices for GRP Piping Use Offshore" documentation suite and API 15LR and develop an ISO standard for GRP piping for use offshore. The target date for completion being December 1997.
(Note, figures 1,2,3 and 5 have been updated from the original paper).

ACKNOWLEDGEMENTS

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In particular, the author would like to acknowledge the direct contributions to the paper from his fellow UKOOA Workgroup members, Dr R.A.Connell of Shell UK Exploration & Production and Dr P.A.C.Medlicott of BP Engineering & Research.
Also the significant contributions to the Workgroup efforts in the last year of the following, J.Alkire and W.Cole of Amoco, Dr P.Boothby of British Gas, R.Watson of Chevron, I.Wattie and G.Walker of Conoco, J.Winkel of Phillips Petroleum Norway, J.Milnes of Shell and last but not least E.Provost of SIPM.

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GUIDANCE FOR FRP USE OFFSHORE

- **ENGINEERING DOCUMENTATION: 3 TIER SCHEME**

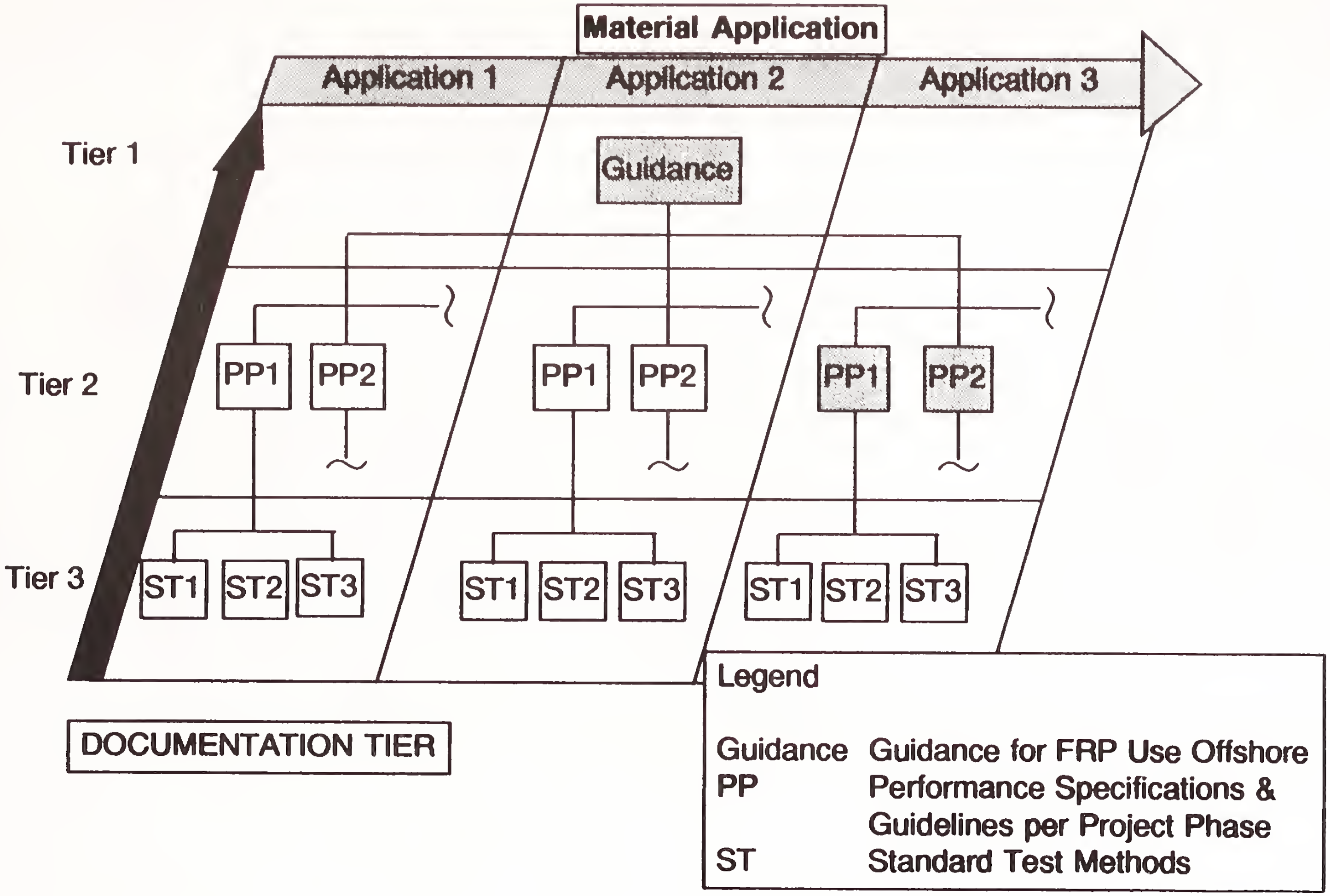


FIGURE 1

FIGURE 2

GUIDANCE FOR FRP USE OFFSHORE

- CONTENTS
  - Scope
  - Purpose
  - Philosophy
  - Component/system performance factors
  - Risk assessment
  - Component/system design
  - Manufacture and quality control
  - Handling, storage and transportation
  - Installation and testing
  - Operational requirements
  - Health and safety
  - Three tier engineering documentation scheme
  - FRP performance (structures/piping)
  - Fire testing logic diagram
  - Glossary

FIGURE 3

FRP Performance Parameters - Piping

Performance parameter	Service (a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
Pressure - internal	Y	Y	Y	Y	Y	Y	P	P	Y	Y
Pressure - external	Y	Y	N	Y	P	Y	N	N	Y	Y
Impact (1)	P	P	P	P	P	P	P	P	P	P
Thermal loads	N	Y	N	Y	Y	Y	N	N	P	Y
Blast overpressure	P	Y	N	Y	Y	Y	N	N	Y	P
Creep	P	Y	P	P	Y	Y	P	P	P	P
Bending loads	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Axial loads	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Buckling	P	P	P	Y	Y	Y	P	P	P	Y
Water hammer	Y	Y	P	Y	Y	P	N	N	P	Y
Fatigue	Y	Y	N	Y	N	P	N	N	Y	N
Erosion	Y	Y	N	Y	P	Y	N	N	N	P
Cavitation	Y	Y	N	Y	P	Y	N	N	P	Y
Abrasion	P	P	P	P	P	P	P	P	P	P
Temperature	P	Y	N	P	P	Y	P	P	P	N
Chemical resistance	Y	Y	Y(2)	P	P	Y	Y	Y	Y	P
Permeation	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
Environment	Y	Y	N	Y	Y	Y	Y	Y	Y	Y
Fire - endurance	P	Y	N	Y	Y	Y	N	N	P	P
- heat release	Y	Y	Y	P	P	Y	Y	Y	Y	P
Surface spread of flame	P	P	Y	P	P	P	P	P	P	P
Smoke - visibility	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
- toxicity	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Electrical conductivity	Y	Y	P	Y	Y	Y	P	P	P	Y

The above Table is only a guide. Performance parameters should be determined for all applications on a case by case basis.

Notes :

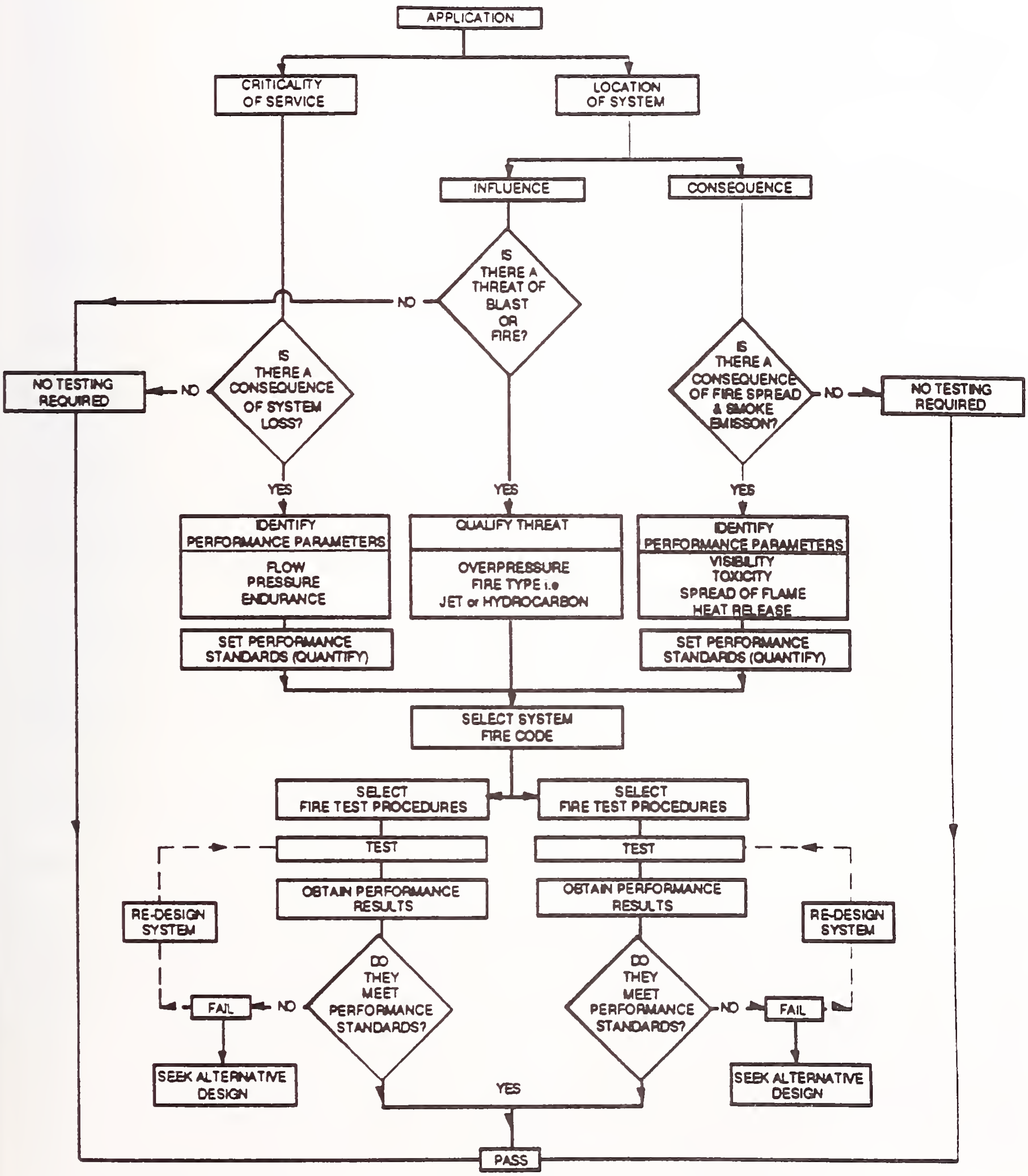
(a) Service water
(b) Cooling fluids
(c) Potable water
(d) Firewater - wet systems
(e) Firewater - dry systems
(f) Produced water
(g) Grey water (non-hazardous waste)
(h) Non-hazardous drains
(i) Chemical injection
(j) Ballast water

Y = Yes
N = No
P = Possible

(1) Impact to be considered if location/routing does not preclude impact.
(2) Water Research Council certification required

FIGURE 5

FIRE TESTING STRATEGY FOR FRP MATERIALS (DECISION FLOW CHART)



OLF'S INVOLVEMENT IN THE GRP INDUSTRY

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Introduction

OLF is the Norwegian Oil Industry Association. 22 oil companies, drilling companies and catering companies are members in this industry association which is the main negotiating party towards the authorities, unions and the rest of the society.

GRP Work Group

In 1990 a GRP work group was established under the Operations and Engineering committee in the OLF organization. The reason for establishing the work group was to propose a new GRP specification, because the existing Norwegian Standard was outdated. Representatives were nominated from Conoco, Elf, Hydro, Phillips, Saga, Shell and Statoil. All of these companies have major operations in Norway, and some are taking advantage of resources in the mother companies.

The Specification was completed in 1991, and normally a work group in the OLF organization should be discontinued when the job was done, however, several important issues had been raised during this period, and we were encouraged to continue the work. It was at a point of time considered if the work group should be upgraded to a sub-committee.

Following are some details on the most important issues which the work group has been involved in:

OLF GRP Specification

In some offshore petroleum projects undertaken in Norway, it had been necessary to undertake parallel detail engineering on the most competitive GRP pipe suppliers. This had been done in order to keep the competition until the contract was signed for the installation. In addition, the existing Norwegian Standard for GRP pipe and fittings was outdated, and needed to be updated. The work group drafted a scope of work, approval was made from OLF for spending some money, and the composite technology contractor AMAT A/S was awarded the contract for drafting The OLF Recommended Guidelines on Specification for Composite Piping Offshore. The GRP work group acted as a steering committee for the work.

The main objective of this document was to provide the member companies with guidelines for qualification testing, manufacturing, piping system design, installation, handling, storage and commissioning of glassfibre reinforced thermosetting plastic piping systems. The document was designed such that the chapters were independent. This would allow the producer, the designer, the fitter and the inspector/maintainer to concentrate on one chapter each. During the development of the document, the suppliers were informed about OLF's activity.

The document is being distributed free of charge on request upon contact to OLF, po. box 547, 4001 Stavanger, Norway, telephone +51 56 30 00, telefax +51 56 21 05 or telex 84 00 144.

Recently UKOOA established a document entitled "Specification and Recommended Practice for Use of GRP Piping Offshore". The document, which has used the OLF specification as one of the building blocks, will be recommended adopted by ISO and possibly API.

Training of GRP Fitters

In a study performed by Veritec and Veritas Research in 1992, it was found that unqualified GRP fitters have approximately 5 times more leakages per installed length of installed GRP systems as properly trained fitters. Because of the results of this analysis, OLF decided to upgrade the existing training for GRP system which is available in Norway. In light of this, OLF awarded a study to TI (The Norwegian Institute of Technology) in 1992 for improving their own training manual. TI is the organization which is undertaking most training of GRP fitters in Norway.

The work has been completed, and presently an improved training program is available to the industry.

Certification of GRP Fitters

In order to ensure a good quality in installed GRP systems, the requirement for a certification system for GRP fitters had been identified quite early. The work group has seen this as a natural follow-up after completion of the improvement of the GRP training program. Because TI is the main training institute in Norway, and also because of their involvement in certification of welders, a proposal was requested for establishment of a certification system for GRP fitters.

The GRP work group has made a request to the OLF management for funding the development of a certification system for GRP fitters on the budget for 1994.

Databank for GRP Installations

The GRP work group has proposed that a project for establishment of a database for installations on the Norwegian part of the North sea should be covered on the budget for 1994. The background for proposing the establishment of this database are several:

*for improvement of safety
*for avoiding same mistakes are experienced at several locations
*for improvement of technology transfer
*for accelerating incorporation of GRP components/systems
*for providing a status of what is going on in this area

Two potential contractors have submitted project proposals. In order to have a bigger population, the databank may be expanded to incorporate all of the North Sea.

Future Activities

The OLF work group is continuously evaluating other issues which may benefit the member companies. Some of the issues which are assumed to be covered in the future are:

*common inspection routines
*guidelines/specification for tanks and/or pressurized vessels
*adoption of the UKOOA specification
*more active cooperation with UKOOA

Conclusion

OLF's GRP work group has so far been involved in developing a GRP-specification and improved training for GRP fitters. It is our ambition to continue solving problems and concerns which prevent the incorporation of GRP systems safely and efficiently in the Norwegian offshore industry.

Acknowledgement

I wish to thank the OLF companies for sponsoring the work, and AMAT and TI for undertaking the projects in a professional manner. Finally I wish to thank R. Aarnes (Elf), J. Malmo/B. Moursund (Hydro), F. Thorstensen/J. Winkel (Phillips, H. Thon (Saga), H. Buvik (Shell) and E. Oren/B. Melve (Statoil) for participating in the work group.

4. Keynote Addresses

PETROLEUM E&P INDUSTRY PERSPECTIVE ON THE USE OF COMPOSITES IN OFFSHORE OPERATIONS

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Introduction

Carbon steel is the backbone of the offshore industry. The petroleum exploration and production (E&P) industry makes a large investment each year in steel structure, steel tubulars, steel pipe, steel vessels and many other steel products. However, carbon steel is susceptible to corrosion, a constant problem in the offshore environment. As a result, the E&P industry puts a great deal of effort into corrosion control. Large sums of money are spent for cathodic protection systems, for corrosion inhibitor systems, for inspection and for maintenance programs. Corrosion resistant alloys (CRA) are available for considerably higher initial costs and they are used in critical applications where corrosion cannot be tolerated. Corrosion control and CRA materials are active research areas supported by the E&P industry. Altogether, these corrosion related programs become a major factor in the cost of E&P operations.

Carbon steel is also a very heavy material of construction. The weight of steel piping and vessels, for example, are factors in the high costs associated with offshore construction. The weight of steel can be a limiting factor in the design of platforms for deep water operations.

There is little doubt that carbon steel will continue to be the back bone of offshore construction. However, the added costs related to corrosion and the limitations cited above indicate that there are opportunities for alternative materials. CRA materials will satisfy some of the needs, but installed stainless steel can cost 4 to 10 times more than carbon steel. So there is an economic incentive to seek alternatives.

In recent years the E&P industry has started to use composite materials on offshore platforms. FRP piping has been shown to be cost-effective and to have the performance characteristics needed for water service. FRP has also been used for secondary structure such as cable trays, walkways, railing and grating. FRP fire and blast resistant panels are becoming popular for new construction in the North Sea area.

The advanced composites industry has evaluated the feasibility of using high modulus fibers in several offshore applications with positive results. Feasibility work on advanced composite production risers, for example, has been in progress in France since 1980, and the results have been positive. Yet there are no advanced composite products in service today offshore, with the possible exception of a few prototypes that are still being evaluated.

The E&P industry certainly has interest in composites as alternative materials, yet the industry has been slow to accept them. This paper examines that acceptance issue and offers some suggestions for gaining improved acceptance in the future.

Industry Acceptance Of FRP Pipe for E&P Operations

The acceptance of composite materials by the E&P industry is best characterized if the technology is first divided into the following four categories: FRP line pipe, FRP downhole tubing, FRP process pipe and other applications for offshore platforms, and advanced composite products. Line pipe and downhole tubing are not offshore products, but the industry has a large experience base with those products that impacts the acceptance of composites for offshore applications.

FRP Line Pipe

The petroleum industry clearly has a need for corrosion resistant line pipe materials. Amoco has been using FRP line pipe for hydrocarbon gathering and transmission lines since 1983. Some of the other petroleum companies also make extensive use of FRP line pipe. FRP is normally used when the service conditions are corrosive and FRP is considered to be lower in cost over the life of the project than carbon steel or carbon steel with a corrosion inhibitor system.

At Amoco, we believe production costs can be reduced with the selective use of FRP and we continue to use these products. We believe, however, there are opportunities to improve industry acceptance of FRP line pipe in the following areas: (1) compliance with API specifications, (2) manufacturer's pressure ratings, (3) product quality, (4) quality of installations, and (5) long term reliability.

Amoco has been conducting long term strength tests (ASTM 2992) since 1985 to establish pressure ratings for commercial pipe products. The American Petroleum Institute (API) now provides purchase specifications (API 15HR & API 15LR) with standardized methods for establishing product pressure ratings, but some of the commercial products are not yet qualified to those standards. Some petroleum companies establish pressure ratings independent of the manufacturer's recommendations. Some companies continue to express concern for the long term reliability of FRP line pipe and use little of it, but Amoco continues to have confidence in these products.

FRP Downhole Tubing

Some of the most demanding corrosive environments are in downhole applications. In those environments, there is a clear need for corrosion resistant tubing materials such as FRP. Commercial FRP tubing products are available, and a few companies have used them successfully for years. Most companies, however, do not use FRP tubing extensively. The primary industry concerns are with difficulties in make-up/break-out, temperature resistance, long term strength with combined loading and long term reliability. FRP lined steel is a related product that eliminates some of the concerns and has been used in the oil patch for many years. API is currently working on the development of API 15TR, a purchase specification for FRP tubing.

Industry Acceptance of FRP Offshore

FRP Firewater Pipe

In 1989, Amoco Norway Oil Company (ANOC) started work on an operations problem with the deluge firewater system on its offshore platform Valhall.[1] Deluge firewater systems are used for fire protection on the wellhead and process areas of offshore platforms. Most of the piping in these systems is dry with open spray nozzles and sprinkler heads. Several miles of 2" to 8" carbon steel pipe are used for these systems on a typical platform. Deluge systems are tested periodically. Residual seawater from system tests and the hostile offshore environment causes internal corrosion of the carbon steel pipe and subsequent blocking of the spray nozzles and sprinkler heads. An extensive maintenance program was instituted for system clean-outs to keep the Valhall system operational.

ANOC facility engineers considered several options for restoring the Valhall system including more extensive maintenance programs, replacement with corrosion resistant alloys (CRA), or replacement with titanium. Alloy steels have been used for deluge systems on newer platforms.[2] Because of the Amoco experience base with FRP line pipe, the ANOC facility engineers also considered using insulated FRP pipe. A preliminary life-cycle cost analysis showed FRP to be an attractive option.

At that time the Norwegian Petroleum Directorate (NPD) regulations restricted the use of non-metallic materials in offshore safety systems. ANOC solicited the advice of AMAT, a Norwegian engineering firm having experience both with composite materials and offshore operations. Together they met with NPD in January 1990 to explore the use of FRP in the Valhall firewater system. Based on that dialogue the following requirements were identified to demonstrate the safety of FRP in firewater systems: a risk assessment study to establish acceptance criteria, fire survivability tests of insulated FRP to demonstrate performance, detailed specifications to define product requirements and a quality control program to assure compliance.

A project team was organized and a plan was generated to address each of the tasks. ANOC sponsored the early work. Technica did the risk assessment study. AMAT undertook the product development work, the pool fire tests and the development of a specification. SINTEF did the jet fire tests. Various insulation systems were evaluated with commercial FRP pipe products. The NPD was consulted and informed of the progress throughout the program. Early results were promising and other operators expressed interest in the project. Conoco Norway, Norske Shell and Statoil joined the program as co-sponsors. The project team completed all the tasks in less than two years. An extensive test program demonstrated that insulated FRP pipe can function in an environment of explosions, hydrocarbon pool fires and jet fires. The program was concluded with a 300 meter pilot installation on Valhall that was completed in December 1991.

FRP Process Pipe and Other Applications

The Valhall program has been a catalyst for several additional activities in 1993 related to the use of FRP pipe on offshore platforms. Amoco installed FRP firewater systems on two new platforms, one in the Netherlands sector and one off Trinidad. Amoco has also installed FRP piping on Valhall for a filtration system and for a drainage system. Other operators are also installing or are planning to install FRP piping systems on their platforms.

There are many active research programs in Norway and the UK that are developing the technology needed for further use of composites offshore. SINTEF SI and Marinetech Research, for example, both have large programs working on topics related to composites offshore. There is little doubt that industry acceptance of composites is developing quickly in the North Sea area. UKOOA is working with HSE to gain approval for FRP pipe systems on platforms in the UK sector. The UKOOA GRP work group initiated work with ODE/AEA to draft a specification for FRP process pipe offshore in January 1993. That specification has been completed and will issue in November 1993.

Industry Acceptance of Advanced Composites

The offshore E&P industry is complex and it has depended on innovations in many different technical areas to achieve the offshore capabilities that exist today. The E&P industry has interest in advanced composites materials as well. There are needs for alternative materials that are high strength, light weight and corrosion resistant. Advanced composites, those systems that use high modulus fibers such as carbon or aramid, have been considered for production risers (and tethers) for floating platforms, coiled tubing, drill pipe and subsea flowlines. Note that these are all primary systems with demanding performance criteria and the consequence of failure is very high for some of them.

IFP/Aerospatiale started development work on production risers nearly 15 years ago.[3] Composite tubes with carbon and glass fiber have been evaluated in offshore environments with positive results. However, very little has happened with composite production risers in recent years. Brunswick Composites attempted this year to organize a JIP for further development of composite production risers, but they have not yet found a sufficient number of subscribers. There is substantial interest in the coiled tubing application. The team of Hydril and MMFG was successful in organizing a JIP for the development of composite coiled tubing using carbon and S2 glass fibers. Conoco is also actively working on a composite coiled tubing product. Conoco has evaluated several advanced composite applications for offshore operations.[4] Still, there are no advanced composites products in service offshore nor are there any commercial products available as we approach the end of 1993.

Building Industry Acceptance of FRP and Advanced Composites

So what is needed to build industry acceptance of these materials? We need to be sensitive to current trends in technology management, we need to understand the key elements in the success of the Valhall firewater program, and we need to follow the example of successful efforts in the North Sea area.

E&P companies are starting to put more effort into the management of the technology development and application process. The focus of E&P industry technology programs is changing from technical discipline to business need. There is more emphasis today on determining the value of new technology elements. In the future, technology programs will be prioritized for funding on the basis of potential value to the business units.

Composites development efforts need to focus first on industry needs to identify the real opportunities for composites. Then, opportunities need to be quantified so the value of the technology is established for specific applications. As champions of the technology we believe that composites can reduce the cost of production. Too often, though, we don't really know to what extent composites can reduce the cost of production. Our focus has been on the technology and the value of that technology for specific applications has not yet been determined. If high value is demonstrated, then the priority for composites projects will also be high and industry acceptance will occur naturally as product performance is demonstrated during the technology development and delivery process.

The Valhall program demonstrated the importance of approaching the development of composites applications with a team. A key element in the success of that program was the involvement of the regulatory agency, the offshore engineering community, the manufacturers and several of the petroleum companies. Also, Valhall was far more than a technology demonstration or a product development program. All of the following important issues were addressed during that short program: life-cycle economics, safety, environmental impact, performance criteria, performance verification, source of supply, purchase specifications, quality assurance programs (manufacturing and installation), consent by NPD and a pilot installation. So the work scopes for applications development programs need to be broad as well as being thorough in the development of the supporting technology. The Valhall program also demonstrates the advantages of performance based specifications for products and materials as opposed to prescriptive based specifications.[5]

Perhaps the most important lesson to be learned from recent events in the North Sea area is the importance of having operator's organizations. The productivity of the OLF and UKOOA organizations together with supporting research from organizations such as Marinetech Research and SINTEF SI are very impressive. The US operators need to find a way to organize their efforts in similar fashion.

Summary

The US petroleum companies must assess needs and opportunities on an industry wide basis. Some of the product development programs will be costly yet they will benefit the industry as a whole. It is best to conduct these programs on a joint industry basis. Technology gaps will be identified. The subsequent R&D programs need to be coordinated and funded on a JIP basis. Finally, the regulatory agencies need to be involved and we need a mechanism for on-going communication with MMS and the Coast Guard.

We need to form an organization that can pull together an alliance of the E&P and supporting industries, the composites industries, the research community and government agencies that are affected by offshore operations. We need that organization to facilitate and provide momentum, focus and direction to JIP programs. And, we need to focus on the development of composites applications that will meet industry needs.

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PETROLEUM INDUSTRY APPLICATIONS OF COMPOSITES IN E&P OPERATIONS

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INTRODUCTION

The use of composite materials in the petroleum industry offers many attractive opportunities to reduce cost and improve performance while maintaining or even improving safety and environmental standards. Production from deep water (over 2000-feet) petroleum reservoirs in the North Sea, west coast of Africa and Gulf of Mexico is expected to become an important source for new development in the twenty-first century. Composite components could help accelerate production from deep water by providing solutions which are both practical and economical. Production in deep water is significantly more difficult and expensive than production onshore or from shallow waters closer to shore and system weight and performance become more important factors. Although weight savings and corrosion resistance are the primary drivers to use composites, the most important factor to encourage wide spread use of composites in the oil industry will be establishment of a clear economic advantage of employing composites versus using traditional materials.

Historically, composite products constructed of glass fiber reinforced plastic (GRP) have been used in onshore oil and gas operations for over 30-years (ref. 1). Early applications included storage tanks and low pressure pipes requiring very little sophisticated technology. In recent years, onshore applications have grown and GRP is used extensively for flow lines, water injection lines, and tubing (ref. 2). Fiberglass product manufacturers have used advanced materials and design methods developed for aerospace and industrial applications to improve their products. As a consequence, the performance and reliability of fiberglass based components have improved significantly and a host of new applications have emerged including high pressure pipes and advanced couplings.

Recent advancements in understanding of fire safety issues (ref. 3) and development of detailed design specifications (ref. 4) have overcome barriers to the use of GRP components on offshore platforms. Consequently, there is high interest in using GRP in new offshore projects and in refurbishment of old facilities. Most recent offshore applications have focused on using GRP pipe for the transport of low pressure water including cooling water, injection water, produced water and for fire water systems.

The expanded interest in the use of composites for offshore operations began around 1986 with a joint industry program focused on fiberglass applications conducted by Center for Industrial Research (ref. 5) and another joint industry program on composite risers conducted by Institut Francais du Petrole and Aerospatiale (ref. 6). In recent years, most major oil companies have hired or reassigned personnel to guide the development of composites for oil industry applications. In addition, major oil companies have sponsored R&D programs investigating composite applications and several workshops on composites with offshore focus have been held including those listed below.

WORKSHOPS FOCUSED ON COMPOSITE APPLICATIONS FOR OIL INDUSTRY

- AMAT/NPD, Norway - 1989, 1990, 1992
- National Research Counsel, Washington - 1990
- MIT Sea Grant, Cambridge - 1991
- Marine Composites, London - 1991
- Maritime/Offshore Uses, New Castle - 1992
- University Of Houston - 1991, 1993

The oil industry represents a significant untapped market for composite applications and the advantages and opportunities are just beginning to be recognized within the oil and composites industries. The support by government funds in the United States and Europe has done much to accelerate the pace of development and significant benefits can be expected in the future.

COMPOSITE MATERIAL ADVANTAGES IN PETROLEUM APPLICATIONS

The primary motivation to use composite products by the petroleum industry is to reduce maintenance costs in production operations and to improve the capability to economically drill and produce oil and gas, particularly from the difficult challenges of deep water (ref. 7). The assets of composite materials which are particularly attractive for oil industry applications include corrosion resistance, reduced-weight, long fatigue life, and the ability to tailor properties to meet unique design requirements.

The corrosion resistance of composites is the primary reason for the rapid growth of GRP pipe and other composite components in recent years. In addition, GRP can provide a positive environmental impact by reducing the need for chemical corrosion inhibitors. High performance requirements demonstrated in fire safety tests and backed by rigid standards has also permitted GRP to be used in safety critical applications such as fire water delivery pipe.

The weight savings potential using composites can be significant since the density ratio of steel to composites is approximately five. Most applications can easily show a direct 50 percent weight savings. As was found for aerospace applications, the maximum benefits of using composites, however, will only be achieved when the weight savings are synergistically additive, not on a direct replacement basis. For example, the weight saved in using a composite riser on a Tension Leg Platform (TLP) reduces the weight of hull needed to provide buoyancy which in turn reduces the size of the tendon needed, etc. If the platform already exists, the only benefit of replacing the riser with composites would be increased payload to counter the weight of unexpected production and equipment upgrades.

For high performance applications, particularly offshore, advanced composite materials including carbon and Kevlar® fibers are being given serious consideration. The higher cost of these materials compared to steel, however, makes the benefit/cost ratio more difficult to justify. Technologically, advanced composites can be shown to have high promise for deep water offshore platform applications where reducing weight is important and for downhole components where composite property tailoring provides enabling capabilities unavailable using metal designs. For example, coiled tubing has very demanding requirements in which steel products are being extended to the limit of performance capability while composites promise to extend the needed operating parameters to operate at higher pressures and to extend further into extended reach well bore holes (ref. 8).

COMPOSITES TECHNOLOGY DEVELOPMENT NEEDED

As noted above, the primary motivating factors to use composites in the oil industry are to save cost and provide new enabling capability. In most cases the cost and performance comparison is with steel for which there is a long established experience base including readily available material suppliers and fabricators, detailed materials data base, refined design guidelines and standards, design experience, and operator familiarity. A similar state of readiness must be established before composites will be fully embraced by the industry on a purely "fit for purpose" economically competitive basis.

Several technology deficiencies were identified at the "National Conference On The Use of Composite Materials in Load Bearing Marine Structures" sponsored by the National Research Council (ref. 9). One of the recommendations from the conference was that a collaborative marine-aerospace-automotive industry effort be launched to address specific analysis and design issues peculiar to the marine application of composite structure. Better understanding of structural mechanics issues, it was felt, would help provide greater confidence to use composites and encourage future commitments to promising application opportunities. Important materials and composite structural mechanics issues recommended for development to support marine and offshore applications included: development of design procedures specific to marine and offshore application requirements, basic material performance in the marine and oil production environment, improved tubular join design, damage tolerance criteria, Non Destructive Test (NDT) methods to assure quality and assess damage, repair procedures, analysis of thick-walled structures, understanding of large deformation responses, improved analysis and test methods to predict failure, and innovative design concepts to provide cost-effective solutions to marine environment problems.

Specific components such as a riser, tether or drill pipe have primarily been developed by aerospace companies seeking to explore new business opportunities. In some cases such R&D efforts have been conducted over long periods of time (as long as a decade) without resulting in actual field implementation. The slow pace of progress from R&D into field service for high-tech applications such as a composite riser discourages commitment to new development. At current oil prices, oil companies are hesitant to make major commitments to production in deep water which means the market for beneficial composite products is uncertain. Another significant reason for the slow pace of applying promising new composites technology is a lack of experience in composite materials by project engineers in the oil companies and by design engineers in the oil service companies. Design tools and training focused on the oil industry are needed to bridge the gap and make the transition to a "fit for purpose" design philosophy in which all materials including steel and composites are evaluated on the basis of performance and cost.

Although a strong foundation in composites has been developed for aerospace and automotive applications, it can not be assumed that this technology is sufficient in all cases to meet the needs of oil industry applications. The application of composites in the oil industry provides significant opportunity for the development of challenging new technology, while at the same time sufficient technology is currently available for near term applications to be on a firm foundation.

OPPORTUNITIES TO USE COMPOSITES

Applications for composites in the offshore oil industry may be listed under four broad categories: (1) Facilities, (2) Platform Structures, (3) Pipe Lines and Subsea Equipment, and

(4) Downhole.

Facilities include the equipment needed on the platform to support the production of oil and gas including the equipment used to separate the produced fluids and gas and treat and remove water. Facilities thus includes pipes and tanks, and in a broader sense also includes the supporting elements of the platform from the fire protection system to walkways and living quarters. The platform structure includes the deck and columns and structural elements which tie the platform to the sea bed. For a Tension Leg Platform (TLP), the platform structure would include the tethers and foundation template.

Circular pipe is the most common structural form used in the petroleum industry. Steel pipe is used extensively in exploration and production operations to carry oil, gas, and water and as a structural form for actual construction of the platform. Specific applications include flow lines, water injection lines, tubing, casing, subsea control lines, drill pipe and many other uses. Welding and threaded joints are the two primary methods of joining steel pipes. Pipe has very demanding performance requirements including high pressure and the associated need for reliability to protect personnel, equipment, and the environment.

Composite materials are also receiving attention in the oil and marine industries for their nonstructural assets including enhanced safety and reduced environmental impact. For example, from a safety perspective, firewater piping has been widely accepted as equivalent or better than steel products. The difficulty of using steel is that the products of corrosion may clog the deluge nozzles which makes necessary frequent operational safety checks. Numerous fire resistant materials have been made available in recent years (many as spin off from aerospace programs) including advanced phenolic resins and intumescent coating. Comprehensive testing in the U.S., U.K. and Norway in recent years has done much to advance the understanding of the fire safety of composite materials and to develop safety standards. OLF (Norway) and UKOOA (United Kingdom Oil Operators Association) have made major contributions to the development of standards for composite applications (ref. 4) and the technology being developed is rapidly extending across international boundaries including into the United States. The environment may also benefit from the use of composite pipes in offshore operations by reducing the need for corrosion inhibitors and paints applied to protect steel components. Much work, however, still needs to be done in the important area of safety and environmental impact.

A white paper describing the need for the development of composites technology for oil industry application was recently submitted to the National Institute of Standards and Technology (ref. 10). Table 1 taken from this paper describes a rough estimate of the quantity and market value of projected utilization of selected composite components during the next ten years. It should be recognized in this scenario that the development cycle for an offshore platform takes at least five to ten years from discovery to first oil. Some of the primary structure components such as the composite tether will thus not be used in quantity until the out years of this period. The long lead time, in fact, is part of the risk factor which inhibits oil companies from committing to composites and is a primary reason for the need for industry supported development and demonstration programs.

The 184-million pounds of composite weight utilization forecast in Table 1 includes composites constructed of carbon, Kevlar® and glass fibers. Stiffness constraints which govern the design of some of the components such as the tether drive the design toward the use of carbon fiber while other components such as facilities which have less demanding structural requirements normally use glass fibers based on lower cost. If one assumes that half the projected weight is for fiber and half the fiber weight is carbon, the carbon fiber consumption in the 10-year period would be 46-million pounds. Compared with the current carbon fiber annual production rate of approximately 18-million pounds, this is a significant quantity. 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 $2.9 billion value forecast in Table 1 for composite components is based on offshore needs including subsea, but does not include additional expected onshore utilization of new composites technology.

Before the forecasts of Table 1 become reality, the oil industry must be convinced that a similar or greater level of cost benefit would occur in E&P operations by adopting composites technology. Although it is a conservative industry, the oil industry rapidly adopts new technology when it is clearly profitable to do so.

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TABLE 1.- OFFSHORE OIL INDUSTRY COMPOSITE APPLICATIONS, ESTIMATED POTENTIAL USAGE AND VALUE IN NEXT TEN YEARS.

Composite Component	Quantity	Composite Weight, Million lb	Component Cost, Million $
Tether	Six TLP's	15	430
Riser	in 3000-ft water	9	180
Tubing Inside Riser	16 tethers, 40 risers per TLP	6	90
Spoolable Pipe	20-million ft 1"-4"	20	300
Drill Pipe	0.5 million ft	25	450
Drilling Riser	0.1 million ft	1	25
Subsea Structure		5	70
Subsea Pipe Line	3000 miles	30	480
Mooring Rope	12 Floating Production Storage Facilities	3	60
GRP Facilities		20	200
Platform Structure		50	600
	TOTAL	184	2,885

COMPOSITE MATERIALS FOR OFFSHORE OPERATIONS

INDUSTRY PERSPECTIVE

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Introduction

Composite materials based on fiber-reinforced resins are not new. Applications abound where high strength, light weight and corrosion resistance are needed in the products we use. Examples from familiar industries listed below range from commonplace to exotic:

- Oilfield (Line pipe, Downhole Tubing, Sucker Rods)
- Industrial (Pipe, Tanks, Stacks, Process Equipment)
- Marine (Boat Hulls, Masts, Pipe)
- Automotive (Drive Shafts, Springs, Body Panels)
- Aerospace (Aircraft Floor Panels, Cargo Liners, Spacecraft, Voyager Aircraft)
- Armaments (Rocket Motor Cases)
- Transportation (Passenger Rail Cars, Trailers)
- Construction (Structural Shapes, Poles, Grating)
- Medical (Artificial Limbs, Braces)
- Recreation (Golf Clubs, Tennis Racquets, Fishing Poles, Skis, Canoes)
- Consumer (Furniture, Appliances, Computer Cases)

These applications developed during the past 40 years. There is every reason to expect that new services will be found in the future. Ameron's fiberglass pipe business has grown at a 15 percent compound rate for the past 30 years, and the future still looks bright.

Offshore oil operations can benefit greatly from use of composites. Elimination of corrosion and weight reduction are primary advantages. Life cycle costs can be substantially lower than competing materials, as illustrated below. Those of us representing the Composites industry must demonstrate that our products are predictable and reliable. The Oil and Gas industry must be willing to embrace new technology. And, together we must work with the regulatory agencies to ensure fire safety.

Materials

At risk of oversimplifying, the properties of any composite can be characterized in terms of a resin matrix that imparts corrosion resistance, and one or more reinforcing materials, usually in fiber form, that provide strength and stiffness.

Setting aside for now the possible future use of *thermoplastic* composites, the primary resin systems currently in use fall into one of three categories, as shown in Table 1. All are *thermosets*, meaning they crosslink during polymerization and do not melt at elevated temperature.

TABLE 1 - TYPICAL RESIN PROPERTIES				
	Tensile Strength (ksi)	Tensile Modulus (psi/10^6)	Elongation at Rupture (%)	Degeneration Temperature (°F)
Epoxy	12	.5	5	500
Polyester	10	.4	5	400
Phenolic	7	.8	2	1000

It should be noted that within each category, there are wide variations in properties depending on specific polymer and cure system. Chemical resistance also varies widely; but, generally, polyesters are best in acids, epoxies are best in bases, and phenolics are best in solvents. Resin system cost is generally as tabulated from epoxies as most expensive to phenolics as least expensive; but again, there are variations within each category.

Typical properties of common fibers are listed in Table 2.

TABLE 2 - TYPICAL FIBER PROPERTIES			
	Tensile Strength (ksi)	Tensile Modulus (psi/10^6)	Elongation at Rupture (%)
E Glass	500	10.5	4.8
S Glass	665	12.4	5.7
High Strength Carbon	560	33	1.6
High Modulus Carbon	420	52	0.8
Aramid (Kevlar 49)	525	12	4.4

An optimum structure generally results when the least cost fiber per unit of tensile modulus is selected. For commercial composites, E Glass is by far the most common. Only where weight savings are exceedingly valuable can other, more expensive, fibers be justified. It should be noted, however, that the cost of carbon fiber is falling with increasing use; and, its conductive nature is indispensable in some applications. Fibers can be supplied as continuous roving, or in a variety of mats and cloths depending on the processing needs of the fabrication.

Advantages

Even for one resin/fiber combination, there exists a wide range of final properties depending on fiber orientation in each layer of the composite. This defines an important advantage, in that material properties can be tailored to fit the individual needs of the application. For the composite product manufacturer and user, this implies a duty to understand application conditions, and to carefully control each step in fabrication of the finished item. A thorough qualification test procedure on prototype products, agreed to in advance between supplier and user, is essential.

Most composite materials which are reinforced with glass fibers (as opposed to carbon or other high modulus fibers) are somewhat more flexible than the metallic materials they replace. Careful design can turn this to advantage. For example, steel pipe subject to temperature variations in service must be provided with expansion joints or loops to relieve internal stresses. Fiberglass pipe, on the other hand, can be locked into supports. The lower modulus of elasticity prevents excessive axial loads due to temperature changes and results in much lower pressure surges on deluge pump startup.

Weight savings in excess of 50% can be realized using glass-reinforced composites. Larger savings are possible with carbon fiber. Advantages of composites are summarized in Table 3.

TABLE 3 - PERFORMANCE ADVANTAGES OF COMPOSITE MATERIALS
• Tailored Material Properties
• Weight Reduction
• Corrosion Resistance
• High Strength
• Improved Fatigue Resistance

These advantages can result in major cost savings.

Cost Comparison

Installed cost data for offshore piping systems have been published recently. The cost comparison of Table 4 represents a fire water system on an Elf Aquitaine platform in the Congo.[1]

TABLE 4 - INSTALLED COST RATIOS FOR REPLACEMENT OF OFFSHORE FIRE SERVICE PIPING SYSTEM

Material	Cost Ratio
Carbon Steel	1.00
Epoxy GRP	1.10
Stainless Steel	1.55
Cu/Ni 90-10	1.80
High Moly Alloy	3.70

Table 5, also taken from Reference 1 gives cost comparisons from real case situations in the North Sea.

TABLE 5 - NORTH SEA PLATFORM PIPING REPLACEMENT COST	
Case	Reduction in Installed Cost
8" produced water, Carbon steel replaced with GRP	60%
30" sea water pipeline, Carbon steel replaced with GRP	65%
10-24" filter package for water injection High Moly stainless compared to GRP	85%

TABLE 6 - INSTALLED COST RATIOS FOR PIPE IN CORROSIVE SERVICE		
	Cost Ratio	
	4" Diameter	12" Diameter
Polyester GRP	1.00	1.00
Type 304L Stainless	1.41	1.24
Type 316L Stainless	1.58	1.38

The installed cost ratios of Table 6 are taken from Reference 2. They represent conditions typically found in corrosive services within the chemical process industry.

Figure 1 shows installed cost in dollars per foot for several alternate materials proposed for yard installation of a fire service system destined for the Gulf of Mexico (Amoco Immortelle Platform). The interesting item here relates to costs for application of intumescent coating for enhanced fire resistance.

Tables 4, 5, 6 and Figure 1 suggest the following conclusions regarding costs:

- Composite materials compete even more favorably in offshore structures than in land based installations. This is particularly true in cases where replacement is required on an operating platform.

- Harsh working conditions, as in the North Sea, further enhance the cost benefits of composites because of light weight and easier joining methods.

- Even when fire protective coatings are required on composites, the installed cost can be less than metallic materials of equal corrosion resistance.

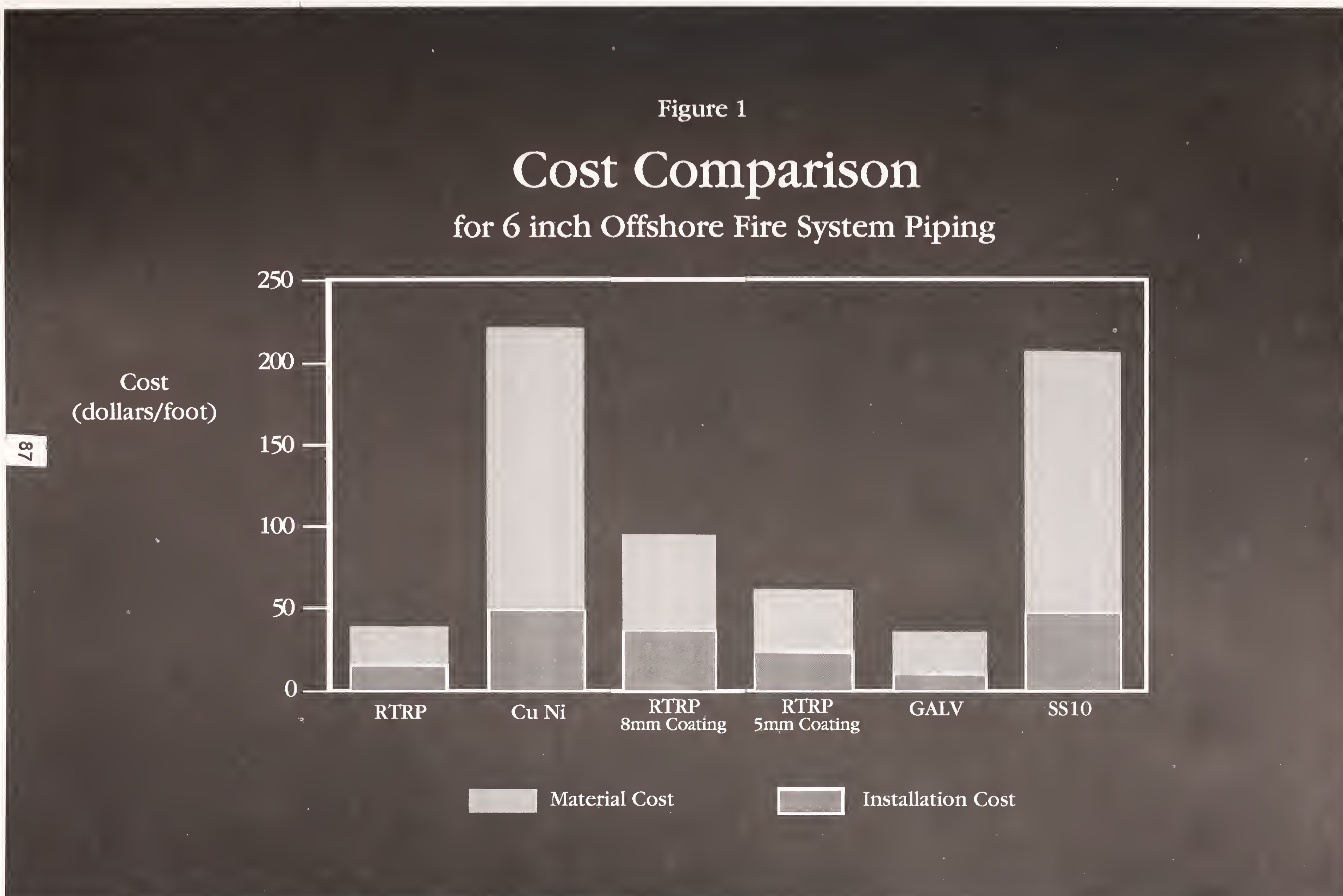
Figure 1
Cost Comparison
for 6 inch Offshore Fire System Piping
Cost (dollars/foot)
250
200
150
100
50
0
RTRP
Cu Ni
RTRP 8mm Coating
RTRP 5mm Coating
GALV
SS10
Material Cost
Installation Cost

So far, only material and installation costs have been considered. This is appropriate for selection between composites and corrosion resistant metallic alloys. However, between composites and carbon steel, the significant benefits on a life cycle basis must be considered. Even if the installed cost of carbon steel is 10 percent lower than a composite product (see Table 4), a single replacement of the system due to corrosion during its service life will produce a strong life cycle benefit for the composite product: (1.0 + 1.0)/1.1 = 1.82 Cost Ratio. In seawater piping systems, two replacements of carbon steel are often required during the service life. In addition, the steel system will require intensive corrosion monitoring and perhaps temporary repairs, the costs of which were not included above.[1] Nor are the benefits of weight savings which approximate 60 percent included.

Challenges

Fire performance of composite materials must be carefully evaluated when used offshore. Uniform standards are needed for:

- flame spread
- smoke density
- gas toxicity
- fire endurance time including jet fires

The fire performance of composites has been studied extensively; but, it is beyond the scope of this paper to comment on the literature. However, it should be pointed out that regulatory criteria which require "fire performance equivalent to steel" are not very helpful. Any fire endurance time, for example, can be obtained at increased cost by insulation of the composite material. Likewise, flame spread ratings can be reduced by application of appropriate coatings. The final product may still be lower in cost than alternates of equal corrosion resistance, as demonstrated above.

The ability to tailor properties to specific conditions of use (an important advantage mentioned previously) may present the user with a bewildering array of choices and alternatives, none of which have a history of successful application offshore. This "job-shop" approach to fabrication leads to a lack of reliable design data. Often the user's response is to simply stick to traditional materials. A more sensible approach involves prior agreement between users and suppliers on the broad range of required performance criteria. This allows the manufacturer to produce a well-defined standard product which can be subjected to the appropriate performance tests in advance of order placement. In this case, the user can design confidently, knowing that standard products are available.

Mutual education and technology transfer between the offshore industry and composite producers will focus on composite material advantages and limitations.

Offshore applications

Composites are being used or contemplated for use in the following offshore applications:

- Vertical pump column (or caisson) piping
- Topside seawater system piping
- Deluge systems, dry and wet
- Chlorination systems
- Subsea flowlines
- Column or caisson wrappers

- Gratings, Railings and I beams
- Living accommodation modules
- Lifeboats
- Pipe hangers and supports

Other applications may prove feasible in the future.

Case Histories

Amoco Trinidad Immortelle Platform - This is a deluge fire service system with factory-applied Pittchar coating on epoxy pipe and fittings. The platform was designed by Brown & Root and fabricated at their Greens Bayou yard on the Houston Ship Channel. It was shipped by barge this year and launched near the coast of Trinidad. Two Amoco platforms at that location will tap 500 million cubic feet of natural gas to supply the energy needs of Trinidad and Tobago. Other platforms in this area have used composite pipe for nearly 30 years. Pipe with fire protective coating has also been shipped recently to Singapore for fabrication prior to installation on an Arco platform intended for the coast of China.

Phillips Platform in North Sea, Norway Sector - Six and 8-inch diameter vertical column piping has become a stock item for Phillips and Statoil in Norway since 1990, as well as Maersk Oil and Gas in Denmark. Column piping normally contains a submersible pump and is used for lifting sea water up to the platform decks.

Statoil Gullfaks A Platform in North Sea - This is a produced water system installed by Kvaerner Installasjon in July 1991. The epoxy pipe ranges from 1-inch to 24-inch diameter. Almost all materials were delivered as prefabricated pipe spools.

Ameron presently has an order to supply the following pipe systems to Phillips' Judy and Joanne Platform, in the UK Sector of the North Sea.

- Seawater supply and return
- Firewater - wet system only
- Sodium hypochlorite seawater injection systems
- Cooling medium supply and return

The pressure rating is 20 bars.

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MARINE COMPOSITES -- THE U.S. NAVY EXPERIENCE

LESSONS LEARNED ALONG THE WAY

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INTRODUCTION

Current seaborne applications of composite materials in the U.S. Navy have been limited. For submarines, these applications include sonar domes and windows, towed array fairings, and prototype diving plane bearings and control surfaces. The focus for surface ships has been for coastal minehunter (MHC-51) hulls[1]. Over the past ten years, however, there has been a growing interest in the development and application of composites for both primary and secondary load-bearing structures (such as lightweight foundations, deckhouses and hulls), machinery components (such as composite piping, valves, centrifugal pumps and heat exchangers), and auxiliary or support items (such as gratings, stanchions, ventilation ducts and screens, etc). This renewed interest in composite materials is a result of the U.S. Navy's need for greater weight savings, reduced maintenance and life cycle costs and enhanced signature control. In many cases, these benefits may be achieved by replacing and redesigning metallic components and structures with composites.

As might be expected, the naval and offshore communities share common interests in the use of composites for their respective applications. These include reduced structural weight, reduced corrosion/erosion effects of seawater, improved fatigue performance, dimensional stability, domestic availability, ease of fabrication, and tailorable properties[2]. At the same time, a number of concerns also are shared by both communities; these include: acquisition costs, damage tolerance (structural resistance to service/impact/shock/ out-of-plane loads), moisture resistance, joint integrity, thick laminate processing and reproducibility, quality assurance and inspection, failure behavior and design criteria and fire performance (flammability, smoke, toxicity and residual strength).

The high specific strength of fiber reinforced composites make them very attractive candidates for pressure hulls for deep submergence vehicles. Composite pressure hulls can have weight-to--displacement ratios which are significantly lower than metal hulls, giving them a greater payload capability. Pressure hulls of glass and graphite reinforced epoxy have been built and tested in a variety of configurations up to 4 foot diameter. Figure 1 shows a typical composite pressure hull configuration being evaluated. Composites also are attractive candidates for a variety of secondary structures for submergence vehicles, such as pressure flasks, tanks, fairings and control surfaces. Figure 2 shows a composite control surface for a deep submergence vehicle. Significant reductions in maintenance costs can be achieved for these structures due to excellent corrosion resistance of composites, and low acquisition costs due to hydrodynamic shaping during fabrication.

Technical issues for composite underwater applications that are being explored in Navy research programs include reduced cost fabrication processes for thick composite structures, methods for increasing tolerance for fabrication defects such as ply waveness, increasing resistance to impact damage, developing design concepts for structurally efficient joints and penetrations, and improving stress and buckling analysis methods and failure models for thick composite laminates under biaxial compression.

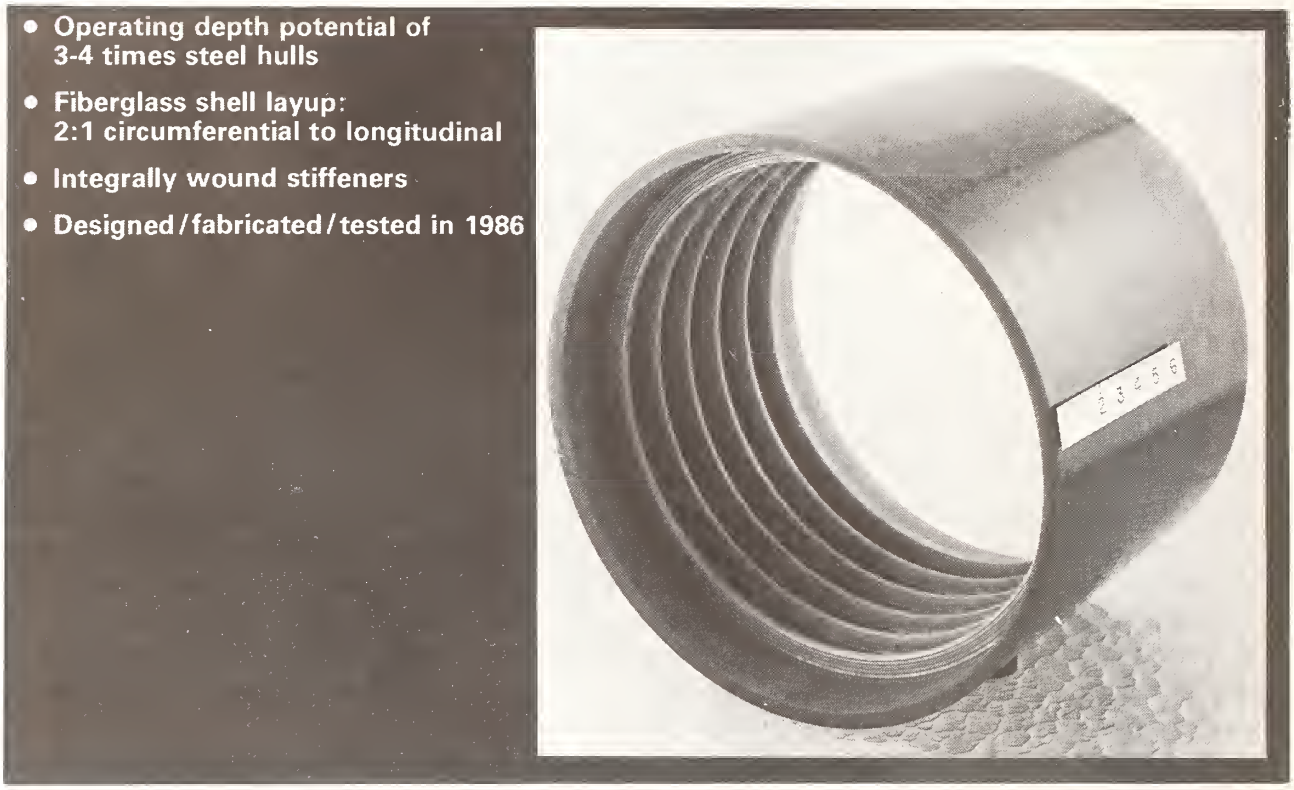

Figure 1. Composite Pressure Hull Prototype (1/22 - Scale)

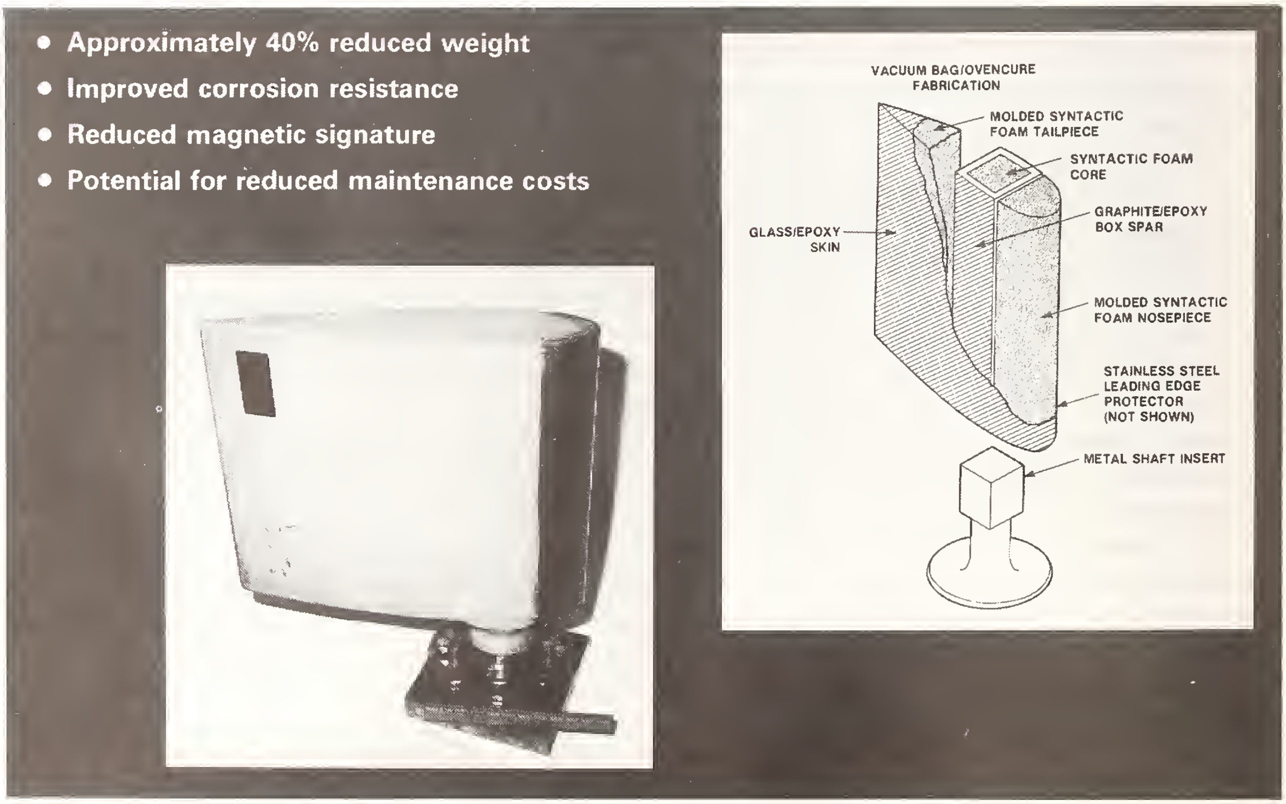

Figure 2. Composite Control Surface (1/4 - Scale Prototype)

TECHNICAL ISSUES

Marine structures tend to be thick and large when compared to aircraft or space composite structures which tend to be thin, stiff and loaded primarily in tension. This has necessitated an extensive development program within the U.S. Navy to address these "seaborne" concerns. Unlike the aerospace composite community, which is large, "high tech" and consists of many defense contractors, the marine composite community primarily includes a myriad of small "low tech" boat builders that rely on "hand lay-up" to produce their boats and craft. The large U.S. shipbuilders, of course, are set-up solely for metal (steel) fabrication and their labor force is trained accordingly.

The use of composite materials in the marine environment offers significant technical challenges. The most important of these issues include: the long term effects of seawater immersion on fiber/matrix adhesion; fire performance, integrity and fire hardening of composite materials; low void, affordable processing of thick section structures; and improved design procedures, test methods, scaling laws, and failure criteria for primary structures. The progress achieved by the Navy in several of these areas will be discussed below.

THE EFFECT OF WATER IMMERSION

In an extensive study sponsored by the Office of Naval Research (ONR) conducted over the past three years, the Carderock Division, Naval Surface Warfare Center (CDNSWC) investigated the effect of long term water immersion on fiber/matrix adhesion by measuring interface dominated mechanical properties of all four major classes of continuous fiber composites (glass/thermoset, carbon/thermoset, glass/thermoplastic, and carbon/ thermoplastic) before and after immersion in 50^{0}C distilled water[3]. The goal was to determine the degree of degradation of the fiber/matrix bond and quantify the effect on mechanical performance.

Thermosets

The glass/thermosets evaluated included vinyl esters (8084, Derakane 510A), and epoxies (SP 365, Tactix 123). All had excellent retention of adhesion following immersion; electron microscopy before and after immersion did not indicate a loss in adhesion. The technology of glass roving sizes and glass fabric finishes is mature. There are effective coupling agents for most (if not all) thermosets used as composite matrix resins, so achieving adequate, hydrolytically stable bonds between resin and glass is generally not a problem if proper processing procedures are followed.

Carbon/vinyl ester compatibility was evaluated with AS4w, XASg, and T300 UC309. Carbon fabric reinforced vinyl esters were found to have poor adhesion as shown in Figure 3. In all cases, electron microscopy shows almost bare fibers in the vinyl ester matrix composites. It appears that carbon fiber sizes are compatible with epoxies, but these treatments are not chemically compatible with vinyl esters.

Thermoplastics

Property retention data and microscopic inspection of the transverse flexure failures for five glass/thermoplastic materials evaluated (E/PPS, E/J2, S-2/PEEK, S-2/PEKK, and S-2/Vectra), indicate a substantial loss in fiber/matrix adhesion. This is shown in Figure 4 for E/PPS. As-fabricated materials appeared well-bonded and had good properties, but water apparently rapidly hydrolyzed the fiber/matrix bonds, reducing adhesion and resulting in low flexure strength. Interestingly,

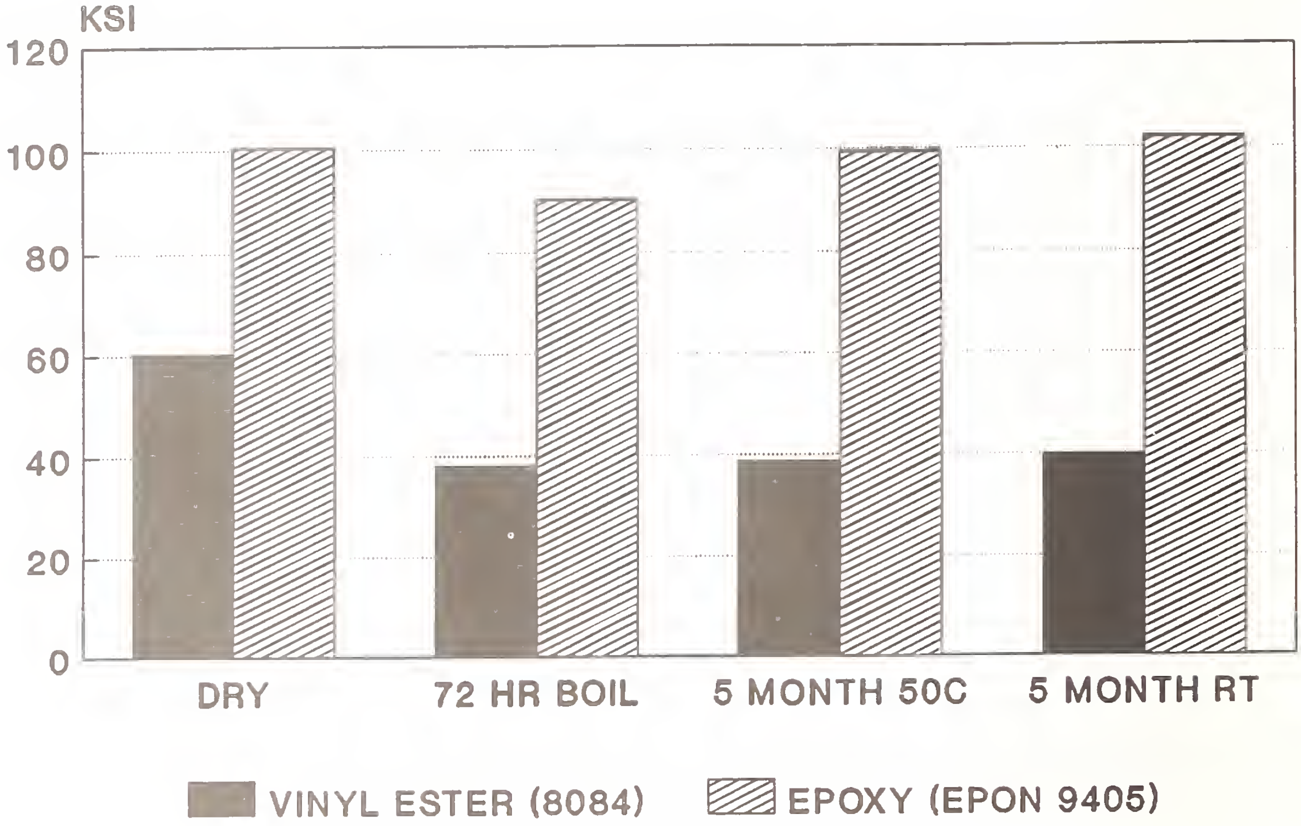

Figure 3. Effect of Water of Flexural Strength of Carbon/Vinyl Ester vs. Carbon/Epoxy

glass-reinforced thermoplastic molding grades (E/PPS and fibers are relatively short in molding grades) fiber/matrix bond strength is less critical in these materials than in continuous fiber composites.

Carbon/thermoplastics evaluated included AS4/PPS, AS4/J-2, AS4/PEEK, and AS4/PEKK. All four carbon/thermoplastics tested had excellent fiber/matrix adhesion, both dry and after water conditioning. Slight matrix-dominated property reductions of AS4/J-2 can be attributed to matrix plasticization since properties return upon desiccation.

FIRE - THE CONSTANT THREAT

Fire aboard a ship or submarine threatens the crew and platform itself and must be fought independently with limited on-board resources. In the fall of 1985, the Chief Engineer of the Navy, VADM Webber, stated that quantified fire performance requirements must be established for composites to be used aboard U.S. Navy submarines. Subsequently, these requirements were developed and the usage of composites inside Navy submarines is now covered by MIL-STD-2031 (SH). Two guiding principles[4] were established for the use of composite systems aboard submarines. First, the composite system will not be the fire source, i.e., it will be sufficiently fire resistant not to be a source of spontaneous combustion. Second, secondary ignition of the composite material must be delayed until the crew can respond to the primary fire source, i.e., the composite system will not result in rapid spreading of the fire. It should noted that the Navy currently has no general fire standard for composites used aboard surface ships. The flammability requirements for surface ships are different than those for submarines and vary with location within the ship. Instead of survivability

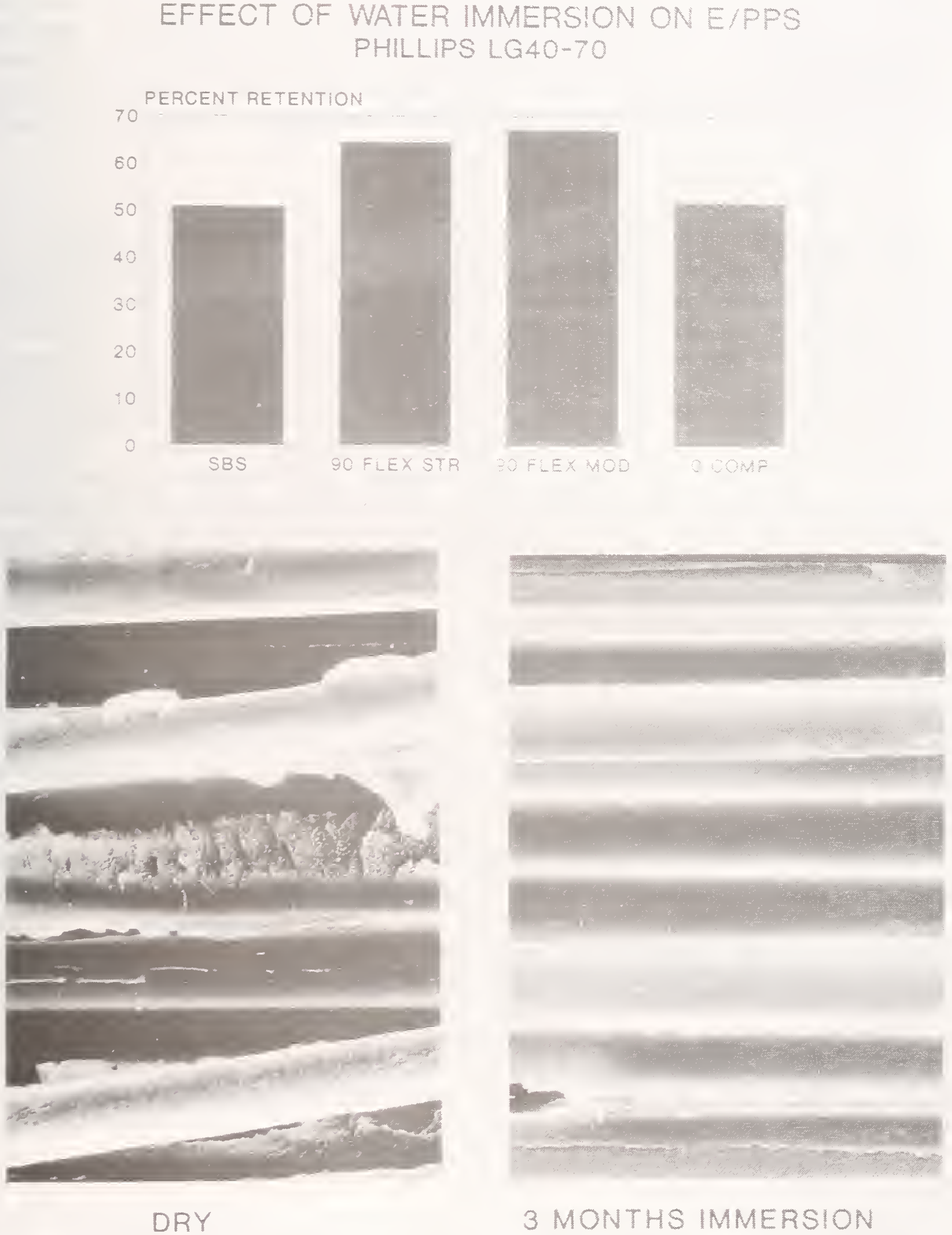

Figure 4. Property Retention and 90° Flexural Surfaces of E/PPS, Both Dry (Left) and After Three Months Immersion at 50°C.

measured in minutes, as it is in submarine fires, the critical issue in surface ship fires is the residual strength of structures at elevated temperatures for a period of 30-60 minutes.

Under ONR and Naval Sea Systems Command (NAVSEA) sponsorship, CDNSWC has been evaluating composites fire related issues for the past several years in collaboration with industry, universities, research institutions and other government agencies. This comprehensive effort includes work on fire performance and test method development[5], thermal and fire barriers to protect the composite structures against fire damage, effects of combustion by-products on toxicity and electronics corrosion, and residual load bearing strength and structural degradation of composites during fire[6].

Fire Performance of Composite Materials

A broad spectrum of thermoset and thermoplastic glass and graphite fiber reinforced composite materials have been evaluated. These include fire retardant vinyl ester (VE), epoxies (EP), cyanate esters (CE), bismaleimides (BMI), phenolics (PH), polyimides (PI), polyphenylene sulfide (PPS), polyether sulfone (PES), polyaryl sulfone (PAS), polyether ether ketone (PEEK), and polyether ketone ketone (PEKK). The flammability characteristics evaluated in this study included flame spread index (ASTM E-162), specific optical smoke density (ASTM E-662), combustion gas generation, residual flexural strength (ASTM D-790), heat release and ignitability as measured by cone calorimetry (ASTM E-1354).

With the exception of vinyl ester, all glass or graphite reinforced composite materials met the requirements of flame spread index (maximum 20). Also, with the exception of fire retardant vinyl ester and thermoplastic J-2, all glass or graphite reinforced composite systems met the requirements of specific optical density at 300 seconds (maximum 100) and maximum smoke density of 200 as per MIL-STD-2031.

The rate of heat release, especially the peak, is the primary characteristic determining the size, growth, and suppression requirements of a fire environment. MIL-STD 2031 requirements for peak heat release (ASTM 1354) at 75 and 100 kW/m^2 are 100 and 150 kW/m2 respectively. Glass or graphite reinforced phenolic, polyimides, and many of the thermoplastics composites met this requirement as shown in Figure 5. MIL-STD-2031(SH) requires the ignitability of organic matrix based composites to be greater than 60 and 90 seconds at radiant heat fluxes of 100 and 75 kW/m^2 respectively. All unprotected composite materials evaluated in this study **failed** to meet the ignitability requirements of this submarine specification.

Thermoset composite materials, in general, have higher heat release rates than thermoplastics, but have higher (better) ignitability resistance. Of all the composite materials evaluated, glass/vinyl ester composites were the least desirable from the fire point of view but most desirable from the affordability point of view. Phenolic based composite materials provided the optimum balance of fire resistance and affordability, however, their mechanical performance for primary structures is generally poor. Advanced thermoplastics, for the most part, have lower heat release rates, but are also accompanied by lower ignitability resistance and lower glass transitions temperatures. It is in this area of ignitability, however, where fire barrier treatments provide the most benefit by delaying the onset of spontaneous ignition by providing a significantly greater time interval for the fire fighters to control the fire.

Fire Barriers (Fire Hardening)

The main conclusion from the fire testing conducted by CDNSWC is that unprotected composite systems cannot fully meet the stringent fire requirements specified for interior spaces of U.S. Navy ships or submarines. Military vessels must perform their mission even when damaged, and

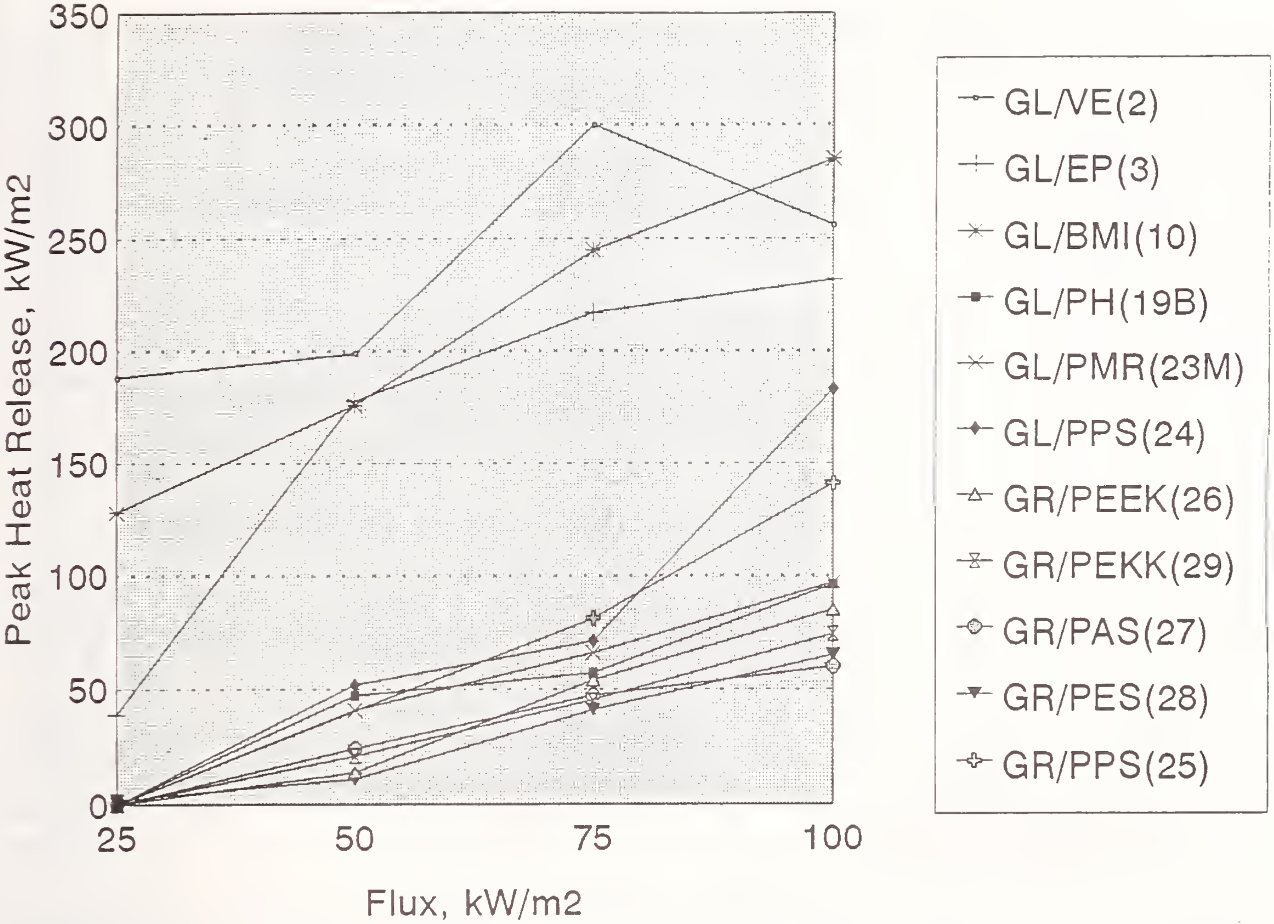

Figure 5. PHR vs. Flux for Selected Composite Materials

must survive the fire for sufficient periods of time to effect rescue missions. To enhance the fire endurance and survivability of composite structures, incorporation of fire barrier treatments is necessary. These treatments function either by virtue of their ability to reflect the radiant heat back towards the heat source or delay heat penetration by their insulative, ablative, or endothermic properties. This delays the heat-up rate and reduces the overall temperature on the back side of, for example, a structural bulkhead. It is important to note, that fire hardened composite compartments can actually serve as an excellent containment area which can prevent, or significantly delay, flashover in adjacent compartments.

In a recent study by U.S. Navy[7], several fire barrier treatments were evaluated including ceramic fabric, a ceramic coating, an intumescent coating, hybrid of ceramic and intumescent coatings, silicone foam, phenolic skin, thermoplastic coatings, APM (ablative protective material), Interam endothermic mat E-IOA, and Interam intumescelt mat I-IOA. The composite systems evaluated with these thermal barrier treatments included glass/vinyl ester, glass/epoxy and graphite/epoxy. Test results show that the intumescent coating, the ablative protective material, and Interam endothermic and intumescent mats were the most effective composite fire barriers. With any of these fire barrier treatments, all composite systems evaluated met the ignitability requirements of 90 and 60 seconds at 75 and 100 kw/m^2 respectively. This is illustrated in Figure 6, which shows peak heat release rates for the bare glass/epoxy panel [1003], glass/epoxy/ APM (0.125" thick) [1004], glass/epoxy/ I-10A (0.125"thick) [1041], glass/epoxy/ I-10A (0.250"thick) [1044], glass/epoxy/ E-10A (0.20"thick) [1042], and glass/epoxy / intumescent coating (0.030" thick) [1047]. In all cases, the panels were exposed to

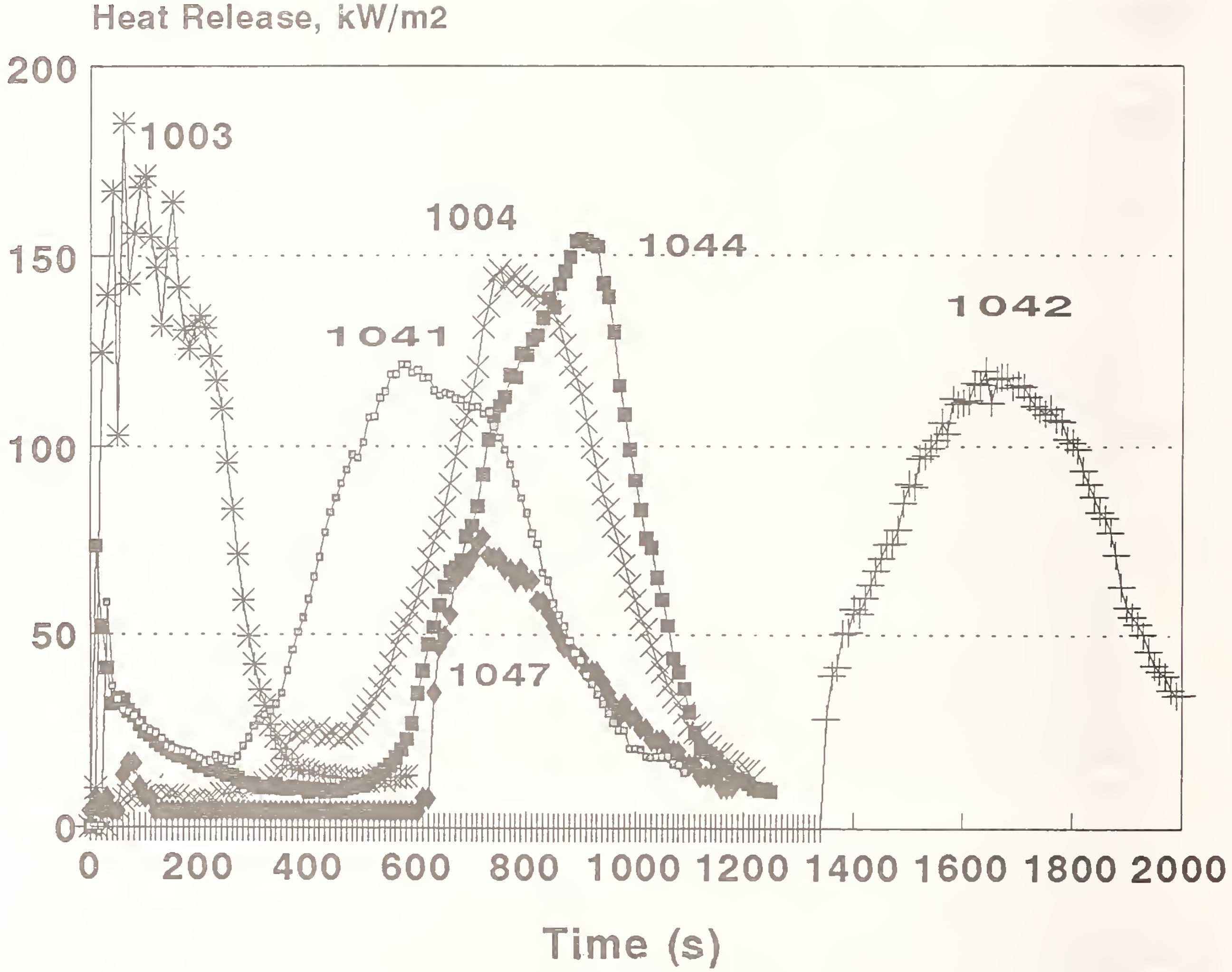

Figure 6. Heat Release Rates for Gl/EP With and Without Fire Barriers

a heat flux of 75 kW/m^2 in a horizontal orientation. Interam E-10A protected the composite from ignition for a period of 30 minutes.

Residual Strength of Composites

Recently, the assessment of composite structural performance during and after fire has become a subject of intense discussion within the Navy community. Our experience indicates that composites made of woven roving or fabric retain higher residual strength after fire exposure than prepreg tapes which totally delaminate during the fire exposure due to resin charring resulting in loss of interlaminar strength.

Since composite materials are made with organic matrices, these resins systems may undergo viscoelastic transitions and/or chemical decomposition during thermal exposure. Below certain critical temperatures, composites will retain most of their load bearing characteristics, but above this "critical" temperature (usually the glass transition temperature), composites begin to lose their mechanical properties rapidly and, in some cases, catastrophically. During a fire, if the resin matrix approaches the glass transition temperature, it can no longer transfer load to the fiber. A critical temperature for irreversible damage is about 500 °F for glass/vinyl ester. However, fully recoverable damage is possible only at temperatures below 200°F.

CDNSWC has initiated a comprehensive effort focused on the issue of structural strength. This is intended to result in analytical models that can be used by naval architects to design full scale fire-tolerant composite structures. This methodology includes determination of basic composite characteristics at elevated temperatures, determination of isothermal material characteristics for use in the computer model, determination of creep characteristics of materials (creep is an unacceptable structural instability), determination of heat transfer characteristics of composite materials exposed to fire, construction of mathematical models of basic shapes under typical loads using ABAQUS finite element analysis, and verification of these models in small and large scale fire tests using the data generated in the full scale ASTM E-119 tests and in smaller scale tests.

Large Scale Fire Testing

The thrust of U.S. Navy's large scale fire testing program has been to understand the behavior of composite structural systems to fire threats, and to determine the effects of various passive protection techniques. Two approaches were taken: ASTM E-119 furnace testing for structural strength investigations and open flame testing to determine ignition, flammability, and thermal vulnerability. These tests have been performed on hardened and unhardened composite panels.

Figure 7 shows two glass/vinyl ester composite wall sections in the ASTM E-119 facility at Southwest Research Institute. They were preloaded to 28,000 pounds to simulate the expected loading aboard ship. The bulkhead on the right was not thermally protected and started to buckle 7 minutes after the test began. The bulkhead on the left was built using a fire tolerant beam, and was thermally insulated. It completed a one hour test in the same furnace.

Figure 7. Two Composite Wall Sections in the ASTM E-119 Facility

Figure 8 is a module 8 ft. x 8 ft. x 16 ft. long made of composite panels. Three modules were tested; in two, the panels were glued and bolted to a steel framework to form the walls and ceilings of a shipboard deckhouse mock-up. In the remaining module, the composite panels were produced with integral composite beams. An interior wall divided each composite module into two

Figure 8. Composite Module During a Post-Flashover Fire Test

compartments. One compartment was used for smaller test fires to the explore material flammability and flashover potential. The other compartment was used for a 2500 kW post flashover test fire. The fire conditions represented by these tests are intended to represent hazards perceived for combatant ships, and to show us how the results from small scale tests would correlate with realistic fires. Conclusions reached from these tests are that remaining uncertainties are resolvable and that future ships will certainly benefit from structural composites.

LOW-COST HIGH QUALITY FABRICATION

A significant issue impeding the use of composites for naval applications is the generally higher acquisition cost of the composite system compared to the incumbent metallic (usually steel) component or structure. For most Navy ship applications, the total material cost may range from 10-25% of the total system cost, and the processing cost may be a very large portion of this total. In recent years, considerable progress has been made on this key issue of affordability through research and development addressing low-cost high-quality fabrication methods combined with innovative design concepts.

A great variety of processing methods are now available for the fabrication of composite materials. These methods include hand layup, pultrusion, resin transfer molding, vacuum bag molding, autoclave molding, injection molding, filament winding, and continuous laminating. Although conventional hand layup glass reinforced plastic (GRP) materials could be used for fabricating large naval composite structures, improved performance is achieved by using aerospace production methods that produce higher fiber and lower void content composite structures. One approach to achieve higher fiber contents in composite structures is to use low-temperature prepreg or wet layup materials combined with vacuum bag and autoclave curing. An even more promising and cost effective method, is a *vacuum assisted resin transfer molding* (VARTM) process employed by the Navy for a number of high performance composite ship structural applications[8,9]. This VARTM method has the advantage of being an **open mold** process which minimizes tooling costs. Fiber contents of 70% (by weight) and void contents of less than 1% have been attained using a particular VARTM process known as SCRIMP, developed by Seemann Composites, Inc. An additional advantage of this process is the incorporated provision for capturing and filtering styrene emissions which minimize the environmental impact.

The improved VARTM method has been exploited by CDNSWC for a variety of development programs for the low-cost fabrication of high quality composite secondary structures for Navy combatants and other ships. To date, the U.S. Navy has successfully demonstrated and evaluated this process for composite deckhouse, mast, foundation and hull applications produced in monocoque, single skin stiffened, or sandwich configurations.

MATERIAL PROPERTIES AND STRUCTURAL DESIGN METHODS

Accurate and reliable mechanical property data are paramount to successful composite marine structures design. Mechanical properties for laminated composites primarily are dependent on constituent mechanical properties, fiber volume fraction and fabrication process quality. Variations in any of these factors can influence the mechanical properties of the material. Consequently, experimentally determined mechanical properties are optimum for composite structural design since measured properties account for these variations. Measured property data, however, exhibit some degree of scatter. Scatter in stiffness data generally is low and average stiffness values are acceptable for design purposes. Scatter in strength data, however, generally is high and strength data commonly is represented using statistical assurances such as A-basis or B-basis.

Ideally, each marine composite structures program would include coupon testing to obtain complete mechanical property data. Comprehensive material testing, however, usually is impractical for short-term programs. In the absence of coupon data, many of the surveyed designs relied on published experimental properties or on theoretically computed properties. Experimental mechanical property data are published in a variety of sources including scientific journals, technical handbooks, and vendor publications. Factors such as the material system, fiber content, void content, and fabrication method for the published material system must match the proposed material system factors in order to effectively use published data for design purposes.

Laminated composite material properties can be determined theoretically from constituent or lamina properties. Theoretical lamina properties can be calculated from constituent properties using a variety of micromechanical theories. Effective laminate mechanical properties subsequently are calculated from lamina properties using, for example, Classical Lamination Theory or Effective Modulus Theory. Measured properties, however, always are desired over predicated properties due to the cumulative effect of assumptions used in these predictions which can lead to inaccuracy.

A typical design process for surface ship structures is initiated by using provided design criteria and a strength-of-materials approach to calculate the induced primary stresses in the deck and, hull bottom. The calculated stresses are used to modify the assumed set of cross-sectional scantlings and the trial-and-error iterative process continued until an optimum set of scantlings is obtained. The same process is applied to other transverse sections. For low L/B ship, transverse strength and torsional strength of the hull must also be checked. This is true especially for a composite hull due to the low rigidity of the composite material.

For calculating stresses in complex structural components, a strength-of-materials approach is generally inadequate and, therefore, a finite element analysis (FEA) must be used. It is possible to model the entire hull structure, but this is seldom done because the lack of knowledge of accurate loads reduces the value of the results. The expense is sometimes justified, however, for new and unusual configurations and materials, and for determining boundary conditions for FEA of local structural components.

COMPOSITE DEMONSTRATIONS AND APPLICATIONS IN THE NAVY

For over twenty years, the U.S. Navy has used extgremely large monolithic composite structures, such as the GRP Sonar Domes (manufactured by HITCO) shown in Figure 9. In order to transition additional composite technology into the fleet, the Navy has worked with industry to design and produce a number of prototype structures and machinery components for material characterization, design evaluation, sea-trials or other full scale tests. Some of the recent composite demonstrations are described below and their salient features highlighted.

STRUCTURAL APPLICATIONS

Advanced Material Transporter (AMT)

The fabrication of a 44-foot long, 0.35-scale manned model of the AMT, a new landing craft concept, is the U.S. Navy's first attempt to exploit the VARTM process for primary hull construction. This is shown in Figure 10. The AMT represents a technologically advanced utility landing craft which provides enhanced speed, mobility, and operational flexibility needed for future Navy and Marine Corps logistic support missions. The design and fabrication of an advanced all-composite structure for the AMT provided an opportunity for the Navy to pursue affordable technology for naval ships that also could benefit the commercial shipbuilding industry[10] .

A hybrid composite structural concept was developed for the AMT with GRP single skin stiffened structure in the hull, and balsa core sandwich structure in the decks, bulkheads, superstructure decks and wingwalls. These structural components were fabricated separately using VARTM as were some of the connection angles for the more critical assembly joints which run in the longitudinal directions. All the GRP laminates and sandwich skins of the AMT model used the 24 oz. woven roving E-glass fabric and a vinyl ester resin. Medium weight balsa wood was used for the sandwich cargo deck while lighter balsa wood was used for the cores of the sandwich bulkheads and superstructures. All stiffeners for hull, deck and bulkheads have light weight non-structural PVC cores and were fabricated in-place using the VARTM process. The use of the same type of fabric and [0/90] laminate of 1:1 woven roving throughout the AMT model is a manufacturing cost saving. For the hull shell, this layup

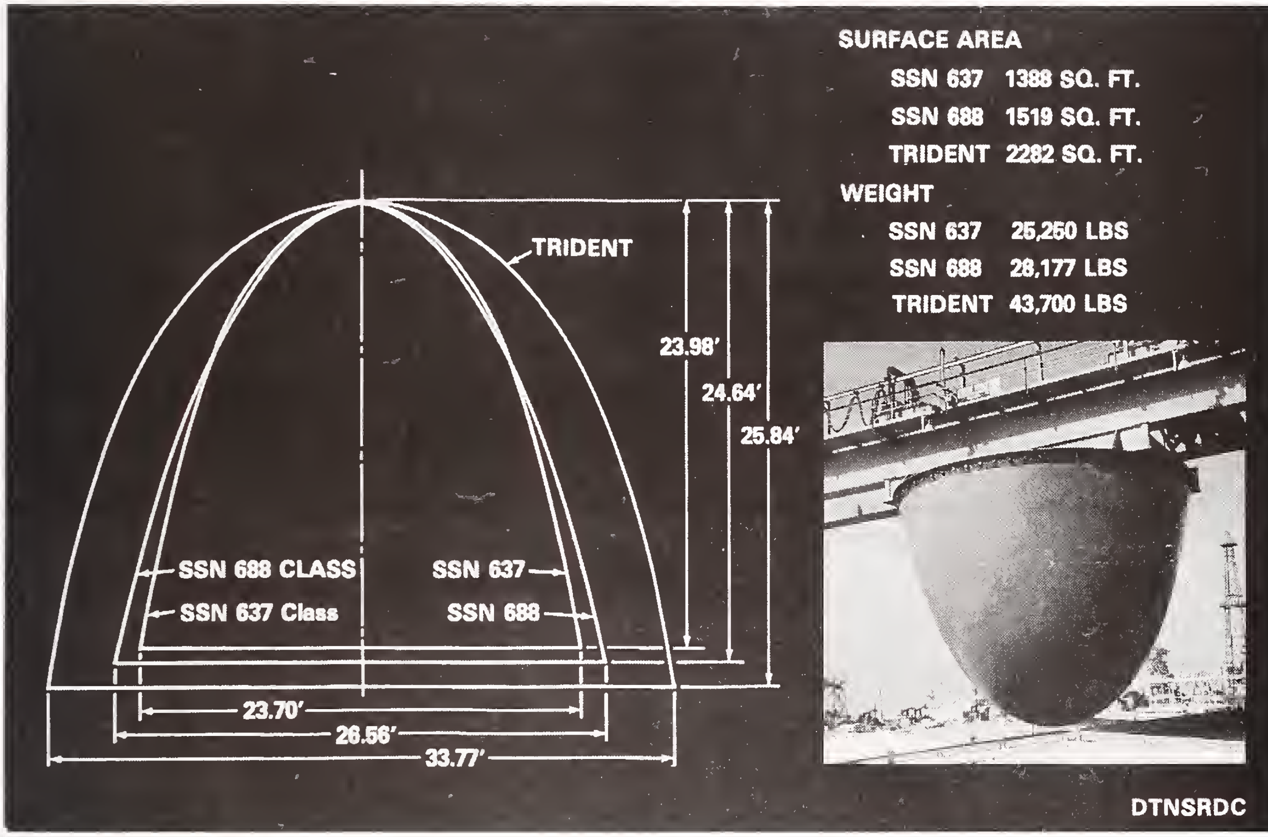

Figure 9. GRP Sonar Dome

Figure 10. AMT Final Assembly

provided adequate stiffness and good damage tolerance under impact due to slamming and beaching while the hull longitudinal stiffeners can sustain the hull bending condition. Bias [+/- 45] plies for the hull sides and transverse bulkheads were not needed for the AMT model, since the design buckling and shear stresses in these components were very low.

The U-shape hull of the AMT model was laid up in full thickness (0.33 in., 14-15 plies) on a female mold and resin injected in less than 3.5 hours using the VARTM process. Progressive resin injection points at increasing distances from the hull center line were utilized to allow the resin to flow outward and up the hull sides without air entrapment or fiber wrinkling. Although a single VARTM injection was suitable for fabricating the hull of the AMT model, multiple VARTM injections may be required to fabricate the much thicker hull of the full scale AMT. (Ply waviness has occurred in the past when using this process for making thick laminates such as that required for a full scale AMT, especially in regions of high curvature.) The GRP hull was then reinforced with longitudinal top-hat stiffeners and transverse frames which were fabricated in-place using VARTM. The shallow stiffeners on the hull sides were put in first, the two transverse frames of medium depth were installed next, and the five hull girders of greater depth were installed last. Based on hat stiffener pull-off tests, the use of the VARTM process for fabricating stiffeners and frames on the AMT hull is expected to provide full primary bond strength.

The AMT cargo deck, bulkheads and superstructures are sandwich construction which were laid up on a simple flat mold and resin injected using the VARTM process in one step. The sandwich deck was completed in 1.5 hours. Narrow vertical slits in the balsa wood allowed the resin to impregnate from the upper to lowerskins of the sandwich components. The sandwich deck and bulkheads were reinforced stiffeners with tapered ends which were fabricated in place using VARTM as described previously for the hull stiffeners and frames. The hull, deck, bulkhead and superstructure elements of the AMT model were assembled using pre-fabricated connection angles or wet layup connections.

The fully outfitted AMT model, equipped with two Hamilton 291 waterjets powered by two Crusader 454 gas engines, recently has been completed by Seemann Composites and delivered to the Navy. Presently, the AMT model is assigned to the CDNSWC's Special Trials Unit at the Patuxent River Naval Air Station, Maryland, for at-sea tests, evaluation and operational demonstration.

Lightweight Foundations

The use of composite materials for Navy ship machinery foundation structures offers many potential advantages over current steel structures including weight reductions of up to 50%, improved shock and corrosion resistance, and reduced noise and magnetic signatures.

To verify the feasibility of using composite materials for important foundation structures, several demonstration projects were conducted. One project included a one-half scale fresh water pump foundation fabricated and subsequently tested under shock loading. The composite foundation was designed to match existing geometrical constraints and resulted in a weight reduction of 40% over the existing steel foundation structure[11]. The structural adequacy of the composite foundation design was verified based on the test results coupled with a finite element analysis. The VARTM process, described earlier, was selected for the foundation fabrication; cost estimates being approximately 50% less than for other methods. An epoxy resin was selected for the foundation based on required strength considerations. The fiber reinforcement was E-glass. The strength of the composite pump foundation was evaluated by high-impact shock tests (per MIL-S-901D) using a Navy medium weight shock test machine. The foundation was tested in four different orientations: vertically, longitudinally, athwartships, and at an inclined angle of 30 degrees. A facsimile steel mass was used to simulate the weight and center of gravity of supported equipment. The foundation was tested both with and without resilient mounts which would be used between the foundation and the equipment bedplate on a full scale application. The composite foundation was able to sustain accelerations of up to 150 g's with no apparent degradation.

A second foundation demonstration structure represented an equipment pallet of the type used to support surface ship topside electronic equipment. The pallet concept allows multiple prepackaged equipment units to be assembled and checked out prior to being lifted aboard ship as a single unit as construction proceeds. The foundation was of filament-wound construction using epoxy resin and high-strength S-2 glass fibers. The fabricated foundation easily met the weight reduction goals of 20% versus aluminum. The final foundation weight actually represents a 44% weight savings compared to aluminum and 60% compared to steel. In the shock qualification test phase, all the general shock related failure criteria were met, and no apparent damage was observed or measured upon completion of the multiple shock test series. During shock testing, the foundation was loaded with 3200 lbs., representing the loading of an electrical transformer. These foundation demonstration projects have shown that composite foundation structures can be designed to exceed Navy combat requirements while offering very significant weight reductions.

For offshore applications, if we assume that machinery and equipment requirements are similar to those of larger combatant ships and the weight savings percentages can be applied to the foundation weight aggregate totals, then the total foundation weight savings for offshore applications could be very significant, particularly for the floating, tethered rigs that depend on buoyancy and hydrostatic stability for their operational mode. As an example of possible weight savings for naval applications, a study of the CG-47 class mid-size cruiser revealed that approximately 390 tons was associated with foundation weight. Assuming a conservative 25-30% weight reduction through the use of composites, a total weight savings of over 100 tons could be realized!

Composite Mast

In order to demonstrate the feasibility of a composite mast for naval combatants, a one-half scale, 36-ft tall, prototype mast (Figure 11) was designed, and fabricated using VARTM. It successfully withstood the air blast test under the DISTANT IMAGE event at White Sands, in June 1991. A hybrid material system of S-2 glass and carbon in a vinyl ester resin system was selected for the main trunk of the mast; S-2 glass to maximize ballistic performance and carbon in +/- 45 layup to provide sufficient torsional stiffness.

BLAST RESISTANT TOPSIDE STRUCTURES

The U.S. Navy has made considerable progress over the last six years in the development and demonstration of blast-resistant composite design concepts and prototypes for deckhouses, superstructures and other topside enclosures for naval combatants. These composite concepts offer significant advantages over conventional steel structures including a 35 to 45% reduction in weight, reduced corrosion and fatigue cracking, and improved fire containment[12].

Two composite design concepts, a single skin stiffened and a sandwich core concept have been developed for topside applications. The stiffened concept was developed first and involved the assembly of prefabricated hat-stiffened GRP panels using prefabricated GRP connection angles and bolted/bonded joint details. Panel stiffeners were tapered to maximize peel resistance, to minimize weight, and to simplify the joints and panel connections. The sandwich concept followed and utilized prefabricated sandwich panels which are attached through bolting and bonding to a supporting steel framework. A steel framework is attractive for the construction of composite topside structures since it is readily erected in a shipyard environment, allows for the attachment of prefabricated high-quality GRP panels, and provides resistance to collapse at elevated temperatures under potential fire insult. The stiffened and sandwich panels were prefabricated using E-glass and vinyl ester resin materials in the VARTM process that yielded significantly higher mechanical properties than achieved using conventional hand layup procedures.

In order to demonstrate the producibility of these concepts and their structural integrity under air blast loading and at elevated temperatures, several full-scale test modules, 16 ft. long x 8 ft. high x 8 ft. wide, as seen in Figure 12, were built and tested. The GRP single skin stiffened module was successfully air blast tested at the White Sands Missile Range under the MISERS GOLD and DISTANT IMAGE events in 1989 and 1991, respectively. The limited, acceptable damage to the module under severe loading, demonstrates the superior toughness of the structure. Fabrication advantages of sandwich construction over single skin stiffened for deckhouse structure include further weight reduction, a flat surface on panel interiors for ease of outfitting and possible lower production

Figure 11. 1/2 - Scale Composite Ship Mast

costs. A tapered sandwich panel concept fabricated using the VARTM process with a balsa core and vinyl ester resin was selected for the construction of a sandwich deckhouse module which was also successfully air blast tested at White Sands.

Under a collaborative effort with the Canadian Navy, blast tube tests were conducted on a variety of one-half scale (4' x 4') sandwich panel designs, including a fire-hardened concept having an additional skin at the mid-layer of the panel. The fire-hardened concept withstood an equivalent static pressure of 155 psi without rupture. Blast tube tests were also conducted on one-half scale stiffened panels having a variety of edge connected details, leading to the selection of a steel connection angle and a refined bolted/bonded detail. The structural integrity of the fire-hardened structure at elevated temperatures (1800 to 2000 degrees F) was dramatically demonstrated when the unprotected stiffened

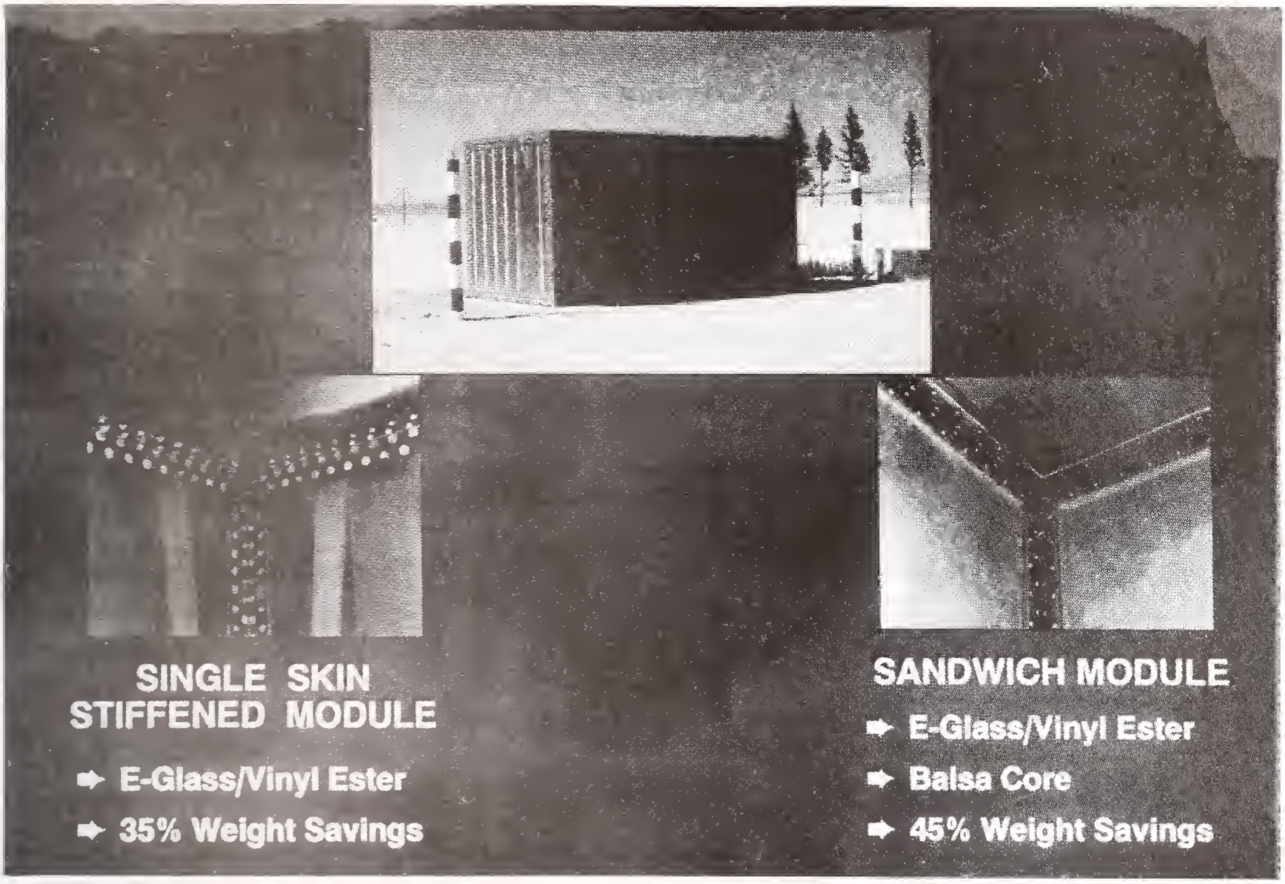

Figure 12. Composite Superstructure

module, without internal insulation and the top statically loaded (90 lbs/ft^2), withstood a 30 minute internal sprayed fuel fire without collapse or without exceeding allowable deflections (span length / 50).

COMPOSITE MACHINERY APPLICATIONS

The Navy's composite machinery program has focused on technologies such as composite centrifugal pumps, valves, piping, ventilation ducting, heat exchangers and composite shafting. These composites employ primarily glass reinforced thermosetting resins such as vinyl esters, epoxies, and phenolics. Graphite reinforced thermosets have been avoided in non-wetted parts because of the concerns of conductive graphite particles becoming entrained in the atmosphere and shorting out electrical equipment in post fire scenarios. Some of these components, like piping, are fabricated by filament winding. Others, like pipe fittings and valves, are made by compression molding. In order to reduce costs, efforts are underway to reduce the number and variety of spare parts and inventory by developing "standard families" of selected machinery components produced with composites.

Primary technical issues of concern for shipboard machinery applications include structural performance under shock (simulation of near underwater explosion) and performance in fire (usually in a hydrocarbon pool fire of 1500-1800^{0}F). The Navy's experience with structural integrity of machinery components under shock is that most composite components can be made to survive the mechanical stresses and potential shock loads in a shipboard environment if properly supported, and if the composite is not expected to carry excessive loads.

Composite Piping

Experience with the fire performance of composite materials has shown phenolics to be the best fire performers among the thermosets. In an extensive study conducted at CDNSWC, several phenolics have shown excellent flammability, smoke, and toxic combustion product performance. For this reason, Navy is focusing on phenolics for development of corrosion resistant supply ventilation ducting and piping.

Advanced composites made from thermoplastics such as PPS, PEKK and PEEK are also being explored as candidates for fluid systems machinery components, especially piping and ventilation ducting. These thermoplastics are tougher than most thermosets and are less susceptible to installation damage. A composite piping or ducting system made from an thermoplastic could be bent, would not require adhesive bonded joints, and would require fewer fittings relative to conventional thermoset pipe. The outstanding flammability, smoke, and combustion gas characteristics of advanced thermoplastics composites are far better than most thermosets, including some phenolics. Questions remain, however, about the full scale fire performance of equipment fabricated from these resins, and about strength retention in water for certain types of glass reinforcement. Prototype S-2 glass-reinforced pipe (1.5" diameter) was fabricated and successfully bent to 90^0. Straight sections of the pipe were successfully hydrostatically tested to 1000 psig after a simulated bend thermal cycle.

Composite piping system fire survivability has also been evaluated using glass reinforced epoxy and vinyl ester piping systems with various fitting joint methods and under dry, stagnant water, and flowing water conditions. The results of these tests are compared with metallic alternatives. For example, 90-10 Cu-Ni sil-brazed joints survive 2-3 minutes with dry pipe and less than 20 minutes with stagnant water in the pipe. Epoxy thermosetting pipe assemblies using tapered epoxy adhesive bonded joints survived less than 3 minutes in full scale fire when pressurized to 200 psig stagnant water. The joints failed catastrophically. However, application of a promising fire barrier around the pipe joints improved survivability time to 23 minutes, and a completely insulated assembly survived for 30 minutes with no leaks after the fire. Some prototype piping and installation is shown in Figure 13.

The Navy is currently attempting to establish fire performance requirements for surface ship composite piping systems and other composite machinery components. One approach being proposed is to tailor performance requirements after International Maritime Organization (IMO) guidelines, many of which are being incorporated into ASTM F1173, "Epoxy Resin Fiberglass Pipe and Fittings to be used for Marine Applications".

Composite Centrifugal Pumps

The most successful Navy composites machinery program to date, involves the development of a standard family of composite centrifugal pumps (Figure 14). The pump family employs a limited number of pump housing sizes, impellers, and drives to cover a wide range of pressure and flow rate requirements. The pump housing can be fabricated from glass-reinforced epoxy, vinyl ester, or polyester[2]. Part of the development effort involved high velocity erosion investigations with various fiber reinforced polymer matrix composite pump materials. These studies showed excellent corrosion-erosion performance of composites relative to gun metal bronze (widely used in marine centrifugal pumps) over a velocity range of 0 to 130 ft/sec. However, the composites did not fare as well under cavitation conditions, where they showed generally inferior performance to the bronze. In most marine pump applications, however, cavitation should not be a problem.

Composite Valves

Another area of Navy interest is in the development of standard composite valves. Extensive mechanical evaluations have been done on a commercial glass-reinforced vinyl ester ball valve. The

CHT TANKS ABOARD JOHN F. KENNEDY AFTER 2 YRS SERVICE

Figure 13. GRP Pipe Installations

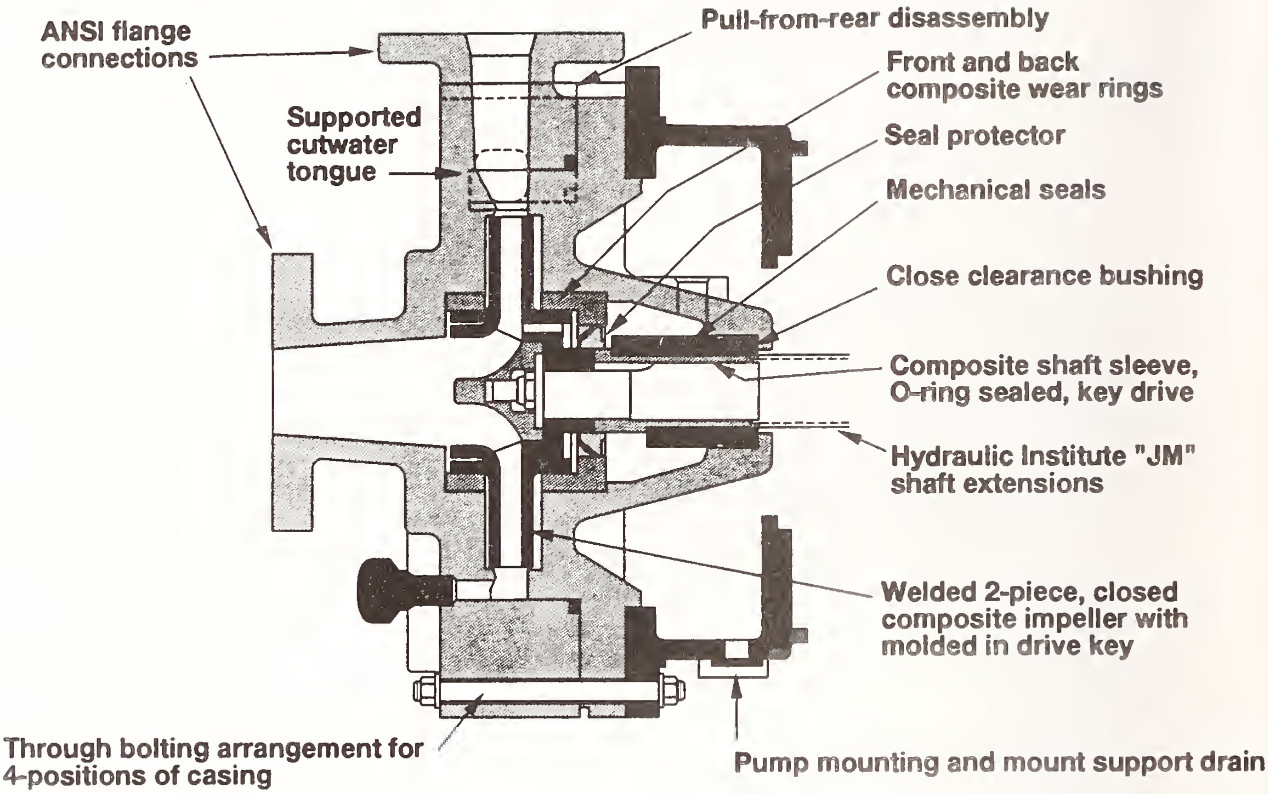

Figure 14. Composite Centrifugal Pump

valve is generally 1/5 to 1/3 the weight of a typical metal counterpart, and 1/4 to 1/2 the cost, depending on size. It is available in the 1 through 6-inch size range. When protected with a prototype fire shield, shown in Figure 15, it survived for 30 minutes in a hydrocarbon pool fire. The valve body remained basically intact. The valve was closed and pressurized on one side to 200 psig. It should be noted, however, that the pressurized flanged joint, which contained a neoprene gasket, leaked during the fire and helped cool the valve. This illustrates the important effect of fluid conditions and joining methods when testing a particular system. Nearly 10 years of shoreside experience at the Charleston Naval Station has shown these valves to require virtually no maintenance.

LESSONS LEARNED IN APPLYING COMPOSITES

Attempt to avoid direct substitute replacement scenarios of incumbent metallic construction materials with either conventional or advanced composite alternatives. Direct substitution, in the sense of filling the existing dimensional design envelope optimized for a metallic alloy, with a vastly different composite alternative (in terms of density, stiffness, strength, fatigue characteristics, corrosion resistance, galvanic nobility, expansion coefficients, thermal and electrical conductivity, etc.) usually prevents performance optimization of many parameters in spite of the freedom associated with the tailorability of composites.

Make an effort to thoroughly understand the characteristics and true limitations of the incumbent or baseline material and design that you are attempting to improve with composites technology. The history of marine materials development has followed an evolutionary trend with materials having performance limitations being continually superseded by superior replacements. Composite materials

Figure 15. Composite Test Valve With Fire Shield

can be viewed as an "enabling technology" for marine engineers striving toward broad objectives such as improved system performance, increased payload, energy efficiency, safety, and extended service lives in the aggressive ocean environment. **Setting realistic goals** associated with measurable performance enhancements, **conducting material trade-off studies** using modern analytical tools, and **not making presumptions** about the ability of an incumbent metallic material or a new alternative composite candidate to meet a particular performance requirement without adequate data, are the ***keys*** to good decisions and opportunities for significant improvements. For example, do not assume that an incumbent component can meet fire performance requirements just because it is metal; and conversely, do not assume composite material candidates can't meet fire requirements just because they include polymer matrix components.

Do not reinvent the wheel. Recognize that polymer-matrix composites have gradually evolved from the fiberglass-reinforced plastic laminates that were first introduced in the United States in the late 1940's. As a result, there is a considerable body of literature and experience on which the marine design engineer can draw. Case histories involving 10 to 30 plus years of continuous service in seawater or in the marine environment can be found for a wide variety of machinery and structural applications such as: piping systems, pumps, tanks, propeller shaft coverings, sonar domes, radomes, floats, sailboats, motor yachts, naval personnel and utility boats, minesweepers, etc.

There are still many areas where improved design and analysis tools are needed. These include: laminated plate design methods for fixed or elastically restrained edges; user friendly design tools for predicting through-the-thickness normal and shear peeling stresses at details, curved sections, stiffeners, joints, and penetrations; automated design tools for thick bolted and bonded joints; improved FEA procedures for thick sandwich panels; quick and accurate method for estimating the natural frequencies of a composite sandwich panels with orthotopic skins; and design tools for predicting the stresses and deflections of sandwich panels under concentrated and patch loads. In addition, a reliable and consistent composite material property database is essential to provide the accuracy and confidence in the design and analysis process.

Navy experience and investigations suggest significant problems exist with fiber/matrix adhesion of continuous *glass reinforced thermoplastics* and *carbon reinforced vinyl esters* when immersed in seawater. These combinations should be avoided for marine immersion applications until suitable improvements are made in fiber sizings.

Low Cost Resin Systems. Evaluations of polyester and vinyl ester laminates have indicated that polyester resins, in general, have low tensile, compressive and flexural strengths and poor impact damage resistance due to their low failure strain, usually less than 2%. However, when an isophthalic polyester with a failure strain of almost 4% was evaluated, it was found to have static mechanical strength and impact damage resistance equivalent to vinyl esters at half the cost.

Resin modulus plays a major role in composite compression and flexural strength. Although this trend has been observed in carbon/epoxy laminates by the aerospace industry, it may not be fully appreciated by the marine industry.

Affordability/Property/Fire Trade-Offs. Of all the composite materials evaluated, glass/vinyl ester composites were the least desirable from the fire point of view, but most desirable from affordability point of view. Thermoplastic composites have good fire performance characteristics, but have seawater or affordability limitations. Phenolic based composite materials provided good fire resistance and affordability, however, their current mechanical performance is generally unacceptable for primary structures.

Fire performance characteristics of *unprotected* composite systems cannot meet the stringent fire requirements specified for interior spaces of U.S. Navy ships or submarines. Military vessels must perform their mission even when damaged, and must survive the fire for sufficient periods of time to effect rescue missions. To enhance the fire endurance and survivability of composite structures, incorporation of fire barrier treatments is necessary.

The Navy experience suggests that composites made of woven roving or fabric retain higher residual strength after fire exposure than prepreg tapes which totally delaminate due to resin charring. Along the way, Navy has learned to design more fire safe structures by paying attention to engineering details during fabrication.

Because of inherent low stiffness of the material, deflection and buckling, rather than strength, frequently govern the structural design. For this reason, many composite ship structures, especially decks and bulkheads, are usually of a sandwich panel construction. Advantages of sandwich construction over single stiffened skins include greater weight reduction, a flat surface on panel interiors for ease of outfitting and possible lower production costs.

Significant design opportunities exist for composite *structural integration*. Concepts are being developed and studied which would allow the deck structures to incorporate structural features that would serve as mounting points for equipment and may, in fact, eliminate the foundation as a separate structural unit. An application such as an integrated deck-foundation system can take full advantage of the inherent design flexibility of composites.

Most composite machinery components can be made to survive the mechanical stresses and potential shock loads in a shipboard environment if properly supported.

Have patience! It took the American Automotive Industry about 50 years to recognize and extensively begin to apply composite body panels which Henry Ford had demonstrated in 1940 (Figure 16). Can the Marine Industry be far behind?

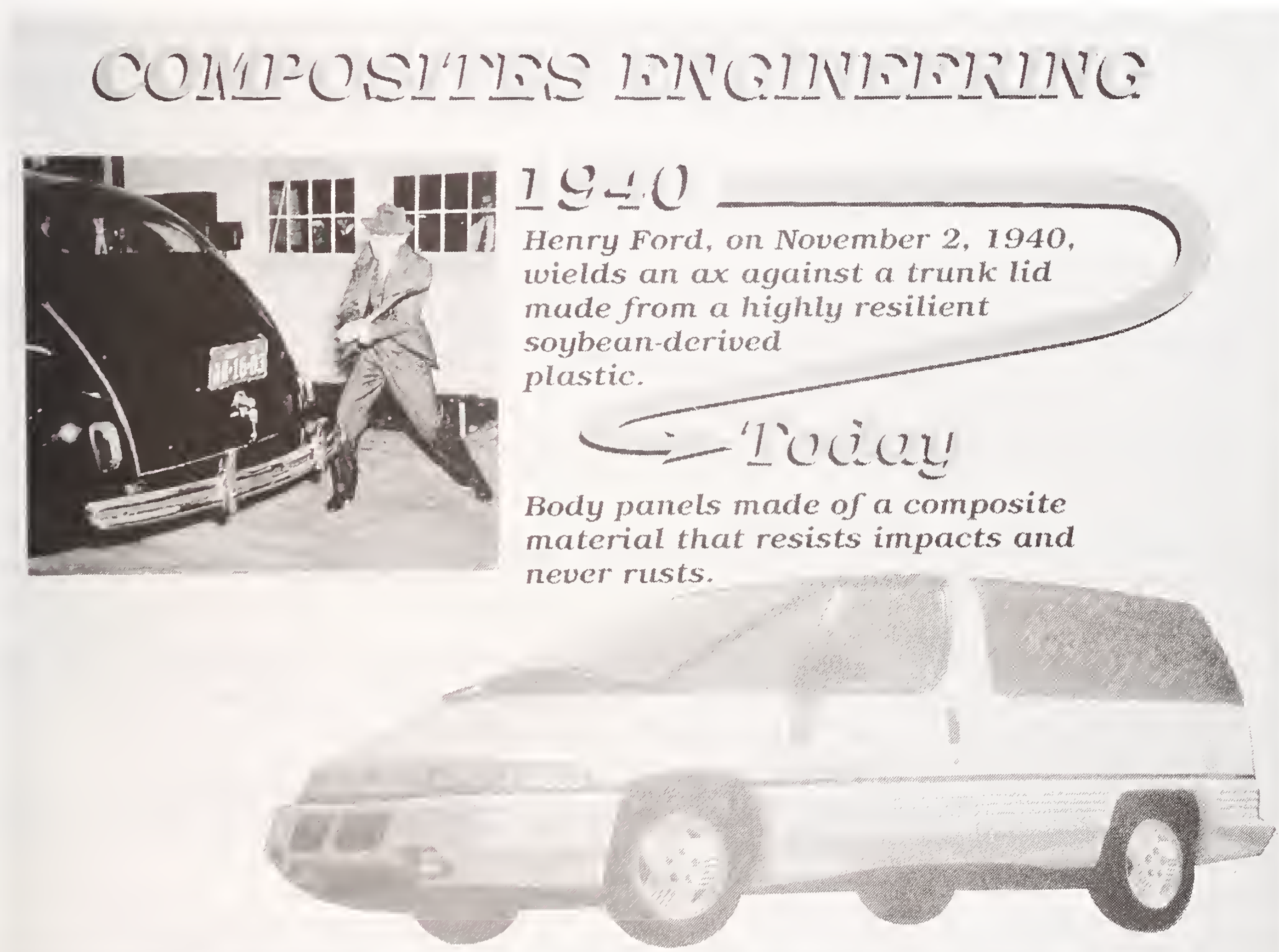

Figure 16. BE PATIENT

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Summary of
ADVANCED COMPOSITES: SHAPING TOMORROW KEYNOTE ADDRESS #5 CHALLENGES AND THE FUTURE

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DuPont has invested more than two billion dollars of capital and R&D in Advanced Materials and Advanced Composites. These technologies represent a major renewal for the corporation. But the worldwide industry is currently poised on the edge of financial collapse.

Why, then are advanced material systems still exciting to us? What will it take for companies and nations to succeed in this field?

Advanced Composites will be among the core technologies that unlock tomorrow's boundaries. Today we are in the midst of a materials revolution. Advanced Composites are at the leading edge of the material systems which are taking us into the future --- in aircraft, space, automotive, industrial, biomedical, sports and electronic applications.

Market Drivers taking us into the future are:

Protection . . .

- F-22 Aircraft whose structure is over 50% composites - allows for greater speed, stealth and flexibility
- Fireman's Turnout Coat and Multi-Threat Suit - Protective Apparel - guarding against bullets, flame, chemicals and disease
- Smart Materials - Submarine - monitoring and reporting on its own

Energy . . .

- Composite Applications for The Tension Leg Platform - reduce weight, address corrosion and fatigue problems and reduce maintenance costs
- Permasep Permeator - separation unit - convert salt water to fresh water
- Extended Reach/Horizontal Drilling - Mud Motor Torque Shaft - less susceptible to wear, fatigue and corrosion - will last longer

Environment . . .

- Commercial Aircraft Tail Fin - 20% lighter - this weight reduction saves jet fuel and reduces CO_2 output.
- Composite Fan Blades in GE Engine - lifetime two to three times that of metal
- Bexloy® Composite Sheet used for fenders on Chrysler's LH series. These bumpers were recycled - HMS Rose's Sails made from recycled bumpers and soda bottles
- Zymaxx™ - graphite-reinforced polymer seal - reduces emissions
- Insituform - repairs leaking underground pipes without tearing up streets and blocking traffic
- Bioremediation Unit for leaking underground storage tanks. Absorption and Regeneration Process - environmentally friendly

Productivity . . .

- Helicopter - Composites enabled part consolidation, fewer parts, more productive
- Satellites and Bike Wheel - examples of faster cycle time
- Bridges - reduced construction costs, faster erection, extended service life, reduced maintenance
- Orthopedic/Prosthetic parts - improves the length and quality of life

Major Issues for Advanced Composites have to do with markets and the forces impacting those markets. The major issues are the "Three C's" that stand as barriers to adoption: Consumption, Conservatism, and Cost. We must replace military consumption with other market pull; overcome conservatism of engineers steeped in the use of traditional materials; and address cost issues with new manufacturing design technologies.

The age of the massive general solution is over. Industry made generic products and found a broad array of uses for a narrow product line. Customers bought what was made -- take it or leave it.

Today, the limiting factor is not capital, it is knowledge. We call this the "Specific Solution". In the business world, the specific solution means customers demand exactly what they want and when they want it. The specific solution completely changes how we work in the market.

Second Key Learning "Systems Approach". We must ask what the whole system is trying to accomplish and then seek the simplest, most efficient solution. To do this, we must establish a network of technology and business partnerships.

Alignment of a nation's industry, academic community and government on a few key goals will win the day in the global race for good jobs, expanding economies and improved quality of life.

Studies Relating to the Use of Fibre Reinforced Composites in the Offshore Industry

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SYNOPSIS *This paper discusses some of the results of the Marinetech Research programme on 'Cost-Effective Use of Composites Offshore'. In particular, the outcome of a study of the fire performance of composites based on E-glass woven rovings and four different thermosetting resin systems: polyester, vinyl ester, epoxy and phenolic will be discussed. It was found that, in terms of ignitability, heat release, smoke and toxicity, the phenolic resins were in a different performance class to the others. It was also found that, in thick sections, composite laminates showed a surprisingly slow rate of burn-through in furnace tests and lower than expected heat release. This phenomenon has led to applications in heat and fire protection. A model for laminate degradation in fire demonstrates that this effect is associated with the endothermic decomposition of the resin. The effect occurs with all classes of resin.*

Introduction

The Marinetech Research programme on the 'Cost-Effective Use of Fibre Reinforced Composites Offshore' has been running since 1987 and involves six academic institutions in the UK, along with over 20 industrial and governmental sponsors. The programme has studied many of the factors, relating to mechanical, environmental and fire performance which influence the possible use of composites offshore. This paper discusses some particularly important results relating to fire behaviour.

The offshore industry, where there have been few applications until recently, is now showing considerable interest in the use of fibre reinforced plastics (FRP) (1-5). This comes as a result of experience with these materials in other areas, including marine applications (6-9), and has been at least partly driven by recent changes in design and regulatory philosophy. One of the results of the outcome of the Piper Alpha Enquiry has been a movement away from prescriptive regulatory measures (which included a rather rigid definition of combustibility) towards a more performance-based approach. This has considerably reduced the barriers to the use of FRP, but composite-based design solutions need to be shown by the operator to be safe and effective in the light of expected hazards. Documentation based on previous installation experience is important in this area, and the UK Offshore Operators Association (UKOOA) has recently been very active in providing procedures for assembling such documentation.

Other factors driving the expansion in offshore use of composites are their relatively light weight and corrosion resistance, which reduce installation costs and through-life costs respectively. The most significant immediate applications and markets lie in two areas:

(a) filament wound pipework for aqueous services, especially fire water, and
(b) lightweight walls and partitions for blast and fire protection.

An example of a glass reinforced epoxy pipework installation is shown in Figure 1. The light weight of the FRP pipes, and the ease with which adhesively bonded joints can be made greatly simplifies and reduces the cost of installation. One application involving fire-resisting panels is shown in Figure 2. In this case, twin-skinned construction, using a special refractory core material, gives an excellent combination of mechanical strength and fire resistance.

Applications rely on corrosion resistance and lightness, but depend critically on the response of the material to fire, a factor which will be discussed later. Given the size of the offshore industry worldwide, the potential market for FRP pipework alone could eventually be in excess of 40,000 tpa. Other applications, such as cladding and panelling can be expected to exceed this.

Limits to Market Penetration

One important factor restraining the offshore market has been lack of knowledge on the part of composite suppliers concerning the structure of the offshore industry. Installation of new or even retrofit components involves a complex interaction between at least four parties:

-the operator
-the offshore contractor
-the operator's design house
-the certifying authority

To achieve market penetration for a particular application it is necessary to convince all four parties of the validity of the FRP solution. Most operators are now aware of at least some of the benefits of using composites and are taking active steps to see that these materials are given consideration. The certifying authorities, too, are increasingly willing to give a fair hearing, so long as appropriate performance-based documentation is provided. Unfortunately, by no means all design houses are familiar with FRP, which results in over-specification or overestimates of installation costs, which lead to alternative materials being chosen. Driven by the operators, the designers and contractors are beginning to show a greater awareness of FRP, but this is an important area where education and documentation are still needed. It is no co-incidence that the companies that have experienced the greatest success in penetrating the offshore market are those which have existing connections or experience in the area of marine and offshore contracting and installation.

Other difficulties which have limited the recent rate of expansion are lack of design data and working experience, problems which are now being rectified: the available documentation and guidelines on the offshore use of FRP are improving and staff are beginning to be trained in the new skills and procedures required for installation.

Fire Behaviour

The aim was to establish a set of baseline performance characteristics for candidate offshore composite materials. The results relate to woven roving laminates with four different matrix resins: isopolyester, vinyl ester, epoxy and phenolic, fabricated by contact moulding. Materials details are given in Table 1.

Table 1 Materials evaluated in the Marinetech Research Fire Test Programme

Reinforcement	OCF Fiberglass woven rovings (1 ply gives ~0.5mm thickness in final laminate)
Resins*	
Isophthalic polyester	DSM Stypol 73/2785
Vinyl ester	DSM Atlac 580/05
Epoxy	Ciba Geigy Araldite LY1927/HY1927 (amine cure)
Phenolic	BP Cellobond J2018/L + Phencat 10 acid catalyst

**Contact moulding grades, laminated, cured and post-cured to manufacturer's directions.*

There is no single property which defines the suitability of a material for use in applications where fire is a hazard: the required attributes vary according to circumstances. Three aspects of fire response are important for offshore use of composites:

(i) ignitability/heat release,
(ii) smoke/toxicity, and
(iii) fire resistance.

Heat Release and Ignitability

Figure 3 shows a comparison of typical cone calorimeter heat release results on polyester, epoxy and phenolic laminates. Vinyl ester has been omitted as it shows very similar behaviour to polyester resin. With polyester and epoxy there is a small induction period followed by a rapid rate of heat release, corresponding to burning of the resin at the laminate surface. Following depletion of the resin from the surface layers of the laminate the heat release rate then falls to a lower value, before a second, much broader peak corresponding to the combustion of gaseous decompositicn products from within the laminate. This is typical of many thermosetting resin laminates. The phenolic resin laminate shows very different behaviour, with longer time to ignition and much lower peak and overall heat release rates.

Figure 4 shows the peak and average heat release rates as a function of irradiance. Once again the behaviour of the phenolic laminates is substantially different from that of the others. It should be noted that the irradiance levels in real hydrocarbon fires, which have been the subject of some debate, are higher than those achievable in the cone calorimeter, possibly of the order of 200kW/m^2. However it can be seen that the heat release begins to approach a steady value with increasing irradiance.

Figure 5 shows the effect of laminate thickness, up to ~21mm, for the four resin systems with woven rovings. The heat release rate has been divided by the thickness to give the release rate per unit volume of laminate. It can be seen that as the thickness increases this quantity falls to a value much lower than that observed for thin laminates. To exploit this potentially useful effect it seems desirable to have laminates about 8 mm or more in thickness.

Figure 6 shows the relationships between time to ignition and irradiance in the cone calorimeter test. Again, the superiority of the phenolic system can be seen. It should be noted, however, that in the region of irradiances covered, there is no threshold level below which ignition or flash-over will fail to occur- it is probable that even the phenolic system would ignite if subjected to low irradiance in this range for a sufficient period. (It is worth noting, by contrast, that the phenolic system shows no significant flame spread in the frequently used BS476 part 7 spread of flame test).

Figure 7 shows average smoke generation rates, again obtained from the cone calorimeter. Again the phenolic system is superior. A range of other smoke and toxicity tests provided further evidence of the superiority of the phenolic system in this respect.

Fire Resistance

The integrity of thick laminates in the furnace tests is impressive, as can be seen from the Table 2, with penetration times of the order of hours for the cellulosic test curve. For the hydrocarbon curve the burn-through times are reduced, but the phenolic composite still lasts for over an hour.

Table 2 Resistance of 9mm thick woven roving laminates in the indicative furnace fire test

Resin Type	Fire Curve	Time to 160°c (min)	Penetration time (min)
Polyester	Cellulosic	28	182
	Hydrocarbon	15	38
Vinyl ester	Cellulosic	20	175
Epoxy	Cellulosic	23	194
Phenolic	Cellulosic	33	110
	Hydrocarbon	18	72

Burn-through of the laminate occurs progressively, the resin being depleted from the surface layers, leaving successive plies of the glass reinforcement, which eventually fall away.

The fire resistance times (for the average temperature of the panel cold face to reach 160°c or for a hot spot to reach a temperature of 170°c) are, as might be expected, shorter than the penetration times. It is interesting to note that the slow burn-through effect is not very resin-dependent. Although phenolics are shown by the cone calorimeter test to be better in terms of heat release this is not strongly reflected in the indicative test, although the phenolic does give the best result for the NPD tests. In fact all four types of resin are currently being used in thick laminates for heat protection applications offshore and elsewhere.

The factors contributing to the slow burn-through of thick laminates in fire, are:

(i) Transport properties of the laminate. The fact that the thermal conductivity and diffusivity of FRP are lower than those of steel is clearly an important factor. However, our computer simulations suggest that that this is not the main effect operating.

(ii) Transport properties of the residual glass. The reinforcement, depleted of resin, remaining on the surface of the laminate has a lower thermal conductivity than that of the laminate itself. We have observed that procedures which help retain the depleted reinforcement on the panel surface, such as the addition of Ceepree (a proprietary ceramic frit, used in fire protection), silica or ceramic fibre plies, can improve fire resistance.

(iii) Endotherm due to decomposition and vaporisation. The processes of resin decomposition and vaporisation are highly endothermic and therefore temporarily delay the conduction of heat through the laminate. The volatilisation of any water present in the laminate will have a similar effect.

(iv) Convection of volatiles. As the gaseous products diffuse through the laminate towards the hot surface they can be expected to produce a cooling effect. In addition, when they reach the laminate surface they may form a protective thermal boundary layer. Although the volatiles are flammable, their contribution in a hydrocarbon fire is probably insignificant, compared to the thermal release taking already place in the fire.

Modelling the Fire Behaviour

A computer model for the fire-ablation process in a hydrocarbon fire was constructed, taking into the above effects. The model was used to investigate the significance of effects (i)-(iv) above and it was found that the most important effect operating was the endotherm due to resin decomposition- the heat absorbed by the resin decomposition process is almost entirely responsible for the interesting and potentially very useful behaviour of thick panels.

The computer model was found to be very effective in predicting the thermal profiles through panels, one example of the output, for a polyester panel, being shown in Figure 8. Once the model had been verified using experimental test data it was possible to use it to design structures for given fire performance. Figure 9, for instance, shows the predicted thickness of single skin panel required to achieve fire protection in a hydrocarbon fire, for a range of different times and acceptable rear face temperatures.

Fire Protection Applications

The slow burn-through effect can be used to great advantage in passive composite fire protection. One application example, relating to riser protection, is shown in Figure 10: here the material acts to give corrosion as well as fire protection.

Development of H60 and H120 Panels

In many areas of offshore use panels are required to achieve the stringent H60 or H120 rating, corresponding to resistance values of 60 and 120 minutes in the NPD test. Twin-skinned construction is attractive and weight-efficient for composite panels. Often, partitions and cladding are required to resist both blast and fire loading. With composite sandwich construction the fire performance of thick laminates can be enhanced by the use of fire-resistant core materials. Special consideration is required when choosing these core materials, as most conventional cores have poor fire performance. The materials with the best thermal performance, ceramics, tend to be either brittle or to be in a non-structural form. Two classes of material are potentially useful: compressed ceramic or cementitious board, and phenolic-based syntactics. Unfilled phenolic foams are too friable for sandwich panels, but syntactic foams containing expanded mineral fillers and other 'endothermic' additives do have suitable properties. There is considerable scope for further development of core materials to achieve the optimum combination of refractory properties, shear strength and density and several manufacturers are responding to this challenge. A number of companies now supply blast and fire-resistant panels, of increasing sophistication, to the offshore industry. An example has already been shown in Figure 2.

Conclusions

There are many potentially promising new applications of FRP in the offshore industry, the more significant areas being pipework (for aqueous services and fire water) and panelling for blast and fire protection.

Phenolic resins have the most favourable performance in terms of ignitability, heat release and smoke generation, so these materials may be favoured for areas involving personnel. All resins, however, show a very useful laminate thickness effect, which results in a slow rate of burn-through that can be used in fire protection applications. This effect is mainly due to endothermic decomposition of the resin.

Acknowledgements

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Fig. 1. An example of an offshore installation of glass reinforced epoxy pipework (courtesy of Elf Aquitaine)

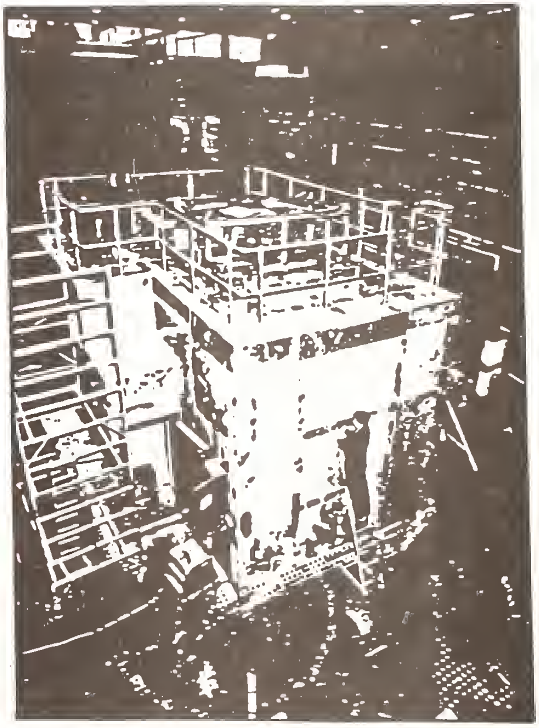

Fig. 2. Fire protection, using twin-sknned composite construction, of a safe enclosure within an offshore module (courtesy of Vosper Thornycroft (UK) Ltd)

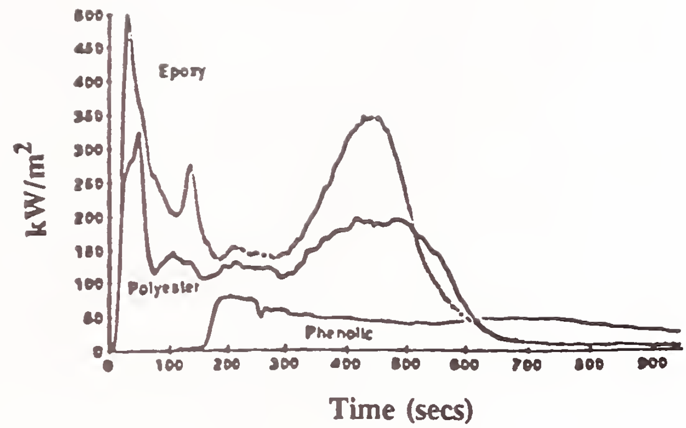

Fig. 3. Comparison of heat release rate vs. time for three resin systems, polyester, epoxy and phenolic at an irradiance of 80 kW/m^2. Woven roving laminates. Thickness: 6 plies

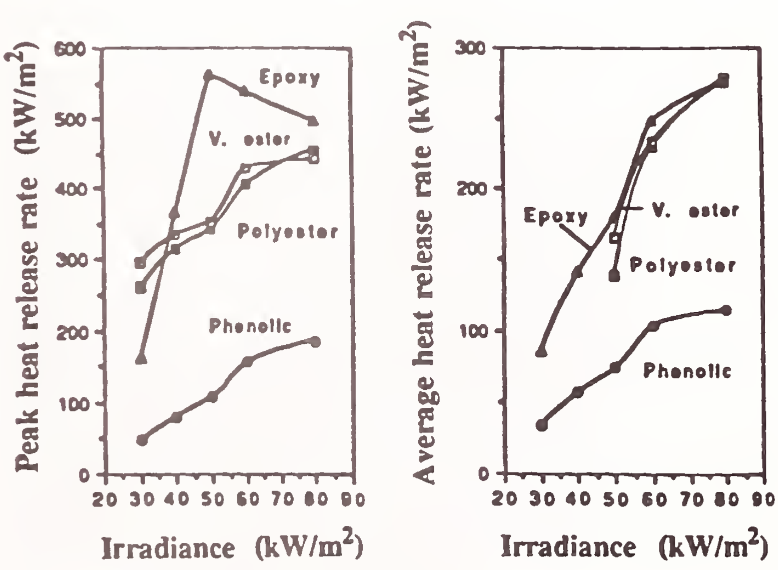

Fig.4. Peak and average release rates vs. irradiance for four resin systems: polyester, vinyl ester, epoxy and phenolic. Woven roving laminates. Thickness: 6 plies (approximately 3 mm).

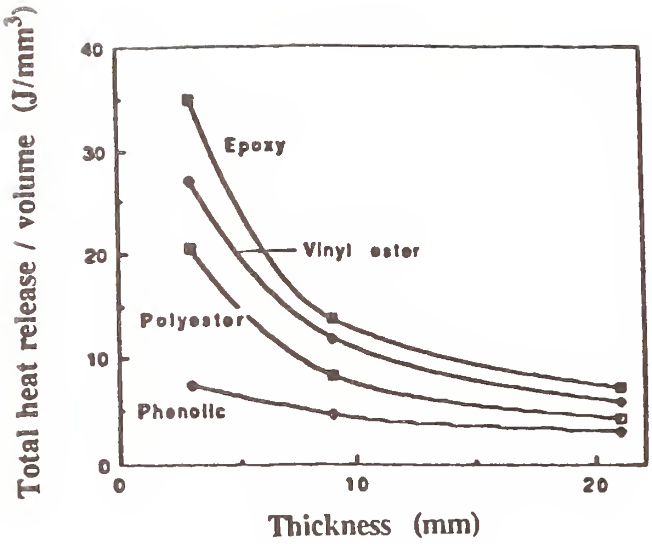

Fig.5. Total heat release per unit volume of woven glass composite laminates at an irradiance of 60 kW/m^2, showing the effect of laminate thickness.

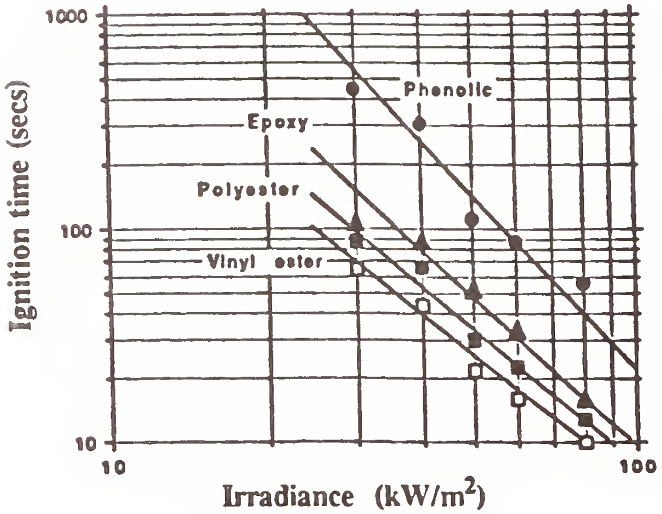

Fig. 6. Log-log plot of ignition time vs irradiance in the cone calorimeter test.

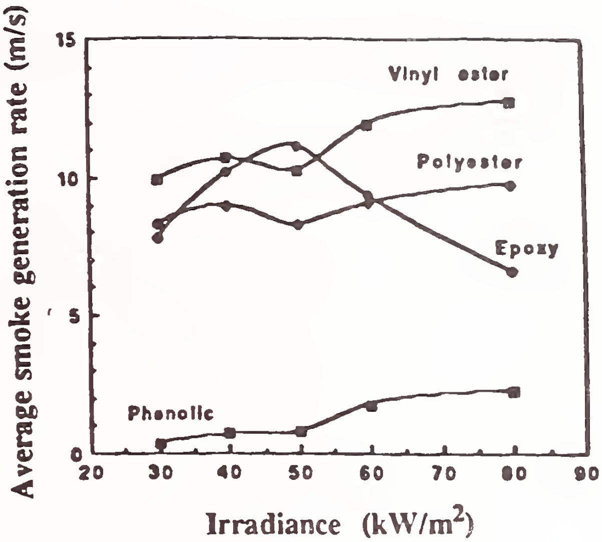

Fig. 7. Average smoke generation rate vs. irradiance for four resin systems. (6 ply woven roving laminates, ~3mm thick).

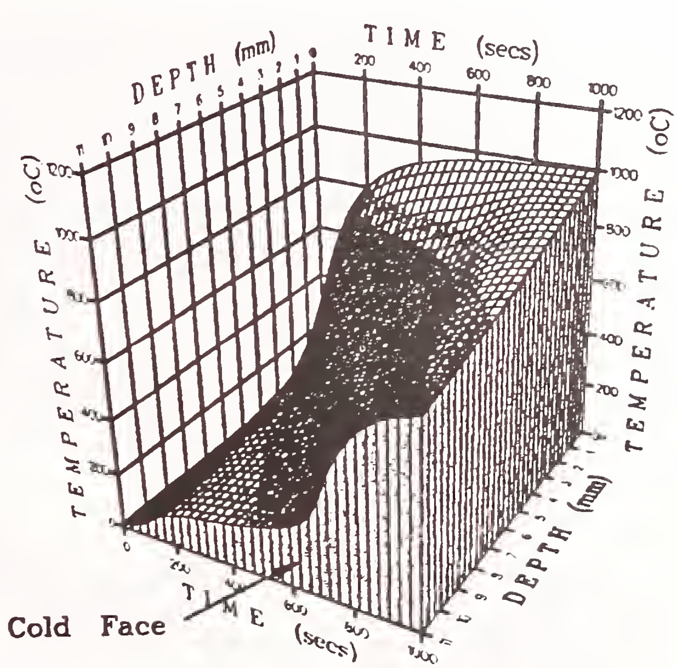

Fig. 8. Predicted thermal profile within an 11mm thick polyester/woven roving panel in a hydrocarbon fire test.

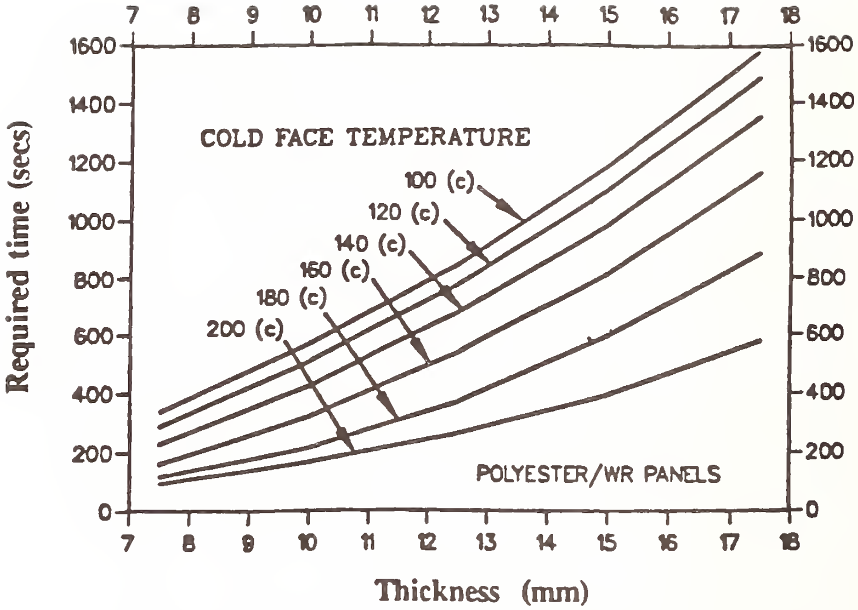

Fig. 9. Relationship, predicted by the computer model, between the laminate thickness and the time for the cold face temperature to reach various levels.

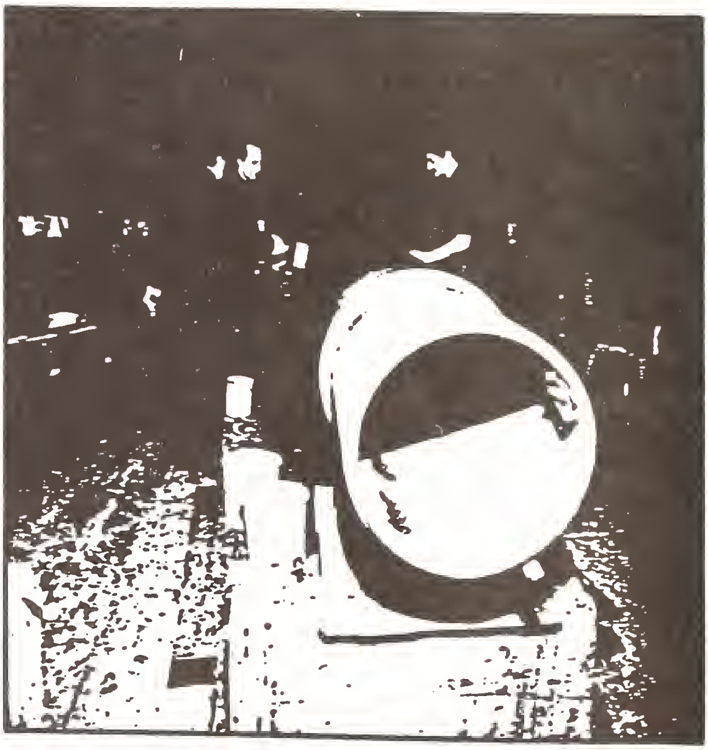

Fig. 10. Cladding of a steel riser with FRP (Courtesy of Vosper Thornycroft (UK) Ltd).

5. Working Group Papers

Materials Development for Cost Effective Fabrication

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Introduction

For composites to be used widely in offshore applications both economic and performance barriers must be eliminated. For the former, emphasis will need to be placed on the cost reduction of the composite part; a substantial element of which is associated with labor intensive fabrication. Performance issues related to composite durability, particularly in aggressive environments, must also be addressed. This paper will consider some of the material development aspects particularly associated with cost effective manufacturing. The ability to *"tailor"* materials over a very wide range, to satisfy fabrication and performance constraints, will be discussed with reference to examples from the aerospace and defense industries.

Material Selection and Development

Material Availability

Composite materials intended for offshore applications are not limited to what is commonly referred to as *FRP*, ie, simple epoxy resins reinforced with low performance glass fiber.

The aerospace industry has initiated the development of a wide range of composite materials to cope with performance, fabrication and economic constraints.

Within the class of "epoxy resins" there are a number of basic *building blocks* that differ in chemistry, processability and in final cured properties. In addition these epoxy building blocks can be extensively formulated and *fine tuned* to provide the necessary processing and properties needed for specific applications.

In addition, higher performance resin systems are available for use in extreme environments. Bismaleimide (BMI) and polyimide resins are available to provide high temperature performance (up to about 300°C). Phenolic and silicone resin matrix based composites are also used for thermal and fire resistance. Phenolic based composites in particular are used in applications that require short term protection at temperatures in excess of 3000°C.

The choice of fibers is also wide. There are several types of glass fiber available that can provide improvements in mechanical properties and corrosion resistance compared to the standard *E glass*. Various PAN based carbon fibers also exist. Properties range from low to high stiffness and prices from $10/lb to over $100/lb. Specialty fibers are also available for certain applications. The aramid fiber *"Kevlar"* is capable of providing composite laminates with good ballistic performance. The fiber is also used extensively in pressure vessels, eg, rocket motor cases. For thermal resistance, composites based on phenolic resins and refractory ceramic fibers are available. These include silica, silicon carbide, quartz and aluminosilicate type fibers.

The selection of a material system does not end with the choice of fiber and resin. The interface plays a crucial role. Performance improvements in the areas of thermo-oxidative stability, toughness and hot/wet properties can be gained by manipulation of the fiber/resin interface. This can be accomplished by fiber surface treatment and/or by applying a *finish* or *size* to the fiber.

Role of the Prepregger

The composite prepregger is responsible for developing the material system. This involves the selection of resin type, fiber and interface. This will be followed by extensive formulation geared to optimize the system for a particular application. The prepregger will impregnate the reinforcing fibers by a variety of routes depending on the material system. The resulting prepreg is sold to component fabricators.

The old industry perception of the prepregger is akin to that of a magician. Resins would be formulated by a hit and miss method employing *"the eye of newt/wing of bat"* approach.

In reality most prepreggers today employ an extremely systematic approach to product development. The high standards required by aerospace have forced the prepreggers to adopt very modern methods especially in quality control. In the case of BP Chemical's Fibers and Materials Division, a stepwise approach to product development is used. This approach leans heavily on the use of TQM principles and as such employs teamwork, problem solving tools (flow charting, Pareto analysis, brainstorming), experimental design and statistical analysis. The aim being is to develop products that are *robust* ie, insensitive to minor changes in raw materials and processing conditions. A key element of this product development approach is, of course, intimate customer collaboration.

The prepregger is capable of tailoring both prepreg and composite properties. This could be extremely important in developing composite materials for offshore application. Resin systems may have to be developed that provide easy processing coupled with good composite performance in aggressive and unique environments. Table (1) below summarizes the tailoring that is possible in the hands of the prepregger.

Table (1) Tailoring of Prepreg and Composite Properties

Area	*Tailored Properties*
Prepreg Lay-Up	* Tack * Drape * Outtime * Spring-back
Fabrication	* Method * Cure temperature * Cure time * Cure pressure * Exotherm
Composite Properties	* Toughness * Hot/wet properties * Temperature resistance * Microcracking resistance * Chemical resistance

Matching Materials to Fabrication Needs

Autoclave Fabrication of Large Structures

In the autoclave fabrication of large structures the material system, ie, prepreg, must be capable of providing the required performance in the composite as well as providing easy lay-up and fabrication. In the case of large structures this is not that easy.

BP Chemical's Engineered Systems Division (Gardena, Ca) manufactures the world's largest composite structure. This structure is a submarine bow dome. Many thousands of pounds of prepreg are needed to fabricate the dome. Prepreg lay-up takes approximately 6 months to complete. The structure is about 40 feet in diameter with a thickness of about 6 inches.

The huge size of the dome places some severe processing constraints on the prepregger. The material system used must exhibit an unusual combination of properties. The lengthy lay-up procedure requires the prepreg to exhibit exceptionally long out-time; tack and drape must be maintained. In addition, and due to the fact that the prepreg must be laid up on almost vertical surfaces, ply slippage must not occur. Prepreg *spring-back* ie, the undesired characteristic of the prepreg to become un-compacted must also be minimized.

Curing of such a large structure is also difficult. From a materials development point of view the candidate resin system must have an extremely low tendency to exothermic decomposition. Epoxy resins do have a tendency to rapid decomposition if the heating rate is high and bulk resin is present.

The prepreg rheological, physical and cure characteristics can be manipulated by formulation of the resin system. In the case of the bow dome such formulation would involve the choice of the exact epoxy resin building block(s) and additives which would seek to control viscosity, tack, drape and cure kinetics. In addition the resin system must provide the subsequent composite with the desired properties, and in the case of the bow dome, would involve meeting the desired mechanical properties and high levels of toughness.

The E719LT resin system developed by BP Fibers and Materials meets all prepreg and composite requirements and has been successfully used in the production of several bow domes. The E719LT resin system could be a candidate for the production of large composite offshore structures.

Filament Winding Using Prepreg Roving

Composite pipes and pressure vessels are routinely made using wet filament winding. For offshore applications there may be a need to develop such parts for higher performance use, eg, in chemically aggressive environments. In certain cases the material system needed for such environments may not be amenable to wet filament winding.

Prepreg roving is generally thought to be a more expensive route than wet winding. However, the advantages of the roving approach may warrant its use. Advantages include:

- accurate control of prepreg characteristics
- the ability to handle complex matrix chemistries
- improved environmental control

Some major defense programs have made use of the advantages of prepreg roving. BP Fibers and Materials was a major supplier of roving to the Peacekeeper strategic missile program. The motor case of the first stage is made from Kevlar/epoxy composite. The case is approximately 8 feet in diameter and about 20 feet long. The burst characteristics of the case must be accurately controlled. This is determined by a number of factors including lay-up sequence and material characteristics. Prepreg roving was chosen over wet filament winding because very accurate control of resin content, resin advancement, the fiber/resin interface and the conditioning of the Kevlar fiber was needed. Such control could only be maintained in the hands of a prepregger and by using the prepreg roving route.

Resin Transfer Molding

Resin transfer molding (RTM) has been shown by a number of companies to be a cost effective method of composite fabrication for *certain* components. Actual economics depend on a number of factors including the complexity of the component and the numbers to be made.

RTM involves the positioning of the fiber or fabric preform in a closed mold. Resin is then injected at elevated temperature usually under moderate pressure or with the assistance of vacuum. The curing operation takes place in the mold; there is no need for an autoclave. The component is molded to net shape with a very high degree of dimensional tolerance. There is no need for a trimming operation.

Suitable RTM resins must possess an unusual or incompatible balance of properties ie:

- low viscosity for easy injection
- long potlife
- single component system
- low cure temperature

.....whilst providing composite properties which exhibit:

- high Tg
- good hot/wet properties
- high level of toughness

There are several resin systems available that can satisfy the above requirements, eg E905L from BP Fibers and Materials.

RTM production parts are made by BP Aerospace Composites, Stockton. These parts are jet engine thrust reverser blocker doors. The doors are fitted to engines that power or will power Boeing's 737, 747, 757, 767 and 777 aircraft. The doors are lighter than the aluminum equivalent and are cheaper to produce.

Continuous Resin Transfer Molding

In a relatively new development, BP Aerospace Composites, Auburn has pioneered a potentially very low cost manufacturing method. The technique is termed *"Continuous Resin Transfer Molding"* (CRTM) and is a hybrid of pultrusion and conventional RTM; resin is injected into a moving fiber/fabric preform.

Trade studies have shown that CRTM is potentially the lowest cost route to the production of continuous constant cross section composite stock.

Again here the development of a CRTM resin must consider an unusual balance of properties. The resin rheological and physical properties are similar to those required by RTM. However, very fast cure is required, in the order of 5 minutes or so. To accomplish this whilst achieving good composite properties is no easy matter. CRTM resin systems are under development at BP Fibers and Materials. One system E907 shows promise and will be further optimized as part of an ARPA funded program on low cost composite processing.

Future Thoughts

Improved economics is *the hurdle* for the widespread use of composites in offshore applications. The cost of the fabricated part must come down and the lifetime must be equivalent or better to that of the metal part.

Fabrication is by far the dominant contributor to the high cost of composites. Kline and Co. estimate this to be about 70% of the total, see Table (2)

Table (2) Contributing Elements to the Cost Of Composite Parts

Element	*% Cost*
Resins	5
Fibers	10
Prepregs	13
Fabrication	72

Consequently, many companies are investigating ways to cut fabrication costs. Aerospace companies are looking at ways to automate tape and tow placement. Cure cycle optimization is possible through the use of cure monitoring techniques (eg, dielectric analysis). Low energy cures are also being considered. Boeing has often talked about *cure on the fly* ie, very fast curing by irradiative methods. The French aerospace company, Aerospatiale, has successfully developed an Electron Beam method of rapid curing and has built a commercial facility for the manufacture of missile parts.

In all cost reduction initiatives material development plays a key role and it will be up to the prepregger to develop new and novel material systems that are truly capable of providing cost effective fabrication.

Conclusions

In developing materials for cost effective fabrication the following points should be borne in mind:

* The aerospace industry has initiated the development of a wide range of material systems.

* Such materials can be fine tuned for specific properties and fabrication methods

* The potential for low cost fabrication exists through the use of novel manufacturing methods coupled with refinements in material systems

* Material development and component fabrication must go hand-in hand.

* Some aerospace technologies could be successfully exploited to help with establishing advanced composites as viable engineering materials for the offshore oil industry

Polymer Composites Program in the Polymer Division at NIST

by

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Introduction

Polymer composites are light-weight, high-strength materials whose properties can be extensively tailored. By using these advantages, products can be dramatically improved for competitive world markets. There are important opportunities in the areas of off-shore oil, infrastructure, automotive, electronics, construction, commercial aerospace, medical, and many other applications. An obvious near term opportunity is the automotive industry, and that is the initial focus of the NIST program. However, the research is of a fundamental nature and is expected to be applicable to many applications including offshore oil. Unfortunately, the potential of composites remains largely unrealized. There are two critical barriers hindering the wide spread usage of polymer composites: (1) the need to improve the speed, reliability, and cost effectiveness of fabrication, and (2) the need to develop a better understanding and predictive capability for long term performance (durability).

The programs in the Polymer Division seek to address both of these challenges. There are major efforts in **Processing Science** and **Durability**. In the processing area, the Division has interests in four fabrication methods: advanced autoclave cure, filament placement, press molding, and liquid molding (LM). The major focus is on LM, which includes resin transfer molding (RTM) and structural reaction injection molding (SRIM). This emphasis is based on the advice of industry obtained through a variety of mechanisms, including NIST sponsored Industry Workshops. The consensus was that LM offers the best possibility to achieve fast, reliable, and cost effective composite production. The work on durability builds on strong programs at NIST on the mechanics of composite resins, including work on viscoelastic properties, physical aging, and toughening. Based on the advice of industry, the work is expanding with a new effort that is studying environmental attack on composites by moisture and temperature.

Processing Science

In LM (fig. 1), the fiber reinforcement is assembled into a preform similar in shape to the final part, and this preform is then placed into a heated mold. The mold is closed, and a polymer resin and curing agent are mixed and injected to fill the mold. The heat initiates chemical reactions in the resin (curing), leading to the final part. In this process, the preform preparation can be automated, and the resin injection can be accomplished quite efficiently. As a result, LM combines some of the speed advantages of simple injection molding with the ability to make the high performance parts associated with continuous fiber reinforcement. Flexibility in the type, amount, and orientation of the reinforcement in every section of the mold enables the generation of very complex parts. Moreover, since the uncured resin viscosity is low, the parts can be quite large and three dimensional.

Because of these potential advantages, LM is the leading candidate for the fabrication of structural composite parts in the automotive industry, and may have equal potential in offshore applications. Effective use of liquid molding requires further developments in both preform fabrication methods and the technology required for process optimization and on-line process control. Preform suppliers and others have large efforts in preform fabrication technology. To complement these efforts, the National Institute of Standards and Technology (NIST) has initiated a major program to address the scientific issues associated with process optimization and control. This program has four tasks: Materials Characterization, Process Simulation Models, Process Monitoring and Control, and Sample Preparation and Application to Parts.

Materials Characterization

The first task focuses on characterization of the material properties associated with processing, i.e. preform permeability, thermal conductivity of the resin with and without the reinforcement, and cure behavior of the resin. Preform permeability measures the resistance offered by the preform to the flow of the resin. Since the reinforcement can have very different resistances to flow in different directions, the permeability, **K**, is a tensor. Thus, several measurements both in the plane and through the thickness of the preform material must be conducted to evaluate **K**. The resistance to flow is also very sensitive to the fiber volume fraction so this dependence must be determined. Several techniques are available at NIST to measure the permeability, and a variety of special molds and data analysis methods have been developed to minimize experimental errors and facilitate measurements at a variety of fiber volume fractions. For many cases where the part geometry is a shell-like structure, it is adequate to determine only the in-plane components of the permeability, and this significantly simplifies the characterization. Further details and examples of permeability measurements are given in ref. [1].

An important result of the permeability measurements is the demonstration that **K**, for woven composite reinforcements, is sensitive to the fabric architecture. The radial filling patterns displayed in Figure 2 were obtained with woven glass fabrics typically used in RTM, and all three fabrics were identical except for their weave patterns. The permeability tensors of the three fabrics were not only different in geometry, as illustrated, but in magnitiude as well. The sensitivity of **K** to preform architecture, and the wide variety of preform designs, leads to the requirement of either standardizing permeability measurements or developing predictive methods of computing **K**. The task of materials characterization therefore has the goal of developing the technology to predict the permeability from a knowledge of preform microstructure and fiber surface treatment. This would be an important advance because a preform could then be designed to optimize both performance and processibility. Although this technology is well beyond current capabilities, progress is being made [2]. In the interim, a standard reference material for permeability is being developed to fill the need for a method of accurately determining the permeability.

The measurement of thermal and cure properties for the materials involved relies heavily on process monitoring facilities at NIST. The objective in developing these facilities was to take advantage of NIST's position as an outstanding measurement laboratory by assembling a wide range of process measurement techniques including a variety of spectroscopic, optical, dielectric, ultrasonic, and viscometric methods. A total of ten different techniques have been adapted to process monitoring in this program [3]. This capability permits the examination of the chemical and physical changes that occur during processing at size scales ranging from individual chemical bonds up to bulk properties such as viscosity and viscoelasticity. By applying these techniques individually and in combinations, a detailed picture of the changes can be achieved.

Process Simulation

The second task in the Processing Science Program is the development of process simulation models. These models can be conveniently divided into two categories: macroscopic and microscopic. Macroscopic models employ the volume averaging approach to achieve computational efficiency. This approach resolves the mold into volume elements that are large enough so that variations in local features such as the arrangement of individual fibers in space, or the interactions between fluid and fibers average out, and thus only the averaged properties appear in the model. Such treatments are generally quite good for analyzing macroscopic events such as mold filling.

The macroscopic models are less useful, however, for predicting other important occurrences such as void formation since these events often depend on local features. To deal with this, microscopic models, which include some or all of the local features, are needed [2,4]. Although it is possible to simulate the entire part in microscopic detail, the computational time becomes prohibitive. As a result, events dependent on local features are simulated by first using macroscopic models of the part to predict boundary conditions on the local area, and then that area is simulated using a microscopic model.

A complete process simulation would include many factors such as resin flow, heat transfer, chemical reactions, etc., as well as the interactions between these factors. Chemical reactions, for example, generate heat which must be considered in the heat transfer relationships. In certain cases, it is possible to separate some of these factors and thereby simplify the modeling. Often, the mold filling may be completed before the chemical reactions produce significant effects. When the use of such simplifications is possible, the analysis can be accelerated. For many cases, the simulation of liquid molding is similar to the reservoir simulations conducted to design oil recovery operations.

Process Monitoring / Control

The third task in the NIST program involves on-line process monitoring. The purpose is to develop this technology and then use it to address two areas. First, experiments are being conducted to test and refine the process simulation models. Second, the technology is being explored for on-line process control. For testing the simulation models, the first step is an examination of flow behavior during mold filling. Complicating factors such as corners, edges, embedded objects, 3-dimensional effects, etc. are isolated and their effects on flow patterns studied. The results are then compared with the predictions of the computer simulations to refine, and verify the underlying flow models. The principal tool in such studies is flow visualization. One drawback of this approach, however, is that visualization, which is performed using molds having one or more clear sides, can provide information only about what is happening at the surface. Consequently, sensors such as fiber optic probes are being developed to measure flow front positions inside the preform.

Cure monitoring is also an important element of the process monitoring effort. A small number of the ten monitoring methods mentioned earlier have been chosen for additional development. For example, a current research effort is using optical fiber evanescent wave fluorescence experiments in an attempt to develop a single sensor for both flow and cure monitoring. Fluorescence has been shown to provide accurate cure monitoring data [3], and this capability is now being applied to liquid molding.

Sample Preparation and Application to Parts

The final task involves the fabrication of samples for testing in another NIST program which considers the performance and durability of polymer composites. In addition, this task is applying the developments in the LM program to the study of realistic parts through cooperative efforts with industry. One such example is a program between NIST and the Automotive Composites Consortium (ACC). The ACC is a joint effort between Ford, Chrysler, and General Motors and was formed to conduct precompetitive research that promotes the use of composites in structural applications. The ACC is demonstrating the results of their research by fabricating a series of full size parts. The first part chosen was the front end structure of a Ford Escort (fig. 3), and the fabrication method of choice was SRIM. NIST is cooperating with the ACC by conducting materials characterization and process simulations to help develop the technology required to optimize the fabrication of such a part. The permeabilities for the different reinforcement materials used in the part were measured and used as input data for the simulation model.

Figure 4 shows the data from a simulation. The flow front positions at various times are indicated by bold lines. As can be seen in the figure, such results can indicate how evenly a mold fills for a given preform and injection point. In this case, the last areas to fill are at the ends of the part which means a minimum of three vent locations would be needed to prevent air from being trapped in these regions. The model also predicts the pressure distribution from which the minimum mold clamping pressures and wall thicknesses can be calculated. Such results are particularly useful for examining the trade-off between injection pressure and filling time. The simulation also predicts many other features of the filling pattern that must be considered in optimizing the tool design and process. For example, it shows regions that are closed off by the flow before they are filled and weld lines where two flows converge. By using this information, process simulation programs can play a critical role in developing cost-effective processing for polymer composite materials.

A final point to note is that the input mesh for the flow analysis was obtained from the mesh used for the stress analysis that helped design the part. This suggests that a unified program could eventually be developed that would permit simultaneous consideration of both design and fabrication. The ability of such a program to balance and optimize both areas is a truly exciting possibility and represents an ideal goal for the future of such programs.

Durability

The newest work on durability focusses on characterizing the response of composites to environmental humidity [5]. This work builds on current activities in the Polymer Division that are developing methods to determine fiber-matrix interface properties [6]. A second major task compliments the interface studies by developing and utilizing techniques to characterize the microstructure of the interface region. Of particular interest is recent work that uses this capability to determine the distribution of moisture near the interface after exposure to water [7]. Finally, a program to study the compression response of composites leverages other expertise in the Polymer Division in the areas of physical aging and nonlinear viscoelasticity of solid polymers [8]. Finite element codes are being developed that incorporate viscoplastic resin behaviors [9]. In the future these codes will include the ability to treat non-isothermal histories and nonlinear viscoelastic material behaviors.

Measurement of Interface Strength and Durability

The fiber-matrix interface is perhaps the least understood feature of a composite, and yet it plays a critical role in behavior such as durability. To study this aspect of a composite, NIST has implemented two widely used methods to determine interface strength: the single fiber fragmentation measurement and the micro-drop pull-off test. There is now an active effort to refine and improve these tests [6]. Studies from this laboratory [5] have shown that the fragmentation sample, which is a single fiber composite, can serve as a useful model system for determining the effects of moisture on the interface. However, it was found that the glass fiber is also degraded by moisture. This finding is important both because it may be an important degradation mechanism in the composite but also because the fiber strength is needed in the analysis of the interface strength. To address this problem, a new analysis method was recently developed which extended work by Wagner [10] to permit the simultaneous determination of fiber strength and interface strength.

In the current program on durability, samples for the single fiber fragmentation test are being prepared by different processing methods and with different fiber surface treatments. In addition, a range of special sizings is being applied and the resulting surface coating characterized by various chemical and spectroscopic methods. The samples are then exposed to water for various periods of time and tested. Initial results show clear indications of degradation in both the fiber and the interface. Analysis of the supernatant water indicates the presence of ions extracted from the fiber (see fig. 6). Through analyses of both the chemistry and mechanics that occur during the exposure, the degradation mechanisms will be identified and characterized. To complement these studies with single fiber composites, a comprehensive series of experiments is planned with actual composite materials. This work is being coordinated with the Automotive Composites Consortium and suppliers to the automobile industry.

Characterization of the Interface Region

To compliment the measurements described above, NIST has developed a novel method to characterize the interfacial region between polymers and solid substrates using neutron reflectivity (NR). Although the technique requires the use of flat surfaces, it can not only determine the segment density of the polymer near the interface, but can also study the morphology of coupling agents and analyze the moisture concentration in the region. For example, the initial work employed a silicon-polyimide (PI) interface and found the existence of an unexpectedly high concentration of moisture in the 25 Å region of polymer adjacent to the solid surface [7]. A high water concentration has long been postulated to explain various moisture related problems encountered in composites, protective coatings, and electronic packaging but had never been demonstrated and quantified prior to this measurement. Figure 5 shows the water content as a function of distance away from the interface after the sample had been exposed to water vapor for a week at 23°C. The water content within this thin layer reached 16% by volume, as compared to the bulk saturation level of 2.4% in PI. Neutron reflectivity provides a unique tool for studying durability of the interface region.

Aging of Polymeric Resins and Performance of Composites

As a part of the overall program on composites in the NIST Polymer Division, there has been considerable effort to characterize the underlying physics of aging of the neat resins. This is because the prediction of the performance of composite materials depends upon the ability to estimate accurately the state of residual stress both in the resin and at the fiber- matrix interface. Without adequate models of the nonlinear viscoelastic response of the neat resin in non-isothermal processing/use histories, estimating the residual stress is very problematical. Of particular importance have been studies that show currently available models to be inadequate for describing the changes in viscoelastic and yield responses of thermosetting resins [8,11]. To this end, work is ongoing to evaluate a series of solid polymer constitutive laws that are based upon the physics of material clocks. In coordination with this work, finite element codes are being programmed to incorporate material nonlinearities such as plasticity [9], and more recently we have begun to consider non-isothermal, viscoelastic codes as well.

A good example of the importance of aging effects in composites arises from an examination of Figure 7, in which the yield response of a model epoxy system is shown at different aging times after a quench from above the glass transition temperature to below it. As can be seen, with just 1000 h of aging, the yield strength increases by over 60%. When the fracture or impact resistance of the resin phase in the composite is important, such resin aging can be detrimental to the performance of the composite because of a concurrent increase in brittleness. In summary, physical aging is expected to play a role in the evolution of composite properties such as stability to water or other solvents, fracture toughness, and the coefficient of thermal expansion. Finally, work is beginning in this laboratory to examine the influence of moisture on the aging response of neat resins.

Summary

The NIST program in polymer matrix composites has two thrust areas, **Processing Science** and **Durability**. Both of these areas are engaged in research designed to solve problems critical to mass production and usage of composites in a variety of applications, including offshore oil. The processing effort is focused on Liquid Molding because that fabrication method has been identified as holding the most promise for mass producing structural parts of complex geometries. The durability effort is focused on environmental effects at the fiber matrix interface because that area has been shown to be of critical importance to the long term performance of composite materials.

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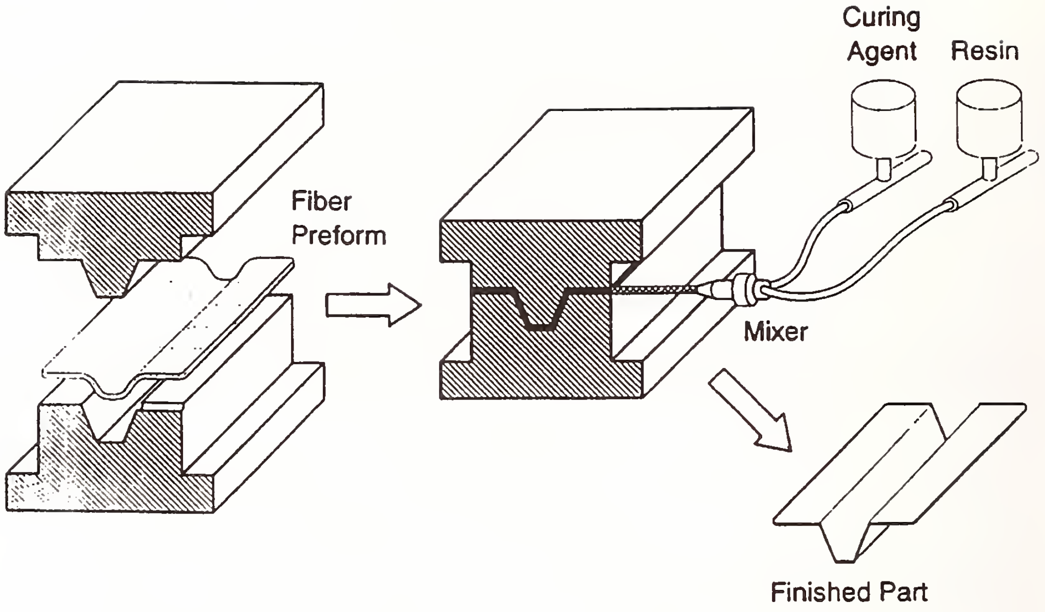

Figure 1: In liquid molding, a fiber preform is placed into the mold, the mold is closed, and a resin system and curing agent are mixed and injected to fill the mold. Chemical reactions are then initiated by heat, and the final part is formed.

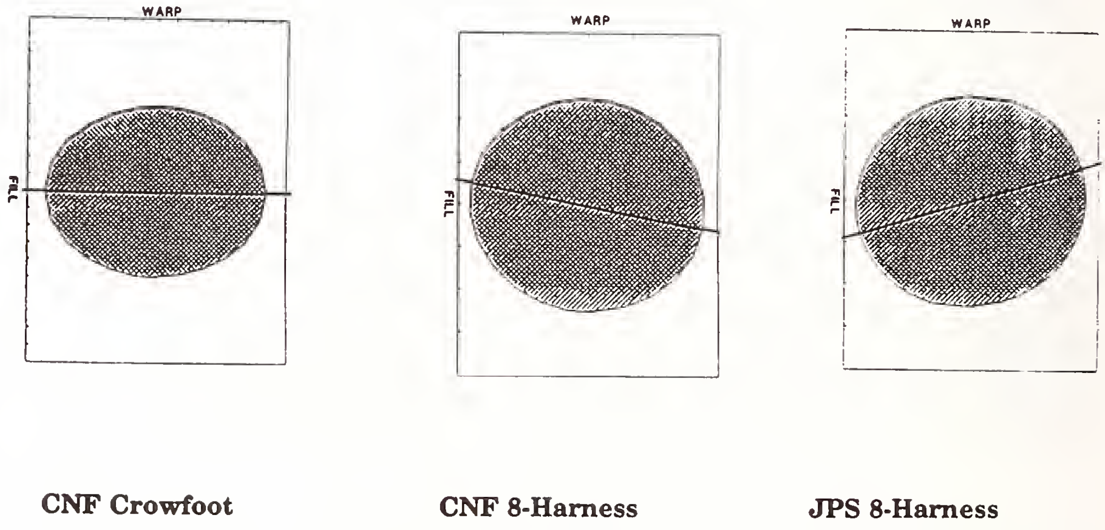

Figure 2: Radial flow patterns of fluid permeating woven glass fabrics.

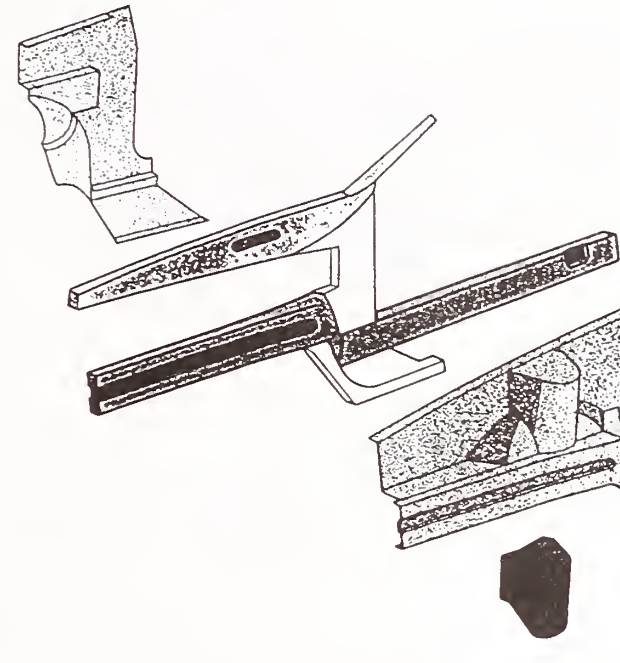

Figure 3: Diagram of the front end structure fabricated by liquid molding in the Automotive Composites Consortium program.

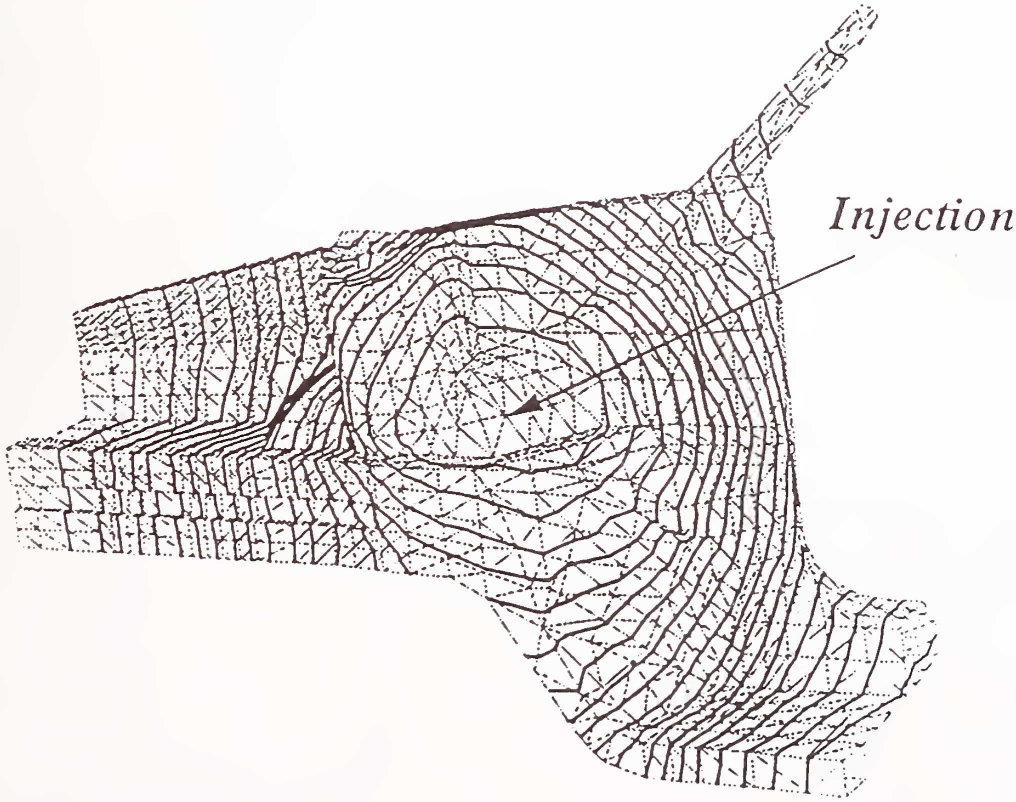

Figure 4: Mold filling simulation for the ACC demonstration part. The bold lines represent the flow front positions at various time during injection.

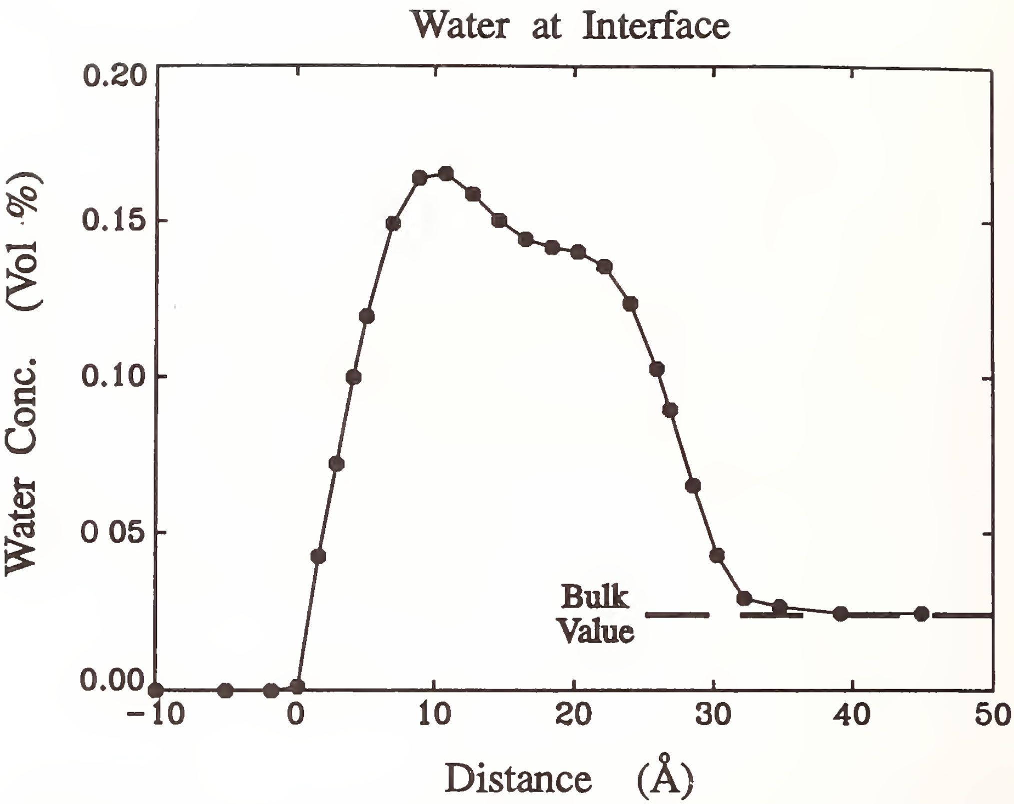

Figure 5: The concentration of moisture is shown as a function of distance into a polyimide film on a silicon substrate.

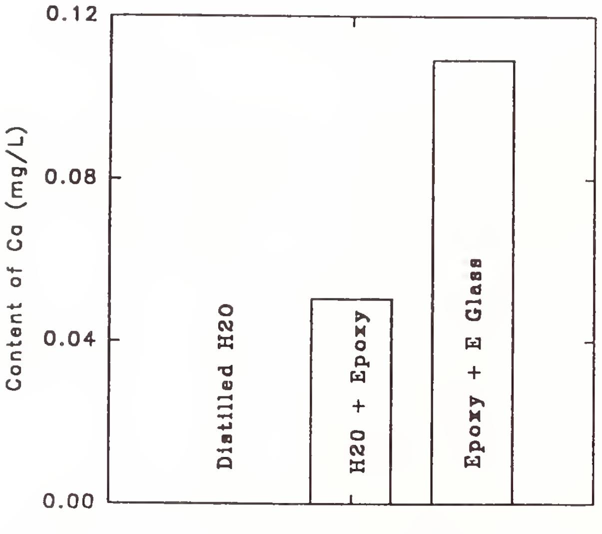

Figure 6: Comparison of the content of calcium in water for distilled water, epoxy and single fiber specimens exposed to distilled water for 5,520 h and 75°C. E-glass fiber in DGEBA/mPDA epoxy.

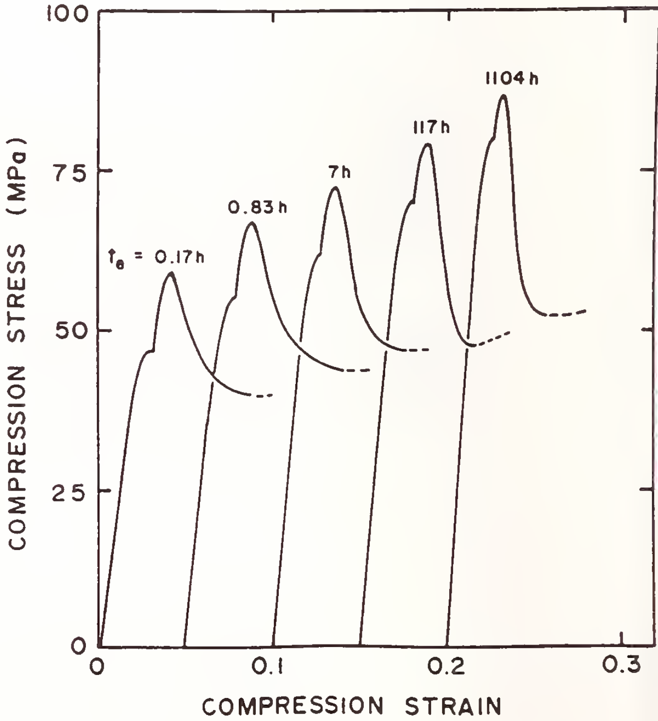

Figure 7: Typical compression stress-strain curves obtained at T_g-10°C for epoxy glass increasing times t_e after a quench fr above T_g.

POLYMER COMPOSITE MATERIALS PERFORMANCE CRITERIA FOR OFFSHORE PETROLEUM PRODUCTION: AN OVERVIEW

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Introduction

Fiber-reinforced polymer composites for structural applications were first introduced into service about 50 years ago, during World War II as radomes and small boat hulls and airframe bodies[1]. The glass fiber reinforced polyester and epoxy polymers introduced at that time, provided a basis for developing consumer and industrial markets that took advantage of the now accepted composite characteristics of light weight, parts consolidation for ease of fabrication, installation, and resistance to chemical attack at moderate temperatures. Examples of current composite product applications include: boat hulls, sewer pipe, appliance bodies, furniture, electronic circuit boards, secondary structural parts in the automotive industry, piping and vessels in the chemical industry, performance parts in aircraft, golf clubs and tennis rackets. In 1992, North American manufacture of fiber-reinforced polymer composites exceeded 1 million tons/year. As illustrated in Table 1, low-cost, moderate performance glass-fiber composites for the transportation and marine industries accounted for about half of the sales. High performance, high cost composites based on carbon or polymer fibers and specialty polymer matrices, were produced in much lower volume for the aircraft and aerospace applications.

TABLE 1
Representative 1992 North American Markets For Polymer Composites.

STATISTIC	AEROSPACE	TRANSPORTATION	MARINE
TONS/YEAR:	10,000	361,000	150,000
USE:	Primary Structural Components	Secondary Structural Components	Secondary Structural Components
EXAMPLE:	Epoxy/Carbon	Polyester/Glass	Polyester/Glass
COST:	$10 - >$100/lb	$3-4/lb	$3-4/lb

(Source: Modern Plastics Magazine, 1993)

Over the past thirty years, low cost polymer composites have been steadily introduced into onshore oilfield production operations, primarily to substitute for carbon steel in relatively low temperature applications experiencing severe corrosion, such as lift pump sucker rods and low pressure produced water lines. For example, glass fiber reinforced polymer (GRP) pipe has been in use since the early 1970's in Exxon's Conroe, Texas field [2] for oil-well flow lines, gathering lines and produced-water injection lines. Based on an acceptable performance in service, the nominal operating limit for existing GRP pipe is ≅ 25 Bar at 100°C [2,3]. Examination of buried pipe after periods of up to 25 years have indicated good retention of properties [4]. Also, pressure testing of new pipe for up to 18 months at 75°F, with 300-600 psi dry or wet CO_2, showed no degradation or chemical attack [5]. In marketing these products to onshore operators, composite manufacturers have had to address the issues of handling, damage tolerance and joining, since composite mechanical behavior differs markedly from that of steel, the structural material of choice in oil fields for the last 100 years. They have not, however, had to cope with the extensive regulatory requirements on flammability, fire safety and toxicity which must be addressed for ship and offshore platform use [6-8]. For example, the

International Convention for the Safety of Life at Sea (SOLAS), 1974, as amended [9], indicates that structural materials for use in marine environments shall be steel or 'equivalent material'. Nevertheless, the U.S. Navy, in conjunction with NIST, has pioneered the use of composite piping for shipboard applications [10], and has sponsored research on the materials flammability and toxicity for shipboard use as piping and deck structures [6-8]. Extensive research and testing in Norway, the United Kingdom and North America has led to acceptance of polymer composites on offshore platforms for secondary structural applications, such as firewater systems, produced water return lines as well as decks and gratings [11]. Figure 1 shows current and potential applications of polymer composites on offshore platforms now being addressed by manufacturers of conventional, low cost polymer composites. Installed offshore platforms number about 5000 in North and South America and about 6100 total Worldwide [12]. Hence, a significant market exists in platform retrofit and in new construction, incorporating state-of-the-art composite materials.

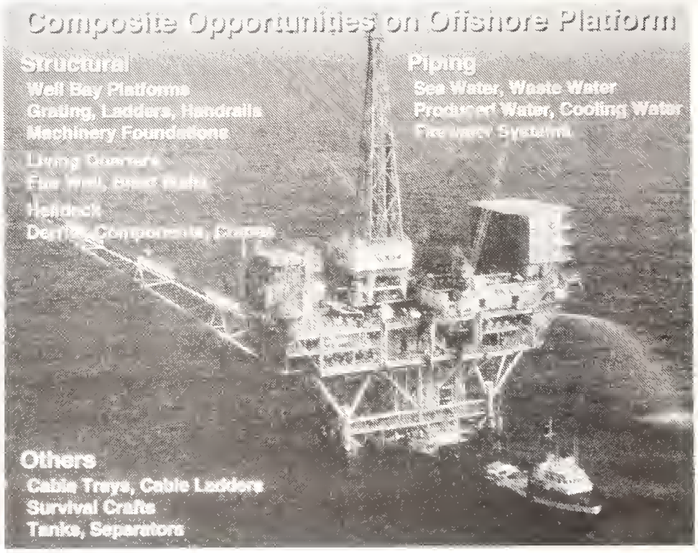

Figure 1
Representative Current and Future Composite Applications on Offshore Platforms

Hence, the research frontier involves developing advanced materials at affordable cost, and establishing life prediction capability for conventional and deep water platforms. For example, Tension Leg Platforms (TLP's), considered in Working Group #7 on Advanced Applications, can capture system design advantages from the use of high performance polymer composites in TLP risers, TLP tethers, topside primary structural components, and downhole tubulars for use up to 220°F.

The purpose of this paper is to provide an overview of fundamental aspects and criteria for mechanical performance and damage tolerance, that is strength, stiffness, impact toughness. In addition, it addresses environmental performance and durability, that is thermal, mechanical and chemical stability, over the range of offshore operating conditions, shown in Table 2. The assessment also includes evaluation of current composite costs and future requirements for widespread offshore use. Near and Long term research initiatives are identified that are required in order for polymer composites to make a significant impact on offshore operations for oil and gas production.

TABLE 2.
Performance Criteria For Composite Application In Offshore Production Operations.

Parameter	Secondary Loading	Primary Loading	Downhole Tubing/Casing
Temperature :	-50°C to + 40°C	-50°C to +40°C	+25°C to +220°C
Environment :	Air, Sea Water	Air, Sea Water	HC's, H_2O, H_2S, CO_2
Stress State :	Tensile, Compressive	Tensile, Compressive	Tensile, Biaxial, Compressive
Reliable Life :	>20 yrs.	>30 yrs.	>20 yrs.

Current Performance and Economics of Polymer Composites Versus Metals

The tensile strength, modulus and price for representative steels, which have been the primary material used historically, offshore, for structural components, pressure vessels, piping and downhole tubulars are summarized in Table 1. The different strength levels used for piping, which is typically welded, and for tubulars, which employ threaded connections, are indicated. From a cost and strength standpoint, low carbon steel is the favored material. When neither corrosion allowance nor inhibitors are acceptable corrosion control strategies, carbon steel can be replaced by higher priced corrosion resistant alloys or alloys of titanium. The mechanical properties of metals over the typical, offshore, operating temperature range of -50°C to +220°C are relatively constant. Hence, for metals, the influence of temperature on corrosion resistance arises primarily from the temperature dependence of interface reaction kinetics and on the stability of protective films formed on the metal surface.

TABLE 3.
Performance And Cost Of Representative Metals Used
In Offshore Applications.

MATERIAL	Density (gm/cc)	Piping Strength (MPa)	Tubing Strength (MPa)	Compress. Modulus (GPa)	Tensile Modulus (GPa)	Price ($/lb)
Low Carbon Steel	7.83	415[a]	760[b]	204	204	0.50
316 Stainless Steel	8.03	208	415	191	191	3.00
2205 Duplex Stainless Steel	8.03	415	760	191	191	4.00
Incoloy 825	8.17	415	760	194	194	8.00
Hastelloy C-276	8.89	415	760	193	193	15.00
Titanium (Grade 2)	4.43	345	760	108	108	25.00

[a]P-60; [b]P-110 ; Prices from Reference 13 and vendor discussions.

Glass fiber polymer composites are of increasing interest in secondary structural applications in offshore operations because of their corrosion resistance at moderate temperatures, low weight and reduced maintenance costs. The intrinsic mechanical properties of representative inorganic and organic fiber reinforcements, thermoset and thermoplastic polymer matrices are summarized in Table 4. Also listed are the current prices for these materials. In contrast with metals, the thermal properties of thermoset and thermoplastic polymers, used in composites, can vary significantly over the temperature ranges given Table 2. Accordingly, it is important to consider the temperature dependence of their mechanical properties and their resistance to corrosion. For operation under ambient offshore temperatures (-50°C to +40°C), empirical near term experience substantiates the reliability of commercial composite products made from glass fiber and thermoset polymers. Neither empirical experience nor predictive methodologies are available for assessing the reliability of composites, exposed for longer times to severe environments and higher temperatures, that is, up to about 220°C.

The mechanical properties of commercial filament-wound composite piping, with 60% by volume of fiber, are summarized in Table 5. The table also lists vendor prices for glass-polyester and glass-epoxy pipe, and estimated prices for developmental, carbon-epoxy pipe, see footnotes to Table 6. It

TABLE 4.
Performance and Cost of Representative Reinforcing Fibers and Polymer Matrices.

REINFORCING FIBERS	Density (gm/cc)	Tensile Strength (GPa)	Axial Modulus (GPa)	Transverse Modulus (GPa)	T(g) (°C)	T(hd) (°C)	T(m) (°C)	Price ‡ ($/lb)
E-Glass	2.56	3.40	76	76	600	600	NA	0.70
*SiC**	3.20	3.50	400	400	NA	NA	>2000	NA
*C (diamond)**	3.52	3.50	1200	1200	NA	NA	>3000	NA
Carbon/AS4 or HS	1.76	4.00	245	14	NA	NA	>3000	9.00
Kevlar 49	1.44	3.70	129	7	NA	>400	NA	10.00
MATRICES	**Density (gm/cc)**	**Tensile Strength (GPa)**	**Tensile Modulus (GPa)**	**Compress Modulus (GPa)**	**T(g) (°C)**	**T(hd) (°C)**	**T(m) (°C)**	**Price ($/lb)**
Thermosets								
Polyester(Isophtalic)	1.27	0.075	3.4	3.4	120	100	NA	0.55
Vinylester	1.25	0.075	3.4	3.4	120	100	NA	0.55
Epoxy(DGEBA/DDS)	1.16	0.080	2.7	2.7	130	120	NA	1.20
Thermoplastics								
Polypropylene	0.91	0.036	1.4	1.4	-8	60	165	0.50
Polyphenylene Sulfide	1.35	0.066	3.8	3.8	88	120	288	3.00
Polyetheretherketone	1.32	0.100	3.9	3.9	143	152	334	30.00

* Intrinsic properties; materials not available. ‡ Prices from Reference 14 and manufacturers.

TABLE 5.
Performance and Cost of Commercial Polymer Composite Pipe.

COMPOSITE MATERIAL[a]	Density (gm/cc)	Weeping Stress (MPa) (hoop)	Ultimate Stress (MPa) (hoop)	Ultimate Stress (MPa) (axial)	Tensile Modulus (GPa) (axial)	Compress Modulus (GPa) (axial)	Price ($/lb)
E-glass/Polyester[1] (218 mm OD, 0.36 mm wall)	2.04	95	>300	70	17.3	0.167	3.10[3]
E-glass/Epoxy[1] (218 mm OD, 0.36 mm wall)	2.00	95	>310	100	16.4	0.23	3.10[3]
C-AS4/Epoxy[2] (96.5 mm OD, 0.92 mm wall)	1.52	Not Measured	1,300	710	36.7	0.42	9.01*

[a] Filament wound pipe, 0.6 volume fraction fiber. [1] ± 55° layup; [2] 90° 6 /± 30° 2 layup; Reference 15.
[3] From A.O. Smith Fiberglass. * Estimated as indicated in Table 6.

is significant that E-glass/polyester and E-glass/epoxy pipe are finding acceptance as produced-water return and fire water lines, in spite of six-fold higher cost/pound and four-fold lower usable stress under fluid containment conditions[2-4, 16], compared with low carbon steel piping. However, because a higher wall thickness is required in carbon steel piping than necessary for pressure containment, for example as a processing requirement and to provide a corrosion allowance, the weight-per-unit length of carbon steel pipe in the 8-12 inch-diameter range can be a factor of 10 higher than for composite pipe suitable for low pressure water usage (150-300 psi at up to 100^{o}C). The authors are not aware of any data on the threshold stress for *weeping* or loss of fluid containment for carbon-epoxy piping. This absence probably reflects aerospace industry practice, where carbon fiber-reinforced polymer composites typically require the use of an internal liner or bladder to guard against loss of fluid containment. Although the cost per pound of carbon-epoxy is a factor of three higher than glass-epoxy, the density is 25% lower and the modulus is a factor of three higher. This suggests the possibility of lower strain, and hence higher stress levels for the incidence of weeping. Hence, carbon-epoxy piping might be cost effective on a cost/foot basis with glass-epoxy piping, if superior weep stress thresholds can in fact be achieved.

Technology and Economic Gaps Between Current Offshore Usage and Future Requirements

The technology hurdles to the use of polymer composites in the offshore involve the entire range of sequential activities, from conception to final retirement. These activities include material design and synthesis, manufacturing processes and fabrication, joining and installation, field inspection and repair and finally recycling. These technical hurdles may be grouped according to three principal categories: 1) Mechanical Performance, 2) Chemical Characteristics, and 3) Environmental Response. Economic gaps are associated with each of these activities, involving costs at time of material purchase, during construction and during life cycle operation.

Mechanical Performance

The mechanical properties that are considered in this paper include strength, stiffness, toughness and damage tolerance as well as the effects of compressive loading, fatigue and creep. These characteristics are the subject of companion papers in Working Group #2. The status of current properties and the short comings of strength and stiffness are illustrated in Table 6, which lists these properties for unidirectional polymer-composite laminate products with 60 volume percent loading of continuous fibers. Included in the table are vendor prices for glass-polyester and glass-vinylester products. With the exception of rod made from glass-fiber and polyester, vinylester or epoxy, which is used as gratings, handrails and ladders offshore and as sucker rods onshore, all the other materials are developmental. To provide a basis for assessing the current and future potential of these materials, under conditions of tensile loading, projected commercial prices of developmental, unidirectionally aligned (UDA) polymer composites are also estimated and shown in Table 6. Rated on price per pound, the most inexpensive UDA polymer composites are six times the cost of 60 ksi low carbon steel. However, for primary structural components, designed to support load in uniaxial tension, polymer composites compare very favorably with metals on the basis of load carrying capacity per unit cost, because of their four-fold lower density and higher strength. A clear comparison between metals and composites in terms of strength, and specific cost, load capacity per dollar, for offshore applications, can be obtained from Figure 2. It can be seen from the figure that unidirectional E-glass/Polyester or E-glass/Vinylester is approximately equivalent in strength and load per unit cost to 60 ksi carbon steel while E-glass/Epoxy has twice the strength of the same steel

TABLE 6.
Performance and Cost of Representative Reinforcing Fibers and Polymer Matrices.

COMPOSITE MATERIAL[a]	Density (gm/cc)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Compress Strength (MPa)	Compress Modulus (GPa)	Flexure Modulus (GPa)	Price ($/lb)
E-glass/Polyester	2.04	600	36	360	----	36	3.06[1]
E-glass/Vinylester	2.03	600	36	390	----	36	3.06[1]
E-glass/Epoxy	2.00	1,000	44	612	----	----	3.21 [2]
E-glass/PPS	2.08	1,060	47	----	----	46	411d
E-glass/PEEK	2.07	1,090	53	----	----	51	11.77[3]
C-AS4/Epoxy	1.52	1,500	150	952	----	----	9.01 [2]
Kevlar-49/Epoxy	1.33	1,360	79	272	----	----	9.15 [2]
C-AS4/PPS	1.60	1,830	134	938	130	117	10.41[3]
C-HS/PEEK	1.59	1,970(av)	134	1,440(av)	119	123	20.44[3]

[a] Pultruded laminate, 0.6 Volume Fraction Fiber. [1] From Morrison Molded Fiber Glass.

[2] Estimated ≅ materials + $2.40/lb fabrication. [3] Estimated * materials + $5.00/lb fabrication.

* Properties from References 16-18.

along with a 40% higher load capacity per unit cost. Other pipe-grade steels and the titanium alloys have significantly lower load/unit cost compared to carbon steel; reflecting the penalty of alloying to achieve corrosion resistance. This comparison validates the cost-effectiveness of E-glass/thermoset composites for decks, gratings, and ladders where the "ideal" strength of UDA polymer composites can be captured together with the excellent corrosion resistance. The figure also highlights the future potential of carbon fiber composites for platform components which are loaded in tension, such as topsides structures and TLP tethers. Metallic materials, such as shown in Table 3, with approximately twice the strength of piping grade metals, are also candidates. But in such applications their increased tendency to stress-cracking adds an additional corrosion control cost, offsetting their higher strength.

Where stiffness is a major structural criterion, Figure 3 illustrates that low carbon steel has about a factor of four higher stiffness per unit cost compared to current UDA polymer composites. However, where corrosion resistance is also a factor, polymer composites may still be favored, since the stiffness per unit cost of composites is approximately equal to stainless steels. In addition, future reductions in the cost of carbon fibers and high performance thermoplastics, such as PPS and PEEK through economies of scale and experience, have the potential to increase the stiffness per unit cost of UDA polymer composites. In biaxial and triaxial loading, however, the strength of composites with multiaxial fiber architectures can be significantly lower than that of UDA composites in tensile loading. This short-fall represents a technology gap which is illustrated by comparing the properties of UDA polymer composites of E-glass with polyester or epoxy in Table 6, with those of filament wound pipe of the same materials in Table 5. The gap is apparent from the very low 'weeping stress' [2-4,16] of filament wound pipe, which results in the factor of 7 lower load/unit cost, shown in Figure 2, compared to the ideal UDA laminates. However, this composite piping is still cost effective on an installed-life-cycle basis compared to carbon steel, due to lighter weight and corrosion resistance, which translate into reduced installation and maintenance costs. Figure 2 also illustrates that composite piping is equivalent or superior in load/unit material cost to any of the corrosion resistant alloys, validating their selection for moderate service temperatures up to about 65°C.

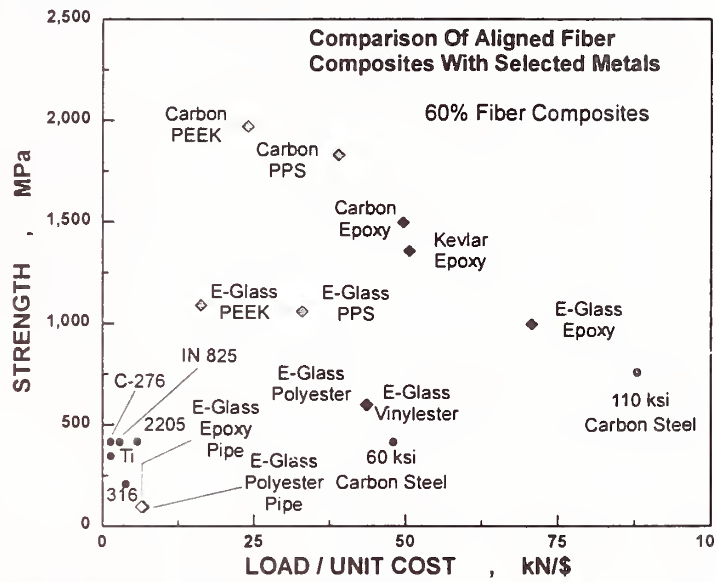

Figure 2
Strength versus load capacity per unit cost for structural materials.

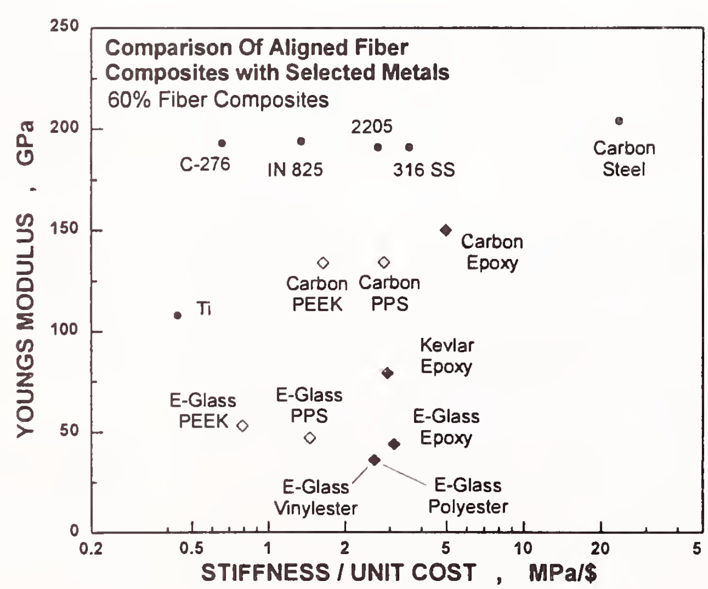

Figure 3
Modulus versus stiffness capacity per unit cost for structural materials.

Chemical Characteristics

The chemical properties of polymer composites impact on a wide range of activities, including polymer and fiber synthesis[20], the thermal properties such as curing temperature for thermosets and melting point for thermoplastics which influence composite processing by filament winding [21] and pultrusion [22], joinability and flammability [6-8]. Technology and cost gaps associated with these properties are discussed in companion papers from the eight working groups of this Workshop.

Environmental Performance

Environmental behavior of polymer composites are a particularly critical area in which there is at present insufficient fundamental understanding, particularly when the effects of temperature and stress are combined with the effects of corrosive environments including hydrocarbons, H_2O, H_2S, CO_2, NaCl and other halide salts, O_2, O_3 and ultraviolet radiation. It is known that water diffuses into thermoset polymers and can affect the mechanical properties of E-glass and carbon fiber composites [23-27].

However, in-depth mechanistic and kinetic understanding is lacking to provide reliable quantitative prediction of composition and properties for the long exposure times, 20-30 years, required for reliable operation of polymer composites on offshore structures. Recent investigation of environmental properties is discussed in companion papers from working group #2. Environmental life prediction is crucial to meet operator and regulator requirements for polymer composite reliability under primary loading and in downhole applications, as will be further discussed in the following section on research initiatives.

DESIGN, SYNTHESIS, MANUFACTURING PROCESSES, FABRICATION, JOINING, INSTALLATION, FIELD INSPECTION, REPAIR

CHEMICAL *(Synthesis, Processing, Use)*	MECHANICAL *(Design and Characterization)*	ENVIRONMENTAL *(Life-Prediction in Application)*
MOLECULAR STRUCTURE AND PROCESSABILITY	PROPERTY MEASUREMENT AND MODELING	DIFFUSION, ABSORBTION, PERMEATION, REACTION
STRUCTURE-PROPERTY RELATIONSHIPS	TOUGHNESS, DAMAGE TOLERANCE, FRACTURE MECHANICS	CHEMIICAL SYNERGY
REACTIVITY AND DURABILITY	MECHANISMS OF STRENGTHENING AND STIFFENING	CORROSION, STRESS CRACKING AND GALVANIC EFFECTS
FLAMMABILITY AND TOXICITY	TEMPERATURE/STRESS EFFECTS (CREEP AND FATIGUE)	BIODEGRADATION AND BIOFOULING

Figure 4
Composite Research Issues For Reliability, Performance and Cost in Offshore Applications.

Research Initiatives To Enable Full Realization Of Composites In Offshore Service

Research Issues

Generic issues critical to composite use in offshore operations are outlined in Figure 4, which cites the industrial infrastructure activities of the fiber and polymer manufacturers, the composite manufacturer, the fabricator and the operator of offshore facilities for oil and gas production. It also links them with specific research activities related to mechanical, chemical and environmental behavior. A number of these issues are addressed in more detail in papers by other panelists on Working Group #2.

Figure 5 emphasizes the linkage between the components of composite microstructure and mechanical properties, through the influence of the state of stress, time and temperature. These effects are particularly dependent on direction because of the different strengths and modulii parallel and perpendicular to the fibers, and because of the critical influence of interfacial bonding on properties. In Figure 6 the potential environmental response of composites under exposure to corrosive species, temperature and UV radiation are indicated. Because the intermolecular forces are weaker in

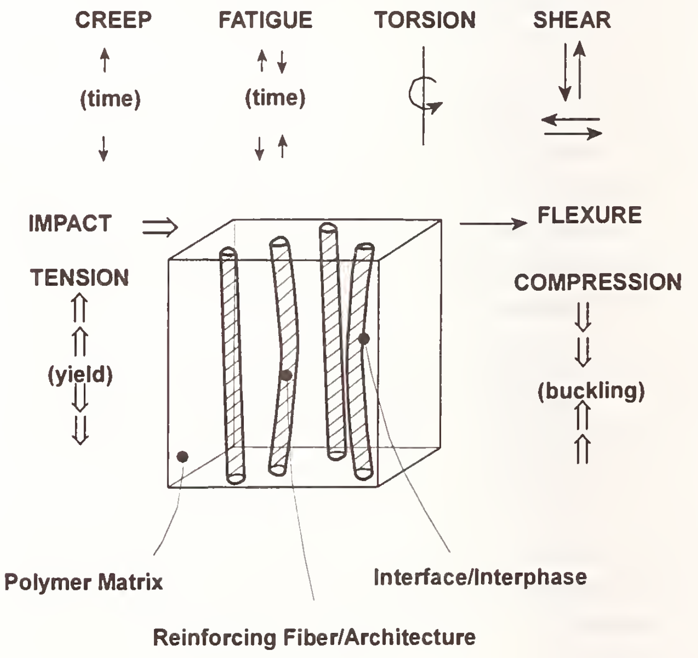

Figure 5
Influence of stress state and time on polymeric composite microstructure and mechanical properties (strength, stiffness and toughness).

polymers than they are in metals, relatively small changes in temperature can exert a dramatic effect on the reactions taking place within the polymer matrix, at the fiber surface, and in the interface/interphase region. Mechanistic and kinetic factors influencing 30-year reliability are still relatively unexplored, and quantitative life prediction methodologies are needed.

Research Initiatives

The oil industry, the composites industry, universities and government have recognized the need for fundamental scientific understanding combined with engineering development and practical training, as a basis for polymer composite use in offshore operations. Continued diffusion of existing, low cost polymer composite technology into offshore applications to address incentives for cost reduction and life extension can be expected. Recent meetings on current status and required research initiatives for expanded polymer composite usage on offshore structures include: the 1990 National Conference sponsored by the Marine Board of the National Research Council [9,12,24], the 1991 Workshop sponsored by the University of Houston and the oil industry, and the 1991 Workshop sponsored by Massachusetts Institute of Technology. The initiatives needed can be grouped into two categories: 1) Development projects to determine the potential value of more advanced materials, such as thermoset and thermoplastic composites incorporating glass, carbon and polymer fibers, and to establish lower manufacturing costs through improved technology and economies of scale in synthesis and processing, and 2) Fundamental materials R&D to achieve radical process and product innovations in polymer composites having superior reliability and performance, at affordable cost.

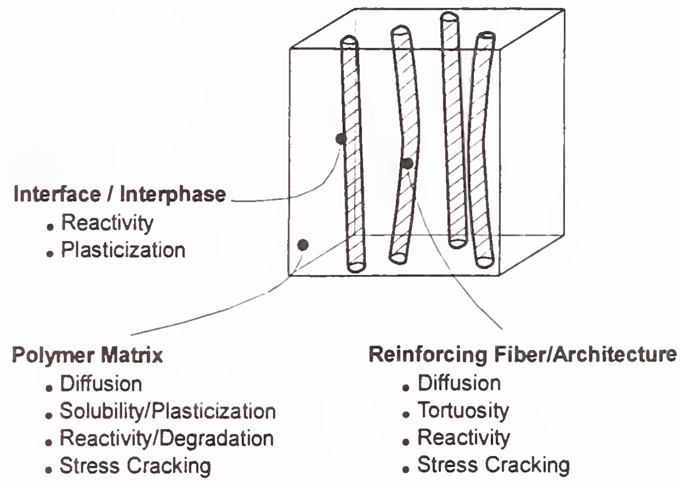

Figure 6

Illustration of potential environmental effects on polymer composites from exposure to hydrocarbons H_2O, H_2S, CO_2, NaCl and other halide salts, O_2, O_3 and UV radiation.

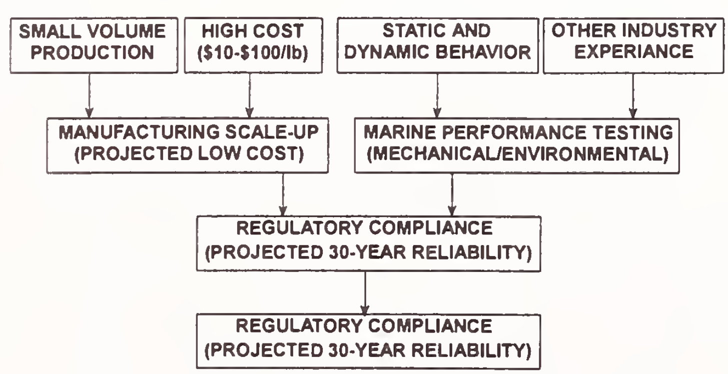

Figure 7

Acceptance path for new polymer composites in offshore applications.

Initiatives in the first category have good potential for success over the next 5-10 years, provided integrated programs are established and engineering expertise in structural design using composites is developed and applied on a systems basis, with appropriate training in how to design with composites compared to metals. A logical path for introduction of advanced composites, based on currently available fiber reinforcements and polymer matrices, is proposed in Figure 7. This approach would draw heavily on existing industry, university and government infrastructure. A conceptual basis for moving from the current generation experience curve for polymer composites to a future generation experience curve is shown in Figure 8. This involves the application of concurrent manufacturing principles to achieve improved performance with conventional reinforcing fibers and polymer matrices at affordable cost. On the longer time horizon of 10-20 years, Figure 8 points out the potential for development and integration of new fiber and polymer synthesis and processing to produce nanoscale[28] composites in a continuous operation. Essentially, this would constitute a *polymer composite refinery*. Such future polymer composites might incorporate the strength of carbon/diamond and SiC whiskers with strong covalent bonding to a thermoplastic matrix. The resulting, truly revolutionary, high performance materials, could be cost effectively either injection, compression or flow molded into final shape. The scientific and engineering challenges, here, are significant, but so also is the potential payoff.

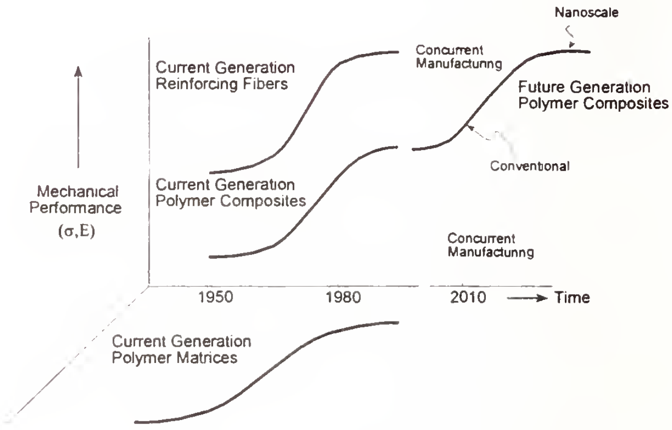

Figure 8.
Concept of the evolution from current to future generation of composites technology.

Summary

The benefits of low cost polymer composites for corrosion resistance for secondary structural applications has been established through steadily increasing onshore usage. Empirical experience and confidence has been gained through their use in piping, vessels and components such as sucker rods. Now that initial regulatory concerns in the offshore, such as flammability, have been successfully addressed, polymer composites are being designed into offshore platforms for oil and gas production. Here they provide improved corrosion resistance and lower life cycle cost. In addition to piping for sea water, waste water, produced water, cooling water and firewater systems, composites are now being used in cable trays and ladders, gratings and handrails, machinery foundations, survival crafts and tanks and separators. New applications include living quarters, fire and blast walls, helidecks, derrick components and cranes. Market potential exists for retrofitting the installed base of about 6000 offshore platforms worldwide, as well as for installation in new platforms.

To address the potential of polymer composites, with 20-30 year reliability, for primary loaded structures in topside structures, platform supports such as tension legs for TLP's as well as risers and downhole tubulars, focused research initiatives are required. In the intermediate time frame, 5-10 years, the potential for developing improved polymer composites, through better and lower cost synthesis and processing of conventional reinforcing fibers and polymers, needs to be addressed. Fundamental understanding of long term mechanical, chemical and environmental reliability must also be developed to provide methodologies and confidence for life prediction. In the long time frame, 10-20 years, breakthrough scientific discoveries and technological innovations will be required to develop isotropic polymer composites having ease of processing, combined with properties comparable to steels, coupled with 30-year reliability.

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CHARACTERIZATION OF COMPOSITE MATERIALS

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Advanced Composite Materials allow the user to take advantage of the extremely high strength and stiffness of these materials. These materials are extremely orthotropic as manufactured. This offers the advantage of having the ability to tailor the structure by putting just enough material in the desired orientations to sustain the expected loading. It also presents the challenge of trying to characterize a material that is very directional in its properties. A unidirectional advanced composite material can be extremely sensitive to flaws. The good news is - even though we measure unidirectional properties we use the material in multiple angle orientations to achieve desired performance. In addition, we have learned much about how to test and characterize advanced composite materials.

Let's talk about a few "lessons learned".

0 Degree Tensile Testing

We have found that when you combine an orthotropic high strength and stiffness fiber with a low strength and stiffness resin that the properties are fiber dominated but that the ultimate failure is one initiated by flaws within the resin rather than ultimate fiber strength. This fact is demonstrated in Figure 1, where it is shown how the ultimate tensile strength of a given fiber in a composite is different with each resin type.

TENSILE STRENGTH WITH VARIOUS RESINS, Ksi

	AS4 FIBER	IM7 FIBER
BRITTLE RESIN	300	350
SEMITOUGH RESIN	315	380
TOUGH RESIN	330	400

Figure 1

In addition, when testing unidirectional advanced composites with brittle epoxy resins it is possible to introduce surface flaws in the test laminate. This is shown in Figures 2, 3, and 4. In these cases, a distinct difference in tensile strength was found when testing with a resin rich surface. We have subsequently found that most of these problems can be avoided by testing the laminates using a 0/90 laminate and calculating the 0 degree strength by multiplying by 2 (since the 90 degree plies have all fractured long before the 0 degree plies).

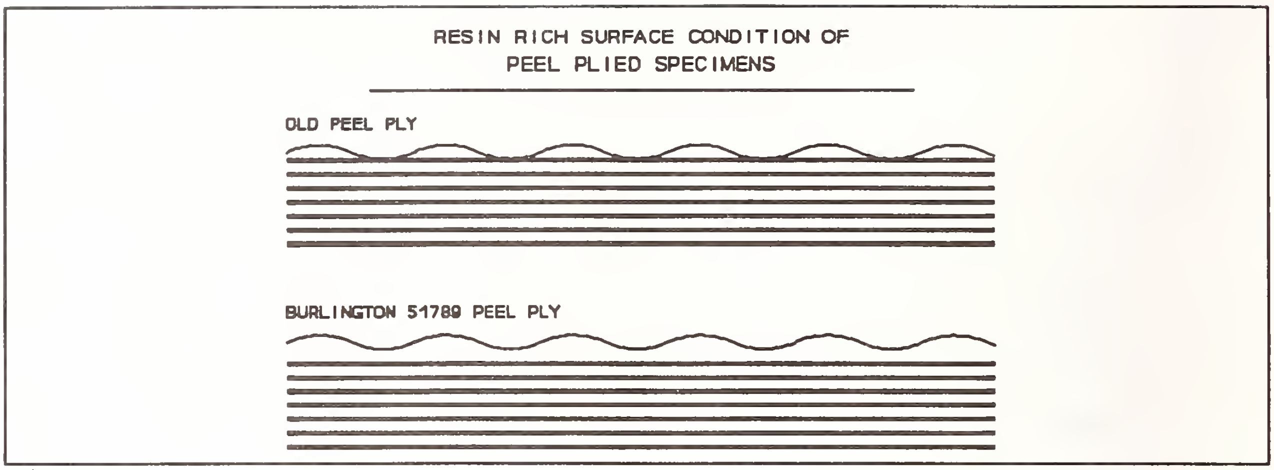

Figure 2

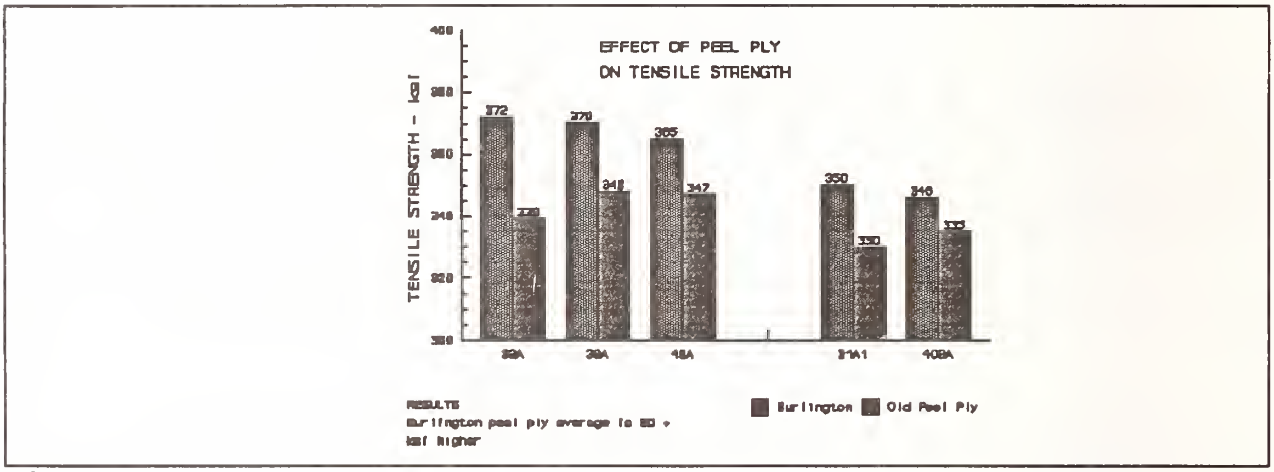

Figure 3

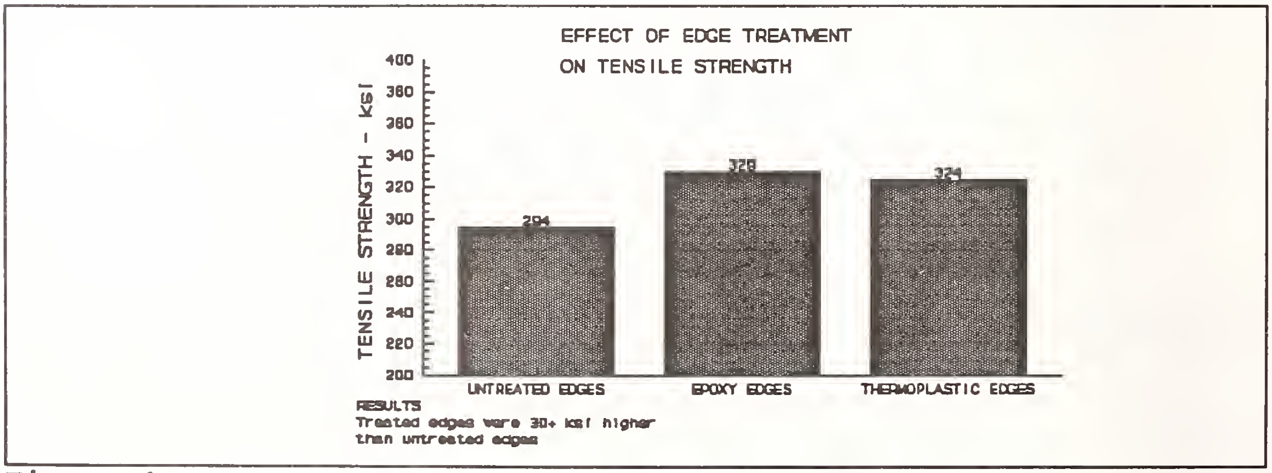

Figure 4

By far the most influential thing to do is to use tender loving care (TLC) in the fabrication of test specimens. Always, always use a water cooled diamond blade when cutting test specimens of advanced composites (Figure 5). We recommend the use of peel plies as a means of surface preparation to eliminate over-sanding and creating surface flaws in the laminate (Figure 6).

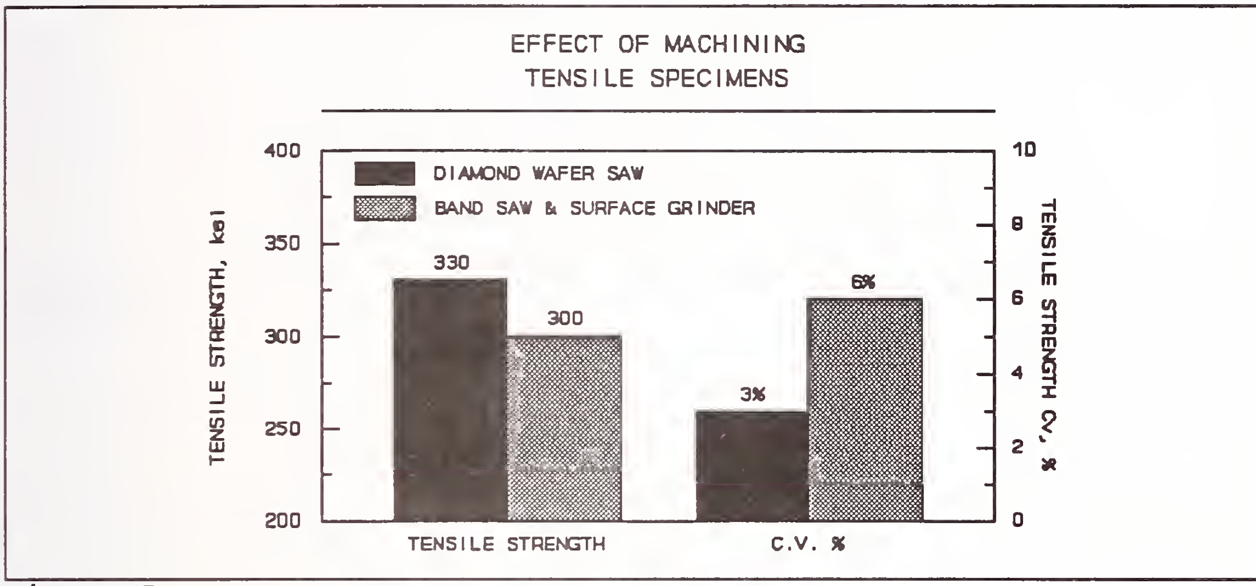

Figure 5

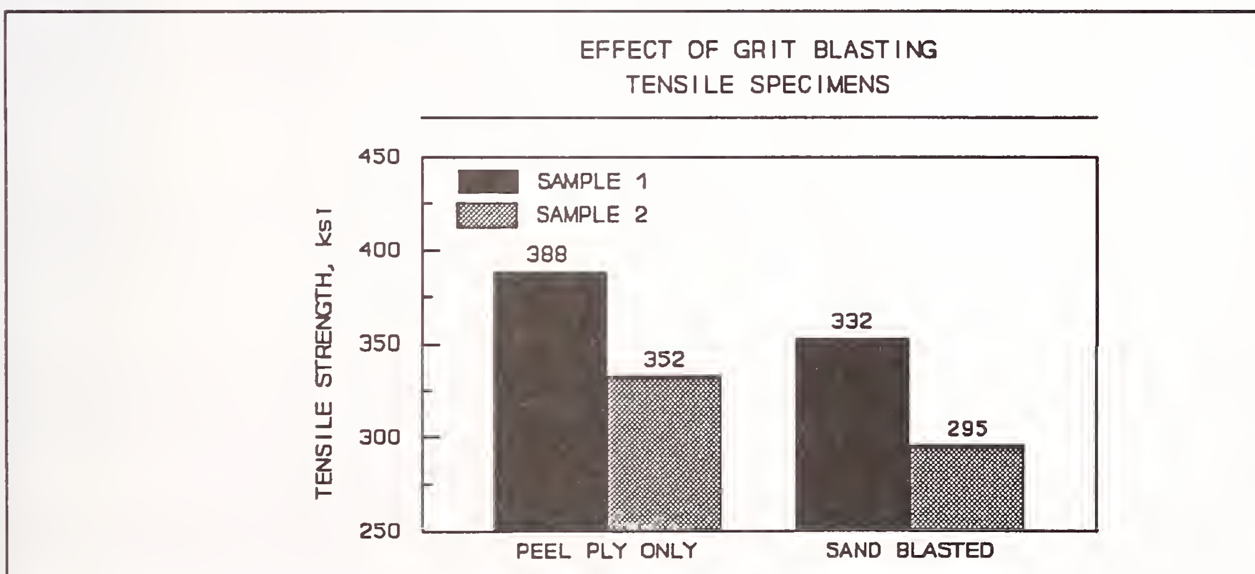

Figure 6

Composite Modulus May Not Be What It Appears To Be

A typical stress-strain curve for a unidirectional carbon fiber laminate is not linear (Figure 7). Unlike metals, the stiffness increases slightly as the strain increases. This means that the measurement of Tensile Modulus is dependent on where on the stress/strain curve the slope is taken.

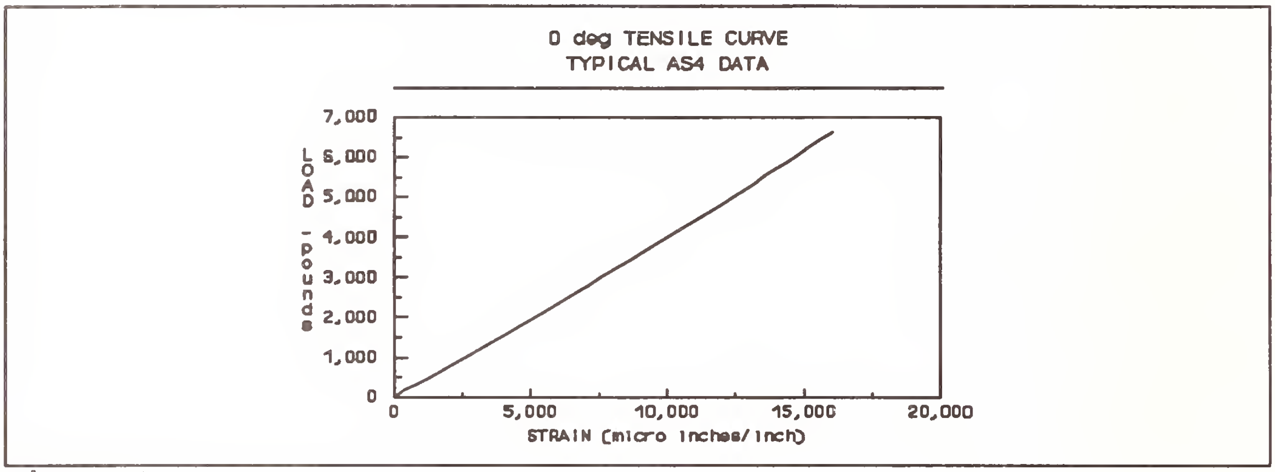

Figure 7

Figures 8 and 9 show how the Modulus of a Carbon Fiber can be interpreted, depending on whether someone would use a tangent or a chord modulus. There is a total range of 42 to 50 Msi on 0° tensile modulus and 0.2 to 0.8 Msi on shear modulus, depending on interpretation.

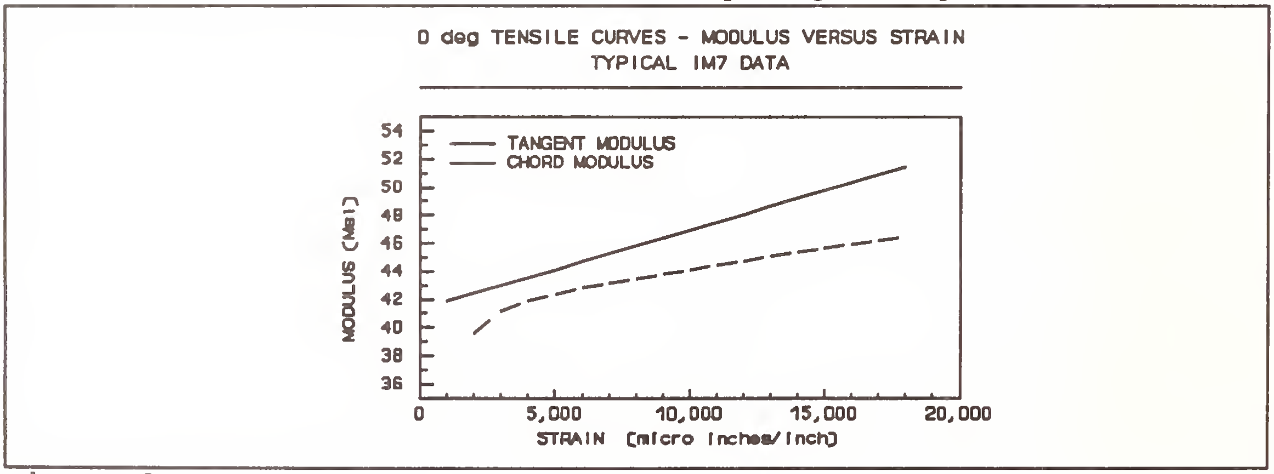

Figure 8

This problem was demonstrated when a study was made in ASTM. Sample load/elongation traces were sent to 8 different laboratories for measurement of the slope of the lines. There were three different curves: Linear, a +/- 20 degrees layup; stiffening, a 0 degree layup; and softening, a +/- 45 degree layup. The variability of this measurement is shown in Figure 10.

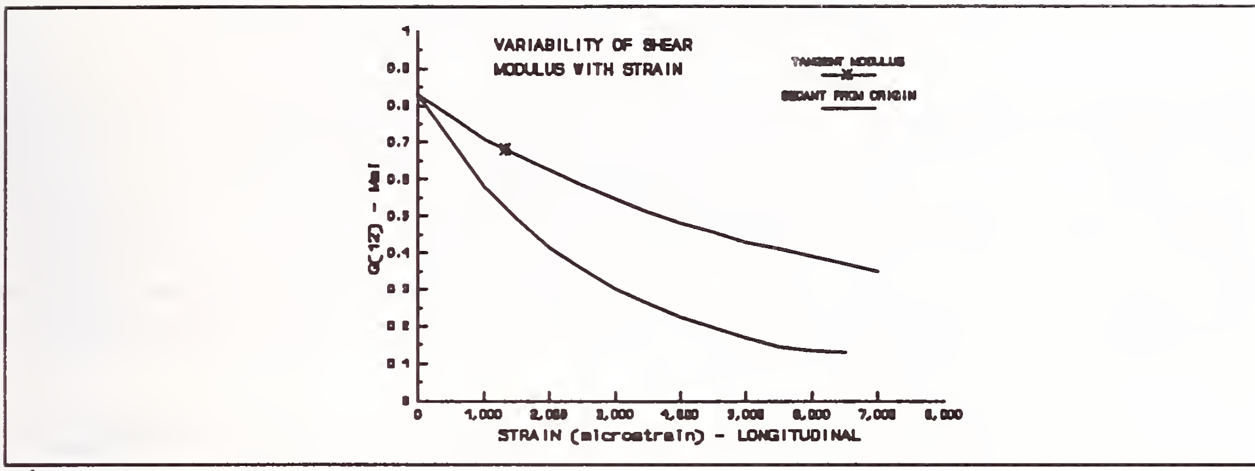

Figure 9

VARIABILITY OF MEASURING
SLOPES OF TENSILE CURVES

LINEAR (+/-20)	STIFFENING (0)	SOFTENING (+/-45)
+/- 1.4%	+/- 3.4%	+/- 20%

Figure 10

Obviously, the error shown in this type of subjective analysis on non-linear data is not acceptable. We must rely on more precise means for measuring modulus. We recommend using chord modulii (i.e.- 6000 microstrain minus 1000 microstrain) based on two finite points for the following reasons:

> The noise in a stress-strain trace takes place in the first 500 microstrain and primarily caused by grip seating and alignment.
>
> Measuring loads at specified standard strains is much more precise than attempting to draw a tangent line to a non-linear curve.
>
> Carbon fiber composite parts are typically designed for use in the range up to 6000 microstrain.

Not All Test Data Can Be Compared

There are a myriad of shear tests available: Short Beam Shear, Off-Axis Shear, Iosipescu, Rail Shear, and In-Plane Shear to name a few. These all provide a value for shear strength. None of these values would be the same. A rose is a rose is a rose does not apply in this case. Compression testing is just as bad. There are many test methods available: Modified ASTM D 695, IITRI, Celanese, with each method having several variations on the theme. The net result has been the inability to compare data between Laboratories. There have been several innovative methods cited in the literature but they have not yet been exposed to the test of time. Much work needs to be done to develop robust compression test methods. There is not much effort being expended due to a general economic decline in the industry.

We Need To Agree On What Tests Should Be Run For Characterization

We need to agree on a standard test matrix which is acceptable to all end-users for product characterization. This would, of necessity, require an agreement on test methods as well. This has been addressed through MIL HDBK 17, a coordination committee which has been functioning for several years. This organization has as one of its objectives to recommend standard ways of doing things in the development of design properties for polymeric composites. Several Tables for recommended test matrices are presented in the MIL HDBK 17 for material characterization, screening, qualification, and development of design properties (Figures 11, 12, and 13). I recommend that you obtain MIL HDBK 17 and use this as a guide in the characterization and use of Advanced Composite Materials. This can be obtained from the Standardization Documents Order Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 1911-5094.

MIL HDBK 17 ALLOWABLES TEST MATRIX

MECHANICAL PROPERTY	SUGGESTED TEST PROCEDURE [2]	TEST CONDITION AND NUMBER OF TESTS PER BATCH [1]			NUMBER OF TESTS
CONDITION		MIN. TEMP DRY	RT DRY	MAX. TEMP WET	
0 (deg) TENSION (WARP)	D 3039	6	6	6	90
90 (deg) TENSION (FILL)	D 3039	6	6	6	90
0 (deg) COMPRESSION (WARP)	D 3410	6	6	6	90
90 (deg) COMPRESSION (FILL)	D 3410	6	6	6	90
IN-PLANE SHEAR (±45)	D 3518	6	6	6	90
0 (deg) SHORT BEAM SHEAR [2]	D 2344	-	6	-	30
					480

1) TESTS PERFORMED ON EACH OF 5 BATCHES
2) FOR QUALITY CONTROL PURPOSES ONLY

Figure 11

MIL HDBK 17 SCREENING TEST MATRIX

TEST	NUMBER OF SPECIMENS CTD	RTA	ETW	EVALUATION EMPHASIS
LAMINA:				
0 (deg) TENSION	3	3	3	FIBER
0 (deg) COMPRESSION		3	3	FIBER/MATRIX
+/- 45 (deg) TENSION		3		FIBER MATRIX
				0 (deg)/90 (deg) SHEAR-LAMINA) (+/- 45 (deg) - LAMINATE)
LAMINATE:				
OPEN HOLE COMPRESSION [1]		3		STRESS RISER
OPEN HOLE TENSION		3		STRESS RISER
BOLT BEARING [1]		3		BEARING
COMPRESSION AFTER IMPACT [2]		3		IMPACT DAMAGE

1 FASTNER HOLE EFFECTS
2 PER NASA REFERENCE PUBLICATION 1092

Figure 12

MIL HDBK 17 PROCESS CHANGE QUALIFICATION TEST MATRIX

LAMINA PROPERTY	NO. OF BATCHES COMPATIBILITY [1] 1[2]	2	3	4a	4b	5a	5b	6
LONGITUDINAL TENSILE	1	2	2	2	3	3	3	3
TRANSVERSE TENSILE	-	-	2	3	3	3	3	3
LONGITUDINAL COMPRESSION	1	2	2	3	3	3	3	3
TRANSVERSE COMPRESSION	1	-	2	2	3	3	3	3
IN-PLANE SHEAR	1	2	2	2	3	3	3	3

LAMINA PROPERTY	REPLICATES COMPATIBILITY [1] 1	2	3	4a	4b	5a	5b	6
LONGITUDINAL TENSILE	4	4	4	4	4	5	5	6
TRANSVERSE TENSILE	-	-	4	4	4	5	5	6
LONGITUDINAL COMPRESSION	4	4	4	4	4	5	5	6
TRANSVERSE COMPRESSION	4	4	4	4	4	6	6	6
IN-PLANE SHEAR	4	4	4	4	4	5	5	6

LAMINA PROPERTY	ENVIRONMENTS [3] COMPATIBILITY [1] 1	2	3	4a	4b	5a	5b	6
LONGITUDINAL TENSILE	2	2	2	2	2	2	2	2
TRANSVERSE TENSILE	-	-	2	2	2	2	2	2
LONGITUDINAL COMPRESSION	2	2	2	2	2	2	2	2
TRANSVERSE COMPRESSION	-	-	2	2	2	2	2	2
IN-PLANE SHEAR	2	1	2	2	2	2	2	2

LAMINA PROPERTY	TOTAL COMPATIBILITY [1] 1	2	3	4a	4b	5a	5b	6
LONGITUDINAL TENSILE	8	16	16	24	24	30	30	36
TRANSVERSE TENSILE	-	-	16	24	24	30	30	36
LONGITUDINAL COMPRESSION	8	16	16	24	24	30	30	36
TRANSVERSE COMPRESSION	-	1	16	24	24	30	30	36
IN-PLANE SHEAR	8	16	16	24	24	30	30	36
	24	48	80	120	120	150	150	180

1) COMPATIBILITY IS DEFINED IN TABLE 2 3 2 3
2) IF ORIGINAL MATERIAL CONSTITUENTS ARE AVAILABLE (FIBER LOT, RESIN MIX) DO ONE BATCH ON NEW LINE. IF THEY ARE NOT AVAILABLE, PRODUCE TWO BATCHES FROM A NEW FIBER LOT/RESIN MIX, ONE ON EACH LINE
3) THE ENVIRONMENTS SHOULD BE RTD AND THE WORST CASE
4) QUALITY ASSURANCE TESTS MUST BE PERFORMED PER INDIVIDUAL SPECIFICATION.

Figure 13

There are organizations striving to assist in the development of data bases of Advanced Composite Materials. A new approach to data reporting is being proposed in ASTM Committee D30 to formalize the link between test methods and computerization guides and to meet the needs of testing laboratories and materials fabricators and users. This approach combines the formats for computerization developed in coordination with Committee E49. Three facets of this approach are fundamental to its success:

Formats for computerization

The use of the formats as the basis for data reporting sections for all lamina/laminate mechanical property

The expanded range of requirement levels

Three formats for computerization of composite materials data have been developed to date:

E1309, Guide for the Identification of Composite Materials in Computerized Material Property Databases

E1434, Development of Standard Data Records for Computerization of Mechanical Test Data for High Modulus Fiber-Reinforced Composite Materials

E1471, Guide for the Identification of Fibers, Fillers and Core Materials in Computerized Material Property Databases

The good news is - people are working the problems for characterization of Advanced Composites Materials. There has been and Ad Hoc Committee for Composites Standardization that has prepared a plan for the harmonization and standardization in the use of Composites. Figures 14 and 15 show the organization of the group and how they would work in concert to develop Standards for:

MATERIAL SPECIFICATIONS
TEST METHODS
PROCESS SPECIFICATIONS
DESIGN ALLOWABLES

We are still seeking government funding to make this happen. The composites manufacturing and using industries have come together and agreed to work toward a common goal - Standardization.

SACMA, ASTM, AIA, MIL HANDBOOK 17, are all working for the common cause of doing things better and more consistently. Participation in these groups would enhance anyone's perspective into the effective use of very complex - and very useful - materials.

I may have painted a gloomy picture. It was only to alert you to the challenges in getting the full use of very versatile and hard working materials. There are many resources available to make it easier and to put you well up on the learning curve. **Use these and enjoy the benefits of a terrific family of Engineering Materials.**

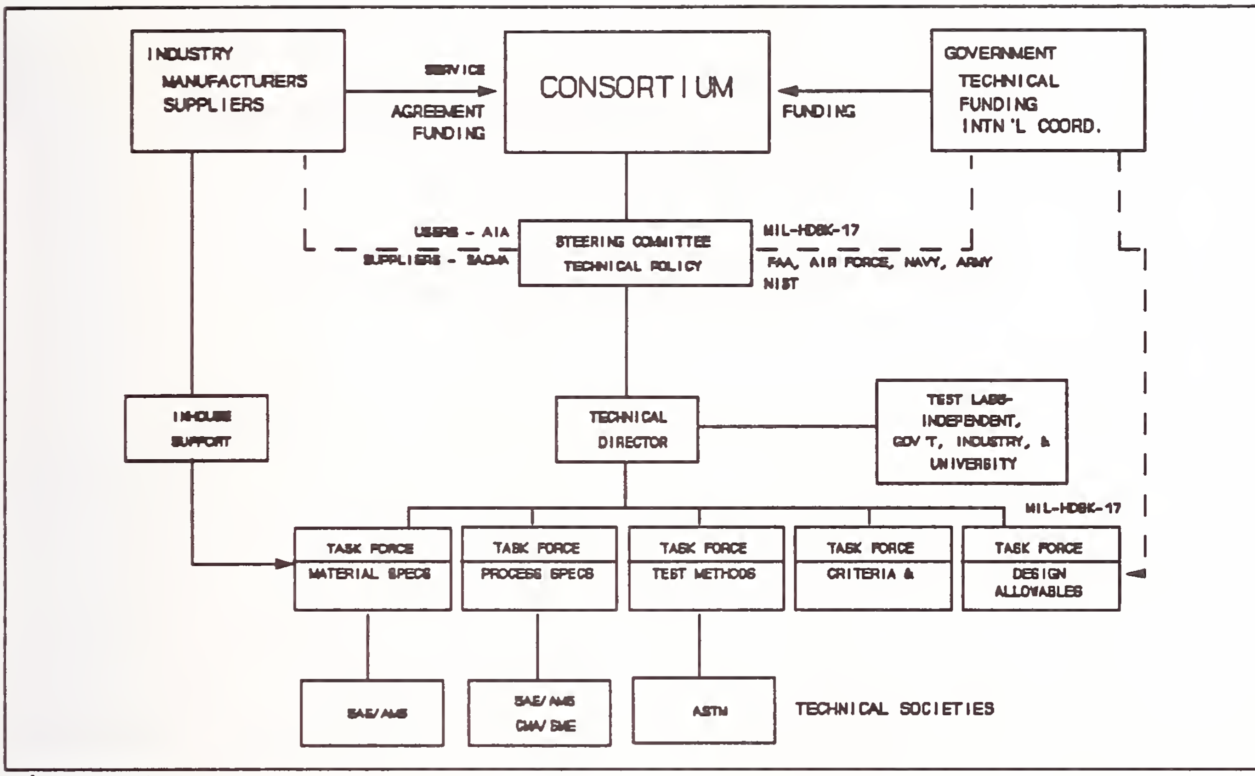

Figure 14

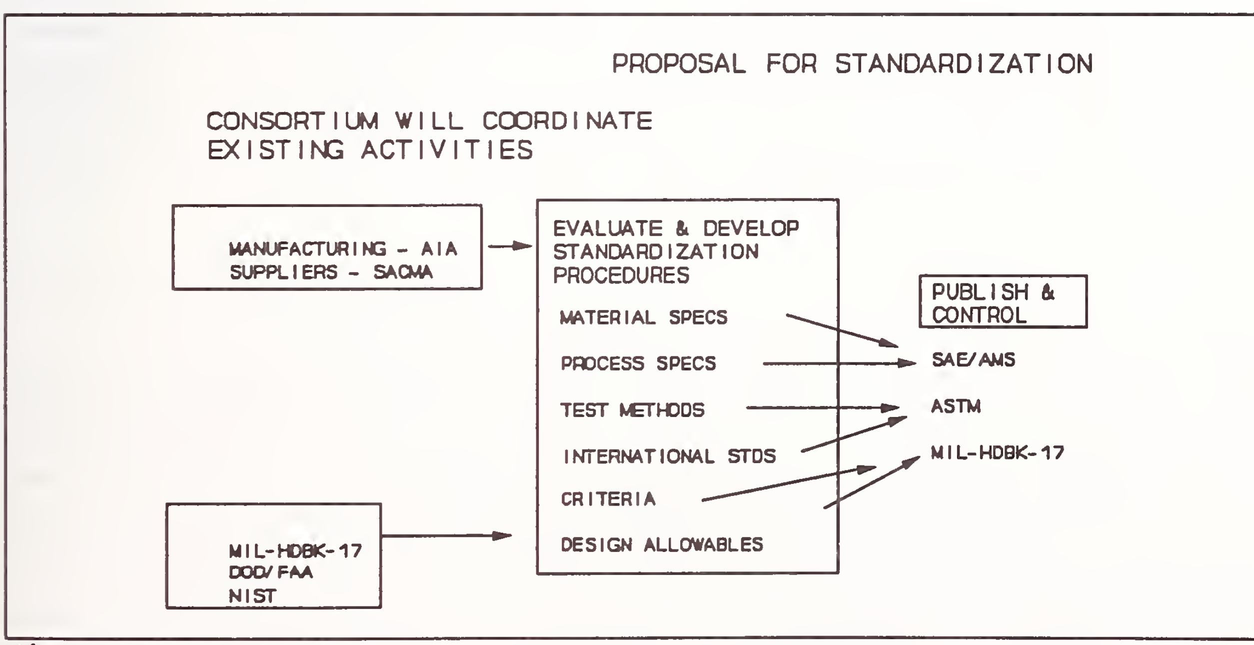

Figure 15

SOME PERSPECTIVES ON THE USE OF COMPOSITES FOR OFFSHORE OPERATIONS

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Introduction

The use of composites for load bearing structural applications entails the simultaneous consideration of a number of issues, including but not limited to, economics (materials costs, fabrication costs, maintenance costs and repair and replacement costs), suitability to task (e.g., are the derived benefits worth the effort), performance factors (e.g., are weight, strength and/or stiffness critical factors) and special considerations such as lifetime, safety and reliability, ease of construction transport to the site and in the case of interest here, environmental resistance. Previous uses of composites have largely been dictated by the need for high strength to density and/or stiffness to density ratios. This is especially true for aerospace applications. In the case of offshore operations, it would appear (based on the author's admittedly scarce knowledge) that environmental resistance benefits (relative to steel, for example) and the potential lifetime benefits deriving therefrom, as well as possible economies deriving from reduced weight and increased specific stiffness may be important life cycle considerations for the use of composites for both structural and piping applications.

Environmental Considerations

It is well known that most thermosetting matrix composites (especially the epoxies) are prone to absorb water to some extent. The result of such absorption generally lowers the glass transition temperature and results in reduced matrix modulus at any given temperature. In addition, it is also well known that when moisture slowly diffuses into a composite but is forced to leave quickly, such as occurs when a hot spike occurs during a supersonic maneuver) the moisture causes damage in the form of delaminations, holes and fiber-matrix separation. While the severity of a hot spike is not likely in offshore operations (at least not to the extent such as occurs in an airplane) there is cause for concern due to the extensive exposure to water which will occur. Thermal cycles which are likely to occur such as in piping may result in some undesired diffusion effects. In addition, hydrostatic pressure effects are also present and must be considered since they will affect the degree of water absorption due to well known thermodynamic principles.

The effects of other solvents present in crude oil may also be of importance and may lead to effects similar to those for water or worse, for example, solvent induced stress cracking such as occurs in many engineering thermoplastics. It is this author's belief that solvent and water effects may in fact be the most important considerations for the selection of matrix materials for composite piping and possibly also for structural components. The choice of a suitable interface sizing for fibers (especially for glass) is also largely dictated by solvent and water effects. It is essential and prudent that the point of view be adopted that matrix cracks will always allow exposure of the fiber-matrix interface to the environment.

The author will address several phenomena associated with the effects of solvents and water on composite structural materials. Previous work has shown that interaction of a solvent (water or otherwise) with the matrix of a composite leads to inhomogeneous swelling, a complex phenomenon which can be modeled using mechanics and thermodynamics. Briefly, the presence of two or more phases having different chemical affinity for the solvent results in concentration and stress gradients within the composite. Under certain conditions, hydrostatic tension centers (cavitation sites) can also be produced, leading to failure of the matrix. Depending on a variety of factors, the solvent concentration can be higher or lower at the interface than away from the interface. In general, the affinity of the composite for either solvent or water uptake can be readily shown to be stress and stress state dependent. Changes in stress level or stress state can cause the internal solvent or water field to move around. Thus it is possible for a "thermodynamic magnet" to exist which drives water to the interface. Hence, the choice of a suitable fiber sizing is emphasized.

Several examples of solvent and water effects in composites will be presented during the workshop. A theoretical framework developed by the author [1,2,3] can be used to understand and predict many environmental effects, using a limited amount of experimental data on the constituents (fibers, matrix and interface) and the microstructure of the composite. Relatively simple experiments combined with the theoretical analysis can provide major insights into the suitability of a given system for long term environmental exposure and the likelihood of success, as well as providing a rational basis for materials selection.

Structural Considerations

One of the more complex tasks encountered by offshore construction of composite materials is likely to be that of joining. Inasmuch as composites are inhomogeneous, highly anisotropic materials, the transfer of loads from one member to another entails stress diffusion. As a general rule diffusion lengths in composite materials are far larger than in isotropic materials.

Consequently, the wrong type of joint may overly load the outer plys of a composite laminate and result in failure of the outer plys and perhaps the whole structure at loads far lower than net section uniform stress calculations would predict. This type of problem, in which the overload occurring in outer plys causes premature failure, is especially important in structural components carrying compression loads. It is especially important that designers of composite structures be aware of the stress diffusion characteristics of composites and that they allow for such effects. A successful engineering and design methodology for composites in offshore applications (both structural and piping) must address the effects of joining methods on stress diffusion in the surrounding structure and its effect on lifetime and environmental resistance.

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MATERIAL PERFORMANCE: MICROMECHANICAL MODELING OF COMPOSITE FRACTURE

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Introduction

Whenever composites are used in structural applications, it is important to be able to predict when they will fail. The field of fracture mechanics can be defined as the engineering discipline that seeks to predict the conditions under which a load-bearing body will experience growth of damage [1]. Thus, what we seek is a fracture mechanics of composites. In homogeneous, isotropic materials, such as metals, it is possible to analyze the stresses at the tip of a generic crack and use those results to predict crack growth. The tools for predicting crack growth are stress intensity factor or energy release rate. In principle, a similar approach can be used for composites, but, in practice, the heterogeneity and anisotropy of composites makes the process difficult. Instead of being describable by generic cracks, damage in composites can take many forms. There can be cracks in the matrix, cracks in the fiber, cracks at the fiber/matrix interface, and cracks with any variety of locally heterogeneous environment. These cracks can grow by multiple paths depending on loading conditions and on the crack-tip environment. Thus we see matrix cracking, fiber cracking, interfacial failure, longitudinal splitting, and delamination. A thorough understanding of composite failure requires analyzing all crack types and all crack paths.

Another term for the fracture mechanics of composites is micromechanical modeling of failure or micromechanics of damage. The development of micromechanics of damage models always involves two equally important steps [2]:

1. Analyzing the stresses in the presence of damage

2. Proposing and verifying failure criteria for the prediction of damage growth

These two steps were the same ones that were followed in developing fracture mechanics of metals. In Griffith's original fracture paper [3], he began with an elasticity solution for the stresses around a sharp crack and calculated the energy release rate for crack growth. For step two he postulated that crack growth occurs when the energy release rate reaches a critical value. This postulate has been verified by many experiments. In composites, the stress analysis step is usually more complex than it was in metals. Indeed, there are many important composite crack geometries for which no exact elasticity solution can be found. Instead, we must resort to approximate methods or to numerical methods such as finite element analysis.

However accurate the stress analysis or refined the finite element analysis, the entire exercise will be for naught, if attention is not paid to step two. Neither stress analysis nor finite element analysis tell us anything about failure; these must be coupled with some failure criterion before predictions of failure can be made. In the fracture mechanics of metals, failure is always predicted by using one of two failure criteria—critical energy release rate or critical stress intensity factor. Because these two failure criteria are uniquely related to each, there is, in fact, a single unifying failure criterion that ties all metal fracture problems together. In contrast, the literature on composite fracture has no unifying failure criterion. We find, for example, assumptions of failure at some maximum level or stress, some maximum level of strain, some quadratic combination of stresses or strains, some average stress over a representative unit volume of material, some shear stress at the interface, or under whatever conditions seem convenient. I suggest that this seemingly random approach to composite fracture is unlikely to be successful.

In this paper, I will discuss some specific examples of developing micromechanics of damage models for composites. For each example, I will cover steps one and two of the analysis process. I will pay particular attention to step two and give experimental evidence to verify or reject any failure criterion. The discussion at the end of the paper will describe the unifying fracture concepts that emerge from the small set of failure problems covered in this paper.

Microcracking

The first form of failure in most laminates is matrix cracking or microcracking in the off-axis plies [4–21]. Microcracking is commonly studied in $[(S)/90_n]_s$ or $[90_n/(S)]_s$ laminates, where (S) denotes any orthotropic sublaminate and microcracking occurs in the 90° plies. There are many reasons for studying microcracking. Microcracks not only change the thermal and mechanical properties of laminates [14, 22, 23], but also present pathways through which corrosive agents may penetrate into the interior of the laminate [9]. When prevention of leakage is important, the mere presence of microcracks may represent a technological failure of the structure. Perhaps most importantly, microcracks act as nuclei for further damage such as delamination [13, 17, 24], longitudinal splitting [8, 9], and curved microcracks [19, 25]. Because microcracks are precursors to the cascade of events that leads to laminate failure, we would have little hope of understanding laminate failure or of predicting long-term durability if we did not first develop a thorough understanding of the phenomenon of microcracking.

The first microcracking problem is predict the onset of microcracking, or the strain to microcrack initiation. Because the first microcracks do not cause catastrophic failure, it is possible to continue loading after microcracking. Typically this loading will cause additional microcracks. The second microcracking problem is to predict the increase in microcrack density with increasing load. Eventually the existing microcracks will nucleate further damage which will propagate into laminate failure. In this section, I will discuss micromechanical modeling of microcrack initiation and of microcrack density as a function of load.

Microcrack Initiation

Before any microcracks form in a laminate, laminated plate theory gives an accurate analysis of the laminate stresses. We thus begin by using laminated plate theory for step one of the micromechanics model. A simple model to predict microcrack initiation, known as first-ply failure theory, is to assume that the 90° plies will crack when the stresses in the 90° plies reach the *strength* of the unidirectional lamina material. We imagine a composite under uniaxial load of σ_0 in the x direction, where the x direction is parallel to the zero degree fibers. The x- and y-direction tensile stresses in the 90° plies of the undamaged laminate can be written as

$$\sigma_{x0}^{(1)} = k_{m,x}^{(1)}\sigma_0 + k_{th,x}^{(1)}T \qquad \sigma_{y0}^{(1)} = k_{m,y}^{(1)}\sigma_0 + k_{th,y}^{(1)}T \tag{1}$$

where k_m and k_{th} are mechanical and thermal stiffnesses of the 90° plies, T is the temperature difference between the specimen temperature and the stress-free temperature ($T = T_s - T_0$), and superscript (1) denotes the 90° plies. The mechanical and thermal stiffnesses can easily be evaluated from laminated plate theory [2].

We denote the transverse and axial strengths of the unidirectional lamina material as σ_T and σ_A. A simple maximum stress failure criterion predicts first ply failure when $\sigma_{x0}^{(1)} = \sigma_T$ or

$$\sigma_0 = \frac{\sigma_T - k_{th,x}^{(1)}T}{k_{m,x}^{(1)}} \tag{2}$$

Because the shear stresses are zero in the 90° plies, the slightly-more-complex Tsai-Hill failure criterion predicts first-ply failure when [26]

$$\sigma_{y0}^{(1)^2} - \sigma_{x0}^{(1)}\sigma_{y0}^{(1)} + \left(\frac{\sigma_A}{\sigma_T}\right)^2 \sigma_{x0}^{(1)^2} = \sigma_A^2 \tag{3}$$

This equation can easily be solved for σ_0. Figure (1) shows some experimental microcrack initiation results and compares them to the predictions of first-ply failure theory. Only one first-ply failure theory curve is shown because predictions using the maximum stress or Tsai-Hill criteria are identical. First-ply failure theory works well for laminates with thick 90° plies. This result is expected because the results must asymptotically approach the results for a transverse tensile test on a unidirectional laminate. For laminates with thin 90° plies, however, first-ply failure theory is completely wrong. Imagine relying on first-ply failure theory to design a cross-ply laminate that resists microcracking. The recommendation would by to maximize the thickness of the 90° plies; the correct answer is to minimize the thickness of the 90° plies.

The problems with strength-based theories led Parvizi *et al.* [7] to propose that microcrack initiation occurs when the energy released due to the formation of the first microcrack exceeds the critical energy release rate

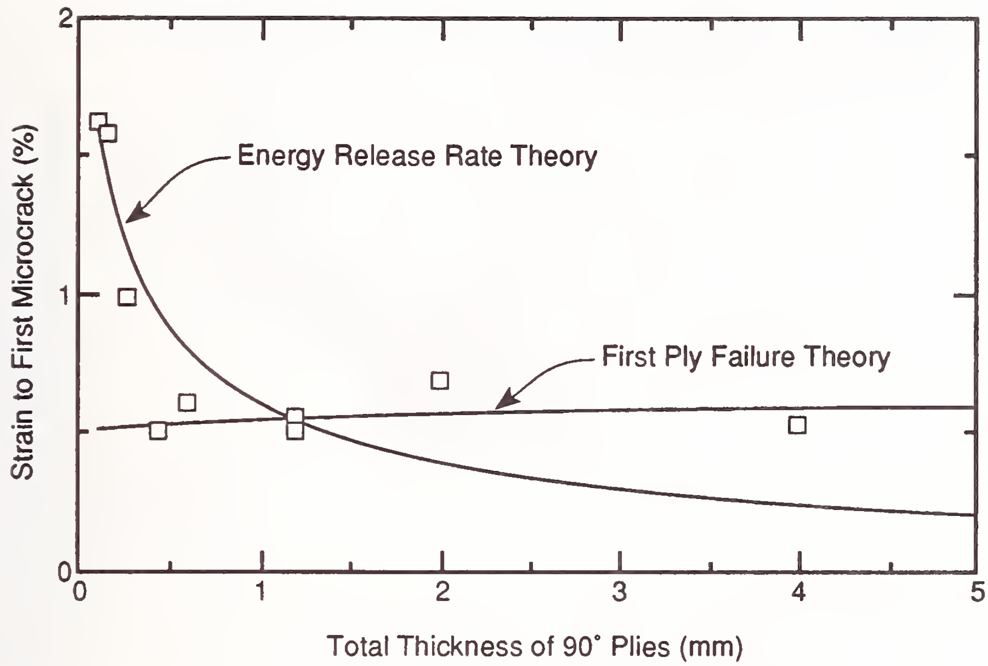

Figure 1: The strain to initiate microcracking in E glass/Shell Epikote epoxy [0/90/0] laminates as a function of the total thickness of the 90° plies [6]. The 0° plies each have a constant thickness of 0.5 mm. The two curves give theoretical predictions for the strain to initiate microcracking using first-ply failure theory (the maximum stress and the Tsai-Hill predictions are identical) or energy theory.

for microcracking—G_{mc}. Laminated plate theory only gives the stresses and energy in the undamaged laminate. To calculate the energy *after* the formation of a microcrack, we need to analyze the stresses in the presence of microcracking damage. Numerous authors have presented one-dimensional solutions to the problem [4, 5, 8, 15, 27–32]. It can be shown that all these analyses reduce to the same shear-lag equation and thus are equivalent [2]. Hashin used variational mechanics to derive the first two-dimensional, analytical stress analysis for a microcracked $[0_m/90_n]_s$ laminate [33, 34]. Nairn *et al.* extended Hashin's analysis to include residual thermal stresses and to handle both $[(S)/90_n]_s$ laminates and $[90_n/(S)]_s$ laminates [2, 21, 24, 35–37].

Using the modified Hashin's stress analysis to calculate the energy release rate for formation of the first microcrack and assuming that the crack forms when that energy release rate exceeds G_{mc}, lead to the following prediction for the strain to initiate microcracking [2]

$$\varepsilon_{init} = \frac{1}{k_{m,x}^{(1)} E_c^0} \left[\sqrt{\frac{G_{mc}}{t_1 \sqrt{C_1} \left(C_4 - C_2 + 2\sqrt{C_1 C_3} \right)}} - k_{th,x}^{(1)} T \right] \tag{4}$$

where E_c^0 is the x direction modulus of the undamaged laminate and C_1 to C_4 are constants that depend on the mechanical properties and geometry of the laminate [2, 36]. A comparison between the predictions of this energy theory and experimental data is given in Fig. 1. The energy theory agrees much better with experimental data than first ply failure theory. In particular, it agrees with the constraint effect that causes the stain to initiate microcrack to rise sharply for laminates with thin 90° plies. The agreement of the energy theory for laminates with thick 90° plies is not as good. This region of poor agreement may represent a region where the approximate variational stress analysis is not good enough to give an accurate calculation of the energy release rate. Unfortunately, it is difficult to resolve all issues by focusing on initiation experiments. Initiation experiments yield only one data point per laminate. The results are thus prone to experimental scatter and sensitive to laminate flaws or to local laminate heterogeneities in toughness. The preferred experiment is to continue loading and measure the microcrack density as a function of applied load. These experiments yield many data points per laminate and the results are less sensitive to laminate variability [2, 21, 36].

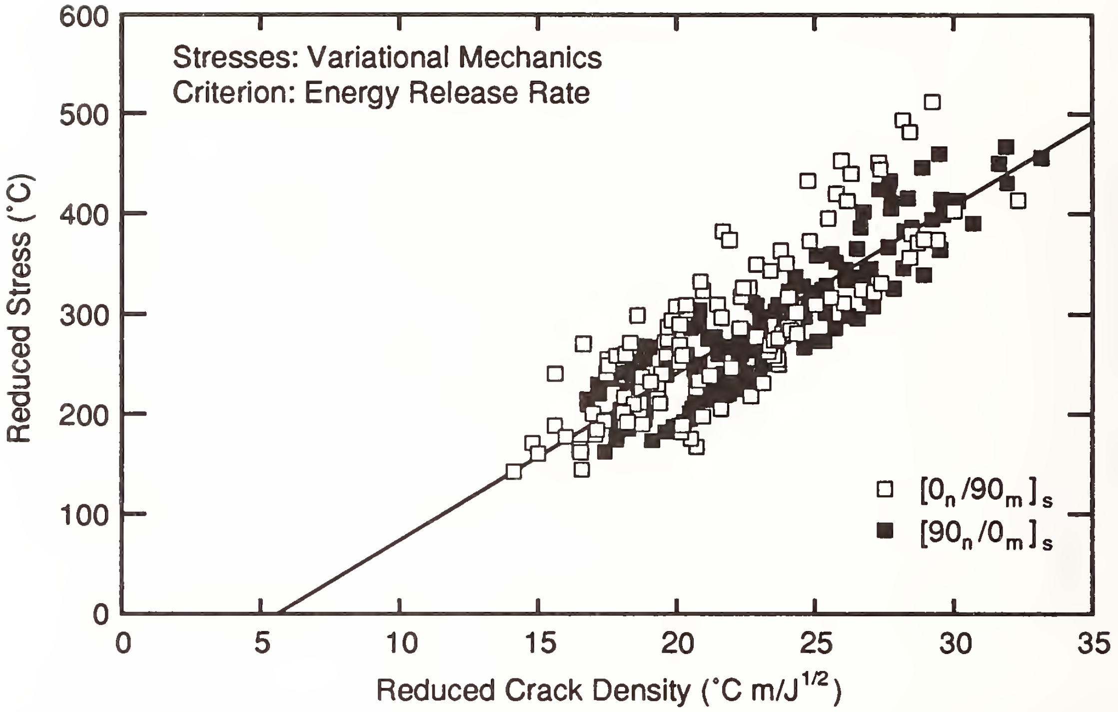

Figure 2: A master curve analysis for 18 Hercules AS4/3501-6 carbon/epoxy laminates [36]. To avoid inherent scatter of microcrack initiation data, results for crack densities less than 0.3 mm^{-1} were eliminated.

Microcrack Accumulation

To predict microcrack density as a function of applied load, many authors have advocated an energy release rate failure criterion [2, 18, 21, 30, 31, 35–37]. In brief, the next microcrack is assumed to form when the total energy release rate associated with the formation of that microcrack, G_m, equals or exceeds the microcracking fracture toughness of the material, G_{mc}. Nairn *et al.* [36] used the modified Hashin's analysis and solved for the applied stress as a function of crack density, D:

$$-\frac{k_{m,x}^{(1)}}{k_{th,x}^{(1)}}\sigma_0 = -\frac{1}{k_{th,x}^{(1)}}\sqrt{\frac{G_{mc}}{C_3 t_1 Y(D)}} + T \tag{5}$$

where $Y(D)$ is a calibration function that depends on crack density, laminate mechanical properties and laminate geometry (see Refs. [2, 36] for an analytical expression of $Y(D)$). Equation (5) leads us to define a reduced stress and a reduced crack density as

$$\begin{aligned} \text{reduced stress:} \quad & \sigma_R &=& -\frac{k_{m,x}^{(1)}}{k_{th,x}^{(1)}}\sigma_0 \\ \text{reduced crack density:} \quad & D_R &=& -\frac{1}{k_{th,x}^{(1)}}\sqrt{\frac{1}{C_3 t_1 Y(D)}} \end{aligned} \tag{6}$$

A plot of σ_R *vs.* D_R defines a master plot for microcracking experiments. If the variational analysis and energy release rate failure criterion are appropriate, a plot of σ_R *vs.* D_R will be linear with slope $\sqrt{G_{mc}}$ and intercept $-T$. Because G_{mc} and T are layup independent material properties, the results from all laminates of a single material with the same processing conditions should fall on the same linear master plot. Thus constructing a master plot of microcracking data for a series of different laminates is an excellent way to evaluate microcracking theories.

Figure 2 gives a master plot for 18 different layups of carbon/epoxy laminates [36]. Among the 18 different layups are laminates with interior 90° plies ($[(S)/90_n]_s$ laminates) and laminates with surface 90° plies ($[90_n/(S)]_s$

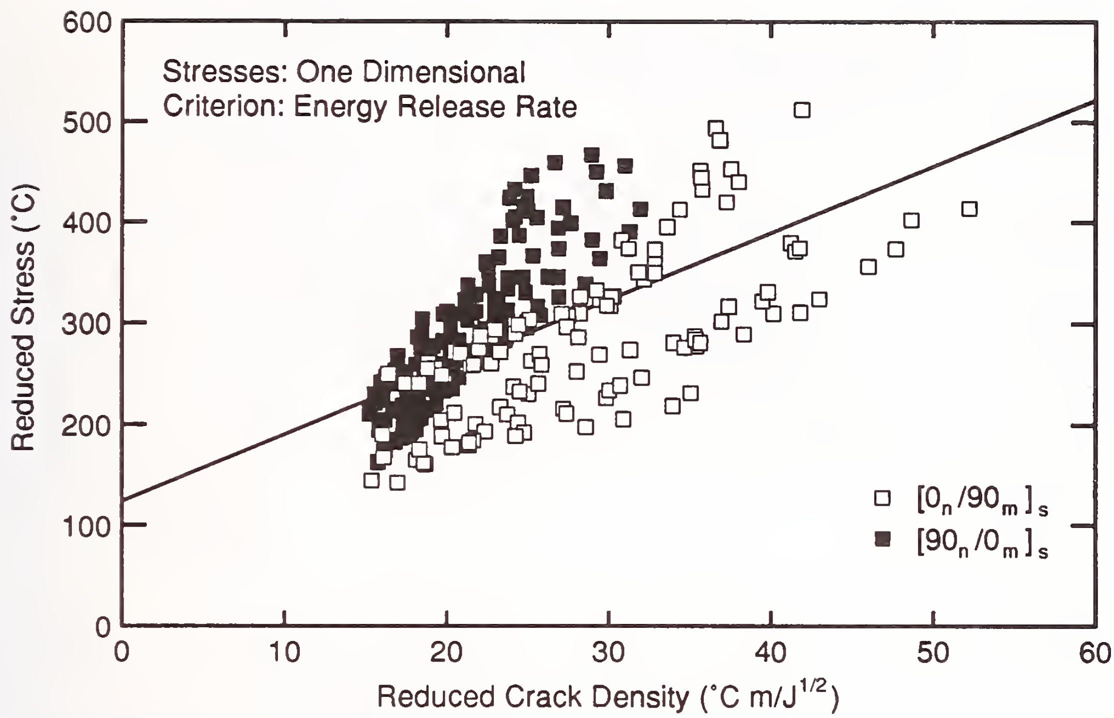

Figure 3: A master curve analysis of all AS4/3501-6 laminates [36] using a one-dimensional stress analysis and an energy release rate failure criterion.

laminates). Among the supporting sublaminates (S) are unidirectional sublaminates (0_n) and angle-ply sublaminates ($\pm\theta$ where $\theta = 15°$ or $30°$). The analysis of microcracking in surface 90° plies requires a new variational mechanics stress analysis [37], but the final results can be reduced to the same master equation in Eq. (5). The only change is that the $Y(D)$ calibration function is replaced by new calibration function specific for cracking of surface plies [36].

I claim Fig. 2 verifies both the validity of an energy release rate failure criterion and the accuracy of the variational mechanics stress analysis. Thus it verifies both steps in the micromechanics model for microcracking. There are three facts that support this claim. First, all laminates fall on a single master curve plot within a relatively narrow scatter band. Second, the results for $[(S)/90_n]_s$ laminates (open symbols) agree with the results for $[90_n/(S)]_s$ laminates (solid symbols). Third, the slope and the intercept of the master curve result in $G_{mc} = 279$ J/m^2 and $T = -93$°C. Both of these results are reasonable measured values for these physical quantities [2].

The master plot treatment is useful for examining the relative importance of the stress analysis and failure criterion steps in a typical micromechanics model for fracture. First we consider replacing the variational analysis with the often used one-dimensional analysis of stresses in cross-ply laminates [4, 5, 8, 15, 27–32]. By using the energy release rate criterion, it is possible to reduce the one-dimensional stress analysis predictions to the same master equation in Eq. (5), except that $Y(D)$ changes from the variational mechanics results to a simple one-dimensional result [36]. Figure (3) gives the master plot for the same 18 laminates in Fig. 2. When compared to the variational analysis, all one-dimensional analyses have serious problems. Most importantly, the results from individual laminates do not overlap each other. A characteristic of one-dimensional analyses is that the results from $[(S)/90_n]_s$ and $[90_n/(S)]_s$ laminates segregate into two groups. One dimensional analyses do not distinguish between $[(S)/90_n]_s$ and $[90_n/(S)]_s$ laminates and thus could never be expected to explain the experimentally observed differences between them [2]. The slope and the intercept of the master curve give $G_{mc} = 44$ J/m^2 and $T = +124$°C. Neither of these fitting constants is reasonable. The residual stress term (T), in particular, must certainly be negative for laminates that are cooled to room temperature after processing.

If one plots laminate stiffness as a function of microcrack density calculated by a one-dimensional analysis and by the variational analysis, the differences are marked, but hardly dramatic [2]. It is thus somewhat surprising

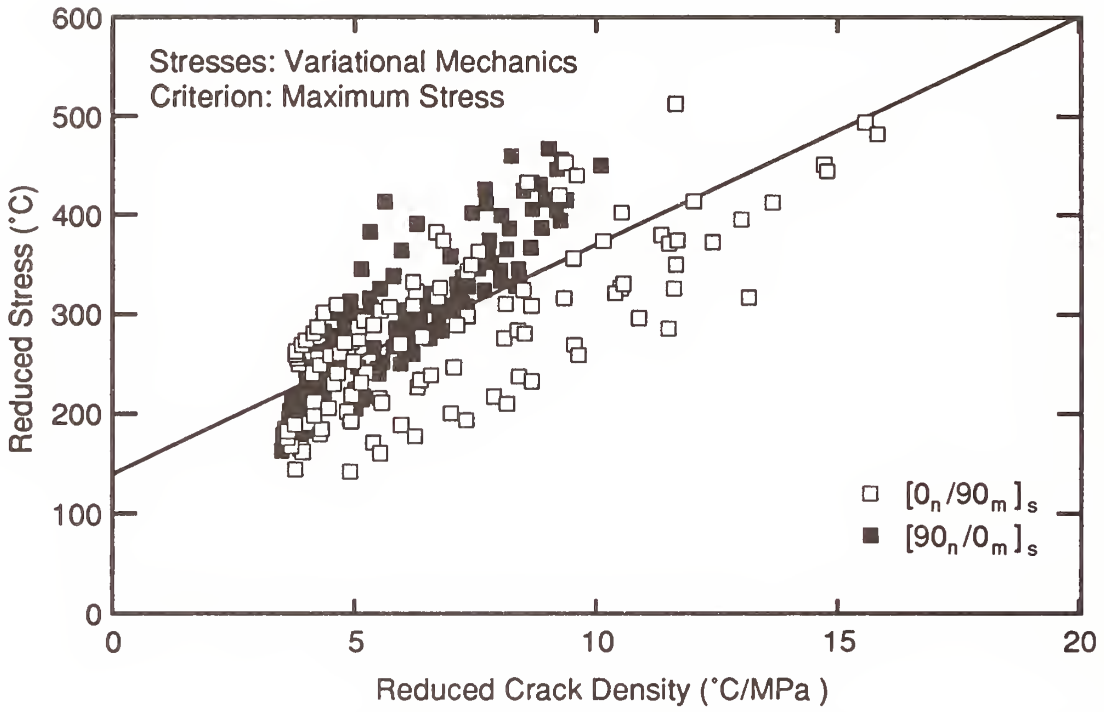

Figure 4: A master curve analysis of all AS4/3501-6 laminates [36] using a variational mechanics stress analysis and a maximum stress failure criterion.

to find truly dramatic differences between the fracture predictions based on the two analyses. A qualitative interpretation of the differences can follow from realizing that stiffness is a global property while fracture is an instability event. It is relatively easy to calculate global properties. When calculating instability processes, however, minor differences in input stresses can lead to dramatic differences in predictions. In other words, the increased accuracy in the stresses attributed to the variational analysis was crucial to the predictions of microcracking.

Accepting the variational mechanics analysis as accurate, we can examine the effect of the failure criterion used in the second step of the micromechanics model. Numerous authors have suggested using strength-based models to predict microcracking [4, 7, 15, 16, 20, 29]. If we implement the strength criterion using the variational mechanics stress analysis we find a master relation of [2]

$$-\frac{k_{m,x}^{(1)}}{k_{th,x}^{(1)}}\sigma_0 = -\frac{1}{k_{th,x}^{(1)}}\frac{\sigma_T}{\left(1-\phi(0)\right)} + T \tag{7}$$

where $\phi(0)$ is a calibration function that depends on crack density, laminate mechanical properties and laminate geometry (see Refs. [2, 33–36] for an analytical expression of $\phi(0)$). For strength theories, the reduced stress is the same as for energy theories, but the reduced crack density is redefined as

$$\text{reduced crack density:}\quad D_R \quad = \quad -\frac{1}{k_{th,x}^{(1)}}\frac{1}{\left(1-\phi(0)\right)} \tag{8}$$

Thus the slope of a strength-theory master plot is the transverse tensile strength of the lamina material.

Figure (4) gives the master plot for the same 18 laminates in Fig. 2. When compared to the energy release rate model, the strength modal has serious problems. Most importantly, the results from individual laminates do not overlap. In particular, the results from $[(S)/90_n]_s$ and $[90_n/(S)]_s$ laminates segregate into two groups. Experimental observation shows that the load required to cause high crack densities in $[(S)/90_n]_s$ laminates is lower than in $[90_n/(S)]_s$ laminates [2]. The energy release rate failure criterion correctly predicts this effect and all results reduce to the same master plot. The maximum stress failure criterion does not predict the surface *vs.*

interior effect. The slope and the intercept of the master curve give $\sigma_T = 23$ MPa and $T = +140$°C. Neither of these fitting constants is reasonable.

Interface Failure

The interface between the fiber and the matrix in composite materials influences many bulk properties. In continuous-fiber composites, the interface affects shear strength, shear modulus, off-axis properties such as delamination and longitudinal splitting, compression strength, impact strength, fatigue durability, and environmental stability. The interface is even more important in short-fiber composites. By influencing the process of stress transfer between the matrix and the short fibers, the interface additionally affects on-axis strength and on-axis modulus. Whenever one contemplates developing or using new composite materials, that development program should include work on the interfacial properties of that composite.

Some popular tests for characterizing the fiber/matrix interface include the fragmentation test [38–43], the fiber pull-out test [44, 45], the microbond test [46, 47], and the microindentation test [48]. All these specimens involve complex stress states, but the test results are almost always analyzed using simplistic equilibrium, shear-lag, or elastic-plastic analyses. In the next section, we consider an improved micromechanics model of one of these tests.

Microbond Test

In the microbond test, a small amount of resin is deposited on the fiber surface in the form of a droplet. The droplet is debonded from the fiber by pulling the fiber while restraining the droplet with a microvise [46, 47]. Qualitatively speaking, the higher the debond force, the tougher the interface. Microbond experiments are usually analyzed using an average shear stress failure criterion. By integrating the equations of stress equilibrium it is possible to derive an exact relation (*i.e.*, the stress analysis step is done exactly) between the average interfacial shear stress, $\langle \tau_{rz} \rangle$, and the fiber force, F:

$$\langle \tau_{rz} \rangle = \frac{F}{2\pi r_f l} \tag{9}$$

where r_f is the fiber radius and l is the length of the microdrop. The simplistic analysis of microbond tests assumes that the interface fails when the *average* shear stress equals the interfacial shear strength, τ_{ic}. The inadequacy of the average shear stress failure criterion can be demonstrated by comparing predictions to experiment. Equation (9) predicts that the force to debond the microdrop is linear in the microdrop length, l. Figure 5 shows some experimental data for epoxy droplets on E-glass fibers [49]. The debond force is not linear in l, but rather levels off for long droplets. These results are experimental proof that failure of the fiber/matrix interface in these specimens is not controlled by the average shear stress along the interface.

The average shear stress failure criterion is poor because it is unrealistic. This result is not surprising because refined stress analysis shows that the interfacial shear stress is nonuniform [50]. There is a stress concentration at the point where the fiber enters the droplet. The largest component of the stress concentration is a *tensile* stress in the radial direction. The average shear stress approach ignores this tensile radial stress and implies a shear failure mechanism. SEM observations, however, suggest an interfacial crack propagation mechanism with the crack initiating where the fiber enters the matrix [51]. One method to account for the complex stress state is to abandon the average shear stress analysis and adopt an energy release rate approach [50].

By extended Hashin's variational mechanics stress analysis for laminates to the axisymmetric geometry of droplets, it is possible to derive an accurate stress analysis of the microdrop specimen [50]. Using this stress analysis, the energy release rate for initiation of a fiber/matrix debond in a microbond specimen is

$$G_i(0) = \beta_1 \sigma_m^2 - \beta_2 \sigma_m T + \beta_3 T^2 (\chi_e'(0) - \chi_e'(\rho)) + \beta_4 \sigma_m^2 (\chi_e'(\rho) + \chi_o'(\rho)) \tag{10}$$

where σ_m is the average stress on the droplet; and β_1 to β_4, $\chi_e(\rho)$, and $\chi_o(\rho)$ are constants and functions that depend on specimen dimensions and on fiber and matrix mechanical properties [50]. An energy-based micromechanics model for the microbond specimen is to assume that the droplet debonds from the fiber when the energy release rate for initiation of crack growth exceeds the fracture toughness of the interface, G_{ic}. The experimental results in Fig. 5 indicate that the energy release rate model provides a much more realistic interpretation of the results. Furthermore, the measured interfacial toughness of $G_{ic} = 218$ J/m^2 is more likely to be a quantitatively useful material property than is an *effective* interfacial shear strength.

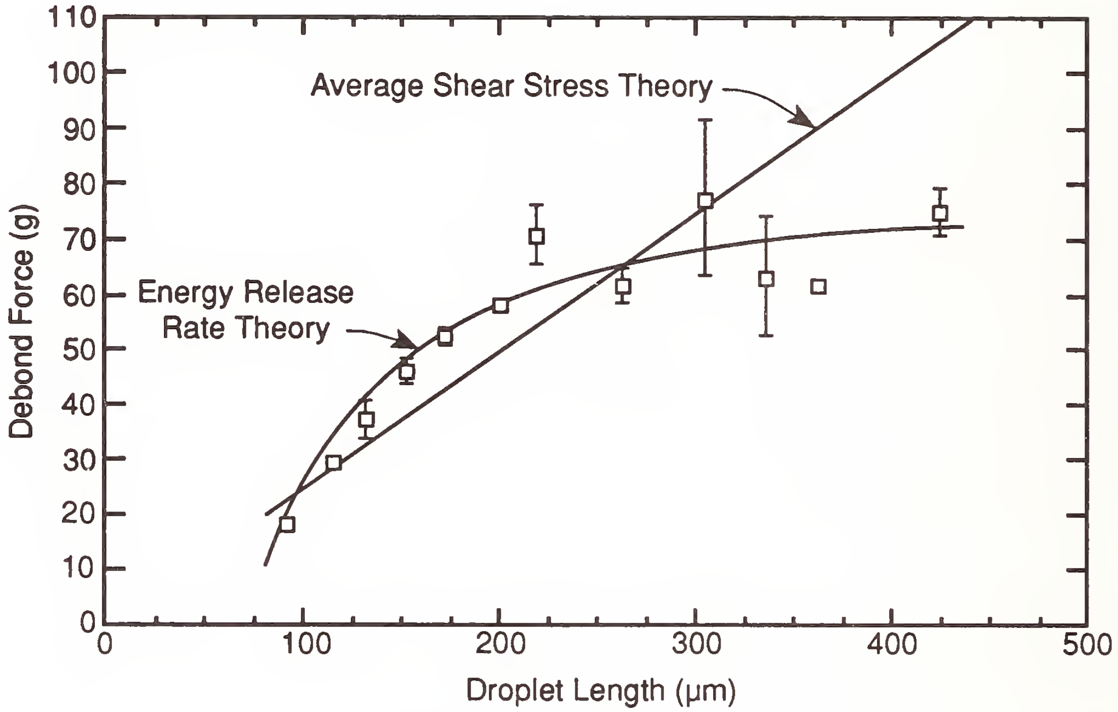

Figure 5: The debond force for a series of epoxy droplets on E-glass fibers [49]. The two curves give theoretical predictions using either an average shear stress or a critical energy release rate failure criterion. The inherently scattered microbond data has been smoothed by taking running averages of data with similar droplet lengths. The error bars indicate the standard deviation of the averaged data.

Discussion and Conclusions

Micromechanics models of composite fracture are an important part of the science of composite materials. All micromechanics models involve at least two important steps—analysis of stresses in the presence of damage and prediction of failure using some failure criterion. The above examples show that if either of these steps is deficient, a seemingly rational model can be contrary to experimental observation.

Consider the stress analysis step first. The complexity of composite fracture problems means that we will always be resorting to approximate solutions or to finite element analyses. When working with approximate solutions, it is important to verify that those solutions are sufficiently accurate. When dealing with fracture problems, the accuracy requirements are more stringent than when dealing with simpler problems such as predicting plate stiffness or displacements. For example, one-dimensional, shear-lag models do a reasonable job of predicting plate stiffness as a function of microcracking damage [2]. Those same stress analyses, however, are inadequate for fracture problems. The only acceptable method of verifying a stress analysis for micromechanics of damage models is to show that it makes valid predictions about *fracture* properties. Hashin's variational mechanics methods [33, 34] have been verified as a useful stress analysis for predicting microcracking [2, 36].

Finite element analysis is a powerful tool for analyzing the stresses in complex structures. In principle, finite element analysis can be used to study many fracture problems, but, in practice, it can be cumbersome. The main problem is that predicting damage growth inevitably means analyzing the stresses for various amounts and various forms of damage. Each new damage state requires a new finite element calculation. For example, predicting the microbond data in Fig. 5 would require a separate finite element calculation for each droplet size. The time and expense required to generate such results prohibits the use of finite element analysis as the primary stress analysis tool. I claim instead that there is great incentive for developing micromechanics models based on analytical stress analyses, especially when composites are being contemplated for new applications such as marine structures. Finite element analysis is best used as a *experimental* technique that can verify the accuracy of the stress analysis or suggest ways it can be improved [2].

It is disappointing to read a paper on composites fracture and find an elegant stress analysis method rendered useless by inattention to the step of choosing an appropriate failure criterion. This problem is too common in the composite literature, but easy to recognize. After spending several pages on the stress analysis or on numerical methods, a typical flawed analysis will deal with the failure criterion in a single unsupported and probably unrealistic sentence such as: "the next crack was assumed to form when the average stress within an element reaches the strength of the material." The examples in this paper show that the failure criterion warrants greater attention. If it is not chosen carefully, the micromechanics model will not work regardless of the accuracy of the stress analysis. A pattern that emerges from the microcracking and microbond experiments is that we should tend to favor fracture mechanics methods, such as energy release rate, and try to avoid strength-based methods. This conclusion is no surprise to anyone accustomed to fracture analysis in metals. No progress would ever be made in the analysis of metal fracture by resorting to simplistic failure criterion such as maximum stress criteria. Likewise, no progress will be made in the fracture mechanics of composites until the models are based on sound failure criteria.

I close with some suggested techniques for reading the literature on micromechanics of damage models. A series of questions should always be asked: How was the stress analysis done? Is it accurate enough? In particular, is it accurate enough to be used in fracture predictions and not just in stiffness predictions? If the stress analysis required finite element analysis, is it flexible enough to handle different amounts of damage? Would you be able to use the analysis to support your own work? (Analytical models tend to be more portable than finite element-based models). Was sufficient attention paid to selection of the failure criterion? Is the failure criterion rooted in fracture mechanics principles? If not, was the selection of a nonstandard failure criterion justified? Most importantly: was the entire micromechanics of damage model verified by comparison to a large body of experimental evidence? (Models that are supported by only a single set of experiments should be treated with skepticism). Finally, an exercise for the reader is to ask these questions about the failure predictions in commercially-available laminated plate theory software. Your answers and results such as those in Fig. 1 show that their calculations should not be trusted.

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IMPACT DAMAGE TOLERANCE OF FRP COMPOSITES IN OFFSHORE APPLICATIONS

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INTRODUCTION

Glass fiber reinforced plastic (FRP) composites offer several advantages over traditional offshore construction materials (i.e., steel and aluminum) due to their low thermal conductivity, excellent mechanical properties, superior corrosion resistance, good chemical resistance and high strength to weight ratio. Composites on platforms can impact the cost through (1) weight reduction that leads to substantial cost savings for floating structures, (2) lower protective requirements (coatings and corrosion inhibitors), (3) lower installation cost, and (4) improved safety and reliability. Though the materials cost may be higher for composites than steel, the savings in total life-cycle costs (including fabrication, maintenance, decommissioning, etc.) may be substantial.

On an offshore platform impact events arise from dropped and falling objects and shrapnel from explosions. One of the impediments to wider use of FRP offshore has been the concern about its resistance and reliability under impact loading. The subcritical damage resulting from an impact may go unnoticed and subsequently reduce the lifetime of the part with failure occurring below the initial design stress level. The extent of damage on composite materials will depend on the shape of the impactor and the velocity of impact. Composites in general absorb impact energy by plastic deformation, delamination and fiber pull out. Compared to metals and thermoplastics, fiberglass reinforced thermosets do not undergo large amounts of plastic deformation. Delamination is a function of interlaminar tensile and shear strengths which depend primarily on matrix properties. The fiber-matrix bond is also critical for increasing energy absorption, thus improving impact strength. The contribution from each type of energy absorption varies widely. As a result, there may not be a clearly defined point at which a catastrophic failure of a component will occur. The failure may have to be defined in terms of tolerable levels of fiber breakage or delamination[1].

Several test methods are available for characterizing the impact behavior of FRP materials. The most commonly used test methods are:

Charpy

Izod

Falling weight

Ballistic impact

The pendulum impact tests with small rectangular test specimens (Charpy, Izod) are of limited value in measuring the toughness and predicting the real impact performance of FRP products[2]. The falling weight tests may be better as they can measure fracture initiation energy, impose biaxial stresses on the specimen, and the results have been shown to relate to other properties related to toughness (microcracking, strain to failure of matrix), and with actual field experience. The instrumented impact tests will provide more information about the various stages of the impact event and the damage mechanisms.

Impact studies on FRP test coupons show that the specimens can sustain the impact without affecting the strength if the level of impact energy is insufficient to produce in the material, stress levels higher than the ultimate strength[3]. There is also evidence that the damage was mostly controlled by the level of impact energy and not significantly affected by the velocity of impact, in these experiments.

FRP gratings, panels, and pipes are beginning to be used extensively in offshore applications. Though the impact resistance is a concern in all these applications, a well established methodology for characterizing impact behavior in these applications has not been established. Some of the published studies on impact behavior of FRP gratings, panels and pipes are discussed below.

FRP GRATING

Impact tests comparing steel with molded and pultruded FRP grating has shown that although composite gratings perform differently from steel grating, they may have equally acceptable impact performance[4]. In these tests a 135 kg (298 lbs) valve was dropped from 2.5 m (8.2 ft) onto an FRP grating; no damage was recorded; in other tests a 35 kg (77.2 lbs) impactor of 75 mm (2.95 in) diameter was dropped from 3.75 m (12.3 ft) on the grating. Post impact observation indicated that all gratings needed to be replaced, but the remaining strength was sufficient to not require immediate replacement (i.e., the grating was strong enough to walk on, but it may not have survived another impact). The pultruded gratings outperformed the molded ones.

Impact study of open composite structures (floor grillage) by Marinetech North West (Project CP-01)[5] has shown that the energy absorption to failure under dynamic conditions is a little larger than that measured under static conditions, and increases with the velocity of impact. Also there was evidence of a threshold value of impactor energy, below which no damage was observed. Above this threshold, permanent damage and a corresponding reduction in strength and stiffness was observed.

FRP grating is considered less impact resistant than steel grating. Impact damage may not be readily visible even though the grating may be substantially weakened due to delamination. Some feel that FRP grating should only be used where there is no risk of dropped objects to be lost by penetration of the grating. Recognizing that the load requirements vary between locations on the platform, some users indicate that they limit FRP gratings to the less severe areas.

FRP PANELS

The fire and impact performance of various composite panels have been the subject of a number of research programs in Europe[6,7,8,9,10]. The superior performance of FRP panels has been successfully demonstrated in these studies. Marinetech North West (Project CP-08)[10] had performed a large number of impact tests on sandwich panels. The variables examined included the effect of skin and core construction, multiple impact, impactor geometry, and impact energy. Models for impact strength retention as a function of impact energy levels were proposed. Static indentation tests were also performed. Comparison of load-deflection curves has shown that the sandwich panels failed at similar loads and deflections in both static and impact tests, thus suggesting the use of static tests for predicting performance. The failure process of the panels were found to be dependent on the geometry of the indentor with the cones and pyramid geometries causing more localized damage. Some of these panels were able to withstand impact energies up to 300 kJ (2.2×10^5 ft-lb) and blast pressures up to 1.33 bar (20 psi).

FRP PIPING

The impact resistance of FRP piping may depend on the accepted failure criterion. If the onset of cracking of the inner layer is defined to be the failure point, that may be reached at rather low levels of impact energy, typically, 5-10 J (3.7-7.4 ft-lbs). If the loss of ability to maintain function until replacement is the criterion, the level of impact energy required may be substantially higher.

A modified ASTM drop weight test procedure (ASTM D2444) was used by Ameron[11] to study impact behavior of FRP pipes. The failure height was defined as the height at which cracking of the inner liner was observed. A linear increase in failure height with increasing wall thickness was observed (diameter kept constant), but only slight increase in failure height was observed with increasing pipe diameter (wall thickness

kept constant).
Impact tests of six different types of 4-inch diameter FRP pipes of 16 to 20 bar pressure rating were used to demonstrate that the pipes were functional after exposure to impacts of about 70 J (52 ft-lbs), an energy level considered typical for impact events on an offshore platform[3]. The instrumented impact studies by Haanes, et al[3] showed two distinct stages in the force -deformation curve: (1) a steep rise to a local peak, possibly indicating the onset of resin microcracking, and (2) a region of gradually increasing force indicating various energy absorbing failure mechanisms (delamination, fiber pull out, etc). The initial stage of failure may be resin dominated and the latter stages may be controlled by the reinforcing fibers.

How different levels of impact energy can influence the ability of the pipes to maintain function (transport water under pressure) was studied by Stokke, et al[12]. In these studies, leakage rates after impact for filament wound 4 inch epoxy pipes subjected to a range of impact energies were measured (Table 1[12]). The leakage of 4.1 ml/min resulting from an impact of 500 J (372 ft-lbs) corresponds to a loss of a drop of water every 3 seconds and is essentially not detrimental to the functioning of the sea water pipe system until repair can be made. They have also shown that the impact damage was independent of (a) the impact location (at a support or in between supports) and (b) whether the pipe was empty or filled with water. At the same impact energy, a larger contact area between the loading nose and the pipe surface will reduce the impact damage[3].

An empirical relationship between the extent of visible damage and the energy level of impact was suggested by Reid, et al[13]. Significant amount of localized damage, mainly in the form of delamination, could occur due to relatively low levels of impact energy (Table 2)[13]. However, the area of delamination was found to be consistently less for the internally pressurized pipes filled with oil than for empty pipes. It was apparent that some of the impact energy was absorbed and distributed by the bulk compression of the fluid in the pipe. The resistance of the pipes to penetration of the projectile was less for oil filled pipes. The pipes behaved as if stiffer when oil filled than when empty, and were perforated at far lower energy levels. Impact tests on internally lined pipes showed less damage and no sign of leakage unless the liner was broken in the impact process.

NEEDS/OPPORTUNITIES

Though impact performance is a concern for offshore applications of FRP composites, there is a need to better define the impact tolerance required for the various applications. The tests available for evaluating impact behavior in these applications should to be standardized and various stages of damage development needs to be understood. These tests must be based on good science, application specific, and acceptable levels of performance should to be established.

Table 1. Leakage Rate (ml/min) After Impact for a FW 4 Inch Epoxy Pipe Impacted by Energies From 20-500 J in Empty Condition[12] (Diameter of Impactor: 75 mm; Support Spacing: 4 m)

Energy Pressure	80 J	80 J	80 J	80 J	100 J	120 J	150 J	200 J	300 J	500 J
10 bar	0	0	0.1	0.2	0.3	0.3	0.8	1.5	1.5	2.1
20 bar	0	0.6	0.8	0.8	1.0	0.8	1.6	2.2	4.0	4.1

Table 2. Observed Damage Sequence for FRP Pipes Under Impact Loading[13]

EVENT	ENERGY (J) WHEN FIRST OBSERVED	
	Wall Thickness = 4.3mm	Wall Thickness = 8mm
Resin Whitening	10	10
Cracking of Inner Liner	10	20
Formation of Parallel Cracks in Resin Rich Top Coat in Direction of Fibers	39	38
Inward Collapse of Inner Liner	86	132
Perforation	638	916*

* Projectile embedded in pipe wall, no visible hole present.

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THE EFFECT OF SEAWATER ON POLYMERIC COMPOSITE MATERIALS

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INTRODUCTION

Polymeric composite materials are being examined as an alternative to traditional steels for the construction of production risers in deep sea oil recovery. The use of light weight polymeric composite risers would significantly reduce the buoyancy requirements and thus the size and cost of the surface structure. The long–term durability of composites in the seawater must be characterized before their full potential can be realized since current utilization of composites is mainly in applications where design stresses are relatively low and moisture effect may not be apparent. It is important to develop a better understanding of the magnitude and mechanisms of seawater degradation.

A composite structure is subjected to moisture absorption and fatigue wave loading in seawater. Several investigations have examined the fatigue behavior of polymeric composites in the seawater environment with general conclusions being some or little degradation in performance, comparing to that in air[1–4]. However, few have studied the effect of seawater exposure on damage development and failure mechanism, which may ultimately determine whether there is any seawater degradation.

In this report, the effect of seawater exposure on failure mechanism and damage development of fiber reinforced polymeric composites was studied with laminate specimens using transverse tensile test and edge delamination test. Since the matrix resin and interface are most affected by the moisture absorption, the transverse tensile test, which is most sensitive to the change in matrix and interface dominated properties, can be used conveniently to study the degrading effect of seawater. It is also important to study the moisture effect on the delamination since it is the most dominant form of damage in the fatigue life of composites[5]. The effect of moisture on the delamination may be beneficial, due to the relief of residual thermal curing stresses and matrix plasticization, or detrimental, due to induced chemical and/or physical degradation of the fiber/matrix interface[6].

In a later study, filament wound tubular specimens were also used in studying the stress corrosion cracking of glass fibers. Although glass fibers are generally susceptible to stress corrosion cracking in both acidic and alkaline environments, there has been few reports on the performance of glass fiber in seawater. It is important to examine the feasibility of using glass fiber from the economic standpoint.

DEGRADATION OF TRANSVERSE STRENGTH

Materials

Three carbon/epoxy systems and four carbon or glass/vinylester systems have been tested. System A is T2C145/F263 (Hexcel), a typical carbon fiber reinforced tetraglycidyl diaminodiphenyl methane/ diaminodiphenyl sulfone (TGDDM/DDS). System B is IM7/977–2. The 977–2 resin (ICI/Fiberite) is a hybrid of TGDDM and polyethersulfone. System C is IM7/SP500–2. The SP500–2 (3M) is a flourene epoxy. Both B and C have DDS as the crosslinker. Two vinylester resins, Derakane 411 and 510 (Dow), were also examined. Systems D and E are 411 and 510 reinforced with carbon fibers. The 510 resin is a flame retardant vinylester. Systems F and G are 411 and 510 with glass fibers.

Experimental Procedures

Specimens were exposed to distilled water, seawater, and seawater at 3,000 psi hydrostatic pressure. Simulated seawater, which was mixed from distilled water and a synthetic sea salt, was used instead of natural seawater. At 3,000 psi, an ocean depth in excess of 5,000 ft is simulated. Moisture absorption characteristics was determined by weight gains at exposure times of 7, 21, and 90 days. Weight gain after one week typically reached about 90% of the weight gain achieved in three months with 4 ply thick specimens, indicating a nearly saturated condition; transverse tensile specimens were also conditioned for periods of 7, 21, and 90 days to determine whether the degradation continued over time.

The transverse tensile specimen had a dimensions of 1.5 inches long by 0.25 inch wide with a reduced cross sectional area in the midsection of the specimen. The purpose of the reduced area was to control the location of fracture and to reduce the likehood of failure due to incipient flaws. Independently, interfacial shear strength were also determined for carbon/epoxy systems. Measurements were performed by Dow Chemical with the Interfacial Testing System.

To study the failure mechanism, post–mortem examinations and in–situ three point bend tests were performed in an SEM. Coated specimens was tested on a loading stage in the SEM in an effort to observe the fracture process in real time. Three point bend test was used because it gave more stable crack growth than the transverse tensile test.

Results and Discussion

Carbon/Epoxy Systems

For the carbon/epoxy systems the moisture gained by specimens conditioned in seawater is lower than those conditioned in distilled water, and a pressure of 3,000 psi didn't seem to have a significant effect on the amount of absorbed moisture. Weight gains at 90 days for carbon/epoxy systems are shown in Figure 1(a) as percentage change of the resin weight. 7 and 21 day data yielded slightly lower levels, but they are not included.

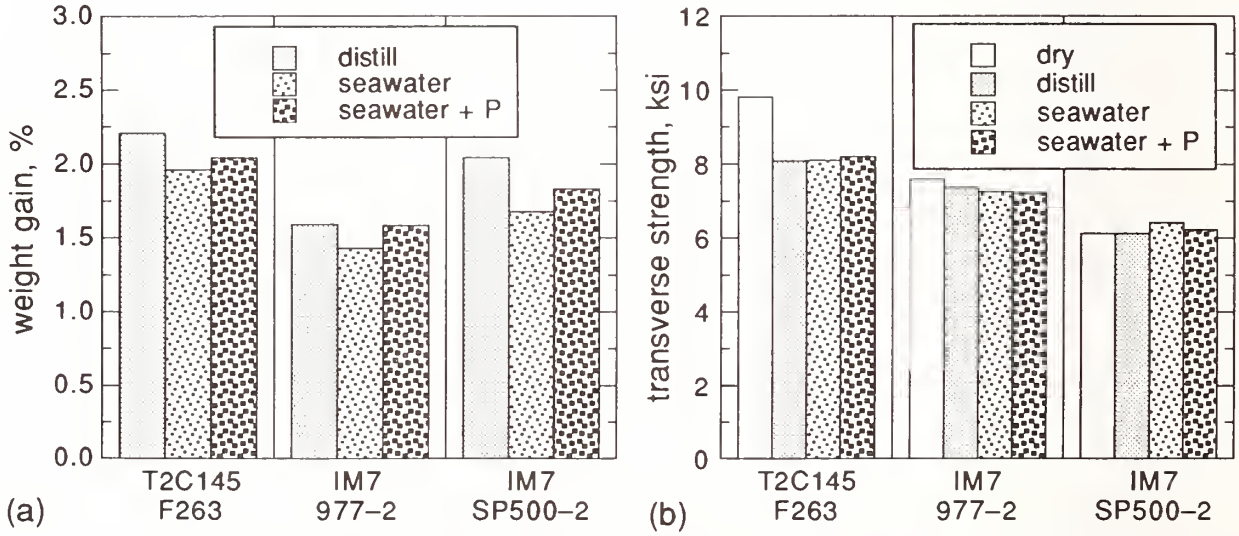

Figure 1. Weight gain and strength degradation for carbon/epoxy systems.
(a)Weight gains after 90 day conditioning
(b)Transverse strength degradation after 90 day conditioning

The lower moisture gained by the specimens immersed in seawater may be accounted for by considering the resin as a semipermeable membrane. If the salt is not absorbed by the resin, osmotic pressure will result and reduce the driving force for the moisture to diffuse into the resin. On the other hand, hydrostatic pressure can have two competing effects. The pressure can reduce the free volume in the resin, reducing the locations where water molecules can accumulate, but the pressure also provides a greater driving force for moisture absorption. From the result presented, it seemed that 3,000 psi was insufficient to have a significant effect, with only a slight increase in the moisture absorption in seawater at 3,000 psi compared to that at atmospheric pressure. Minimal pressure effects also have been observed in other thermosetting resin composite systems[7,8].

The result of transverse tensile tests is shown in Figure 1(b), comparing the results from dry and conditioned specimens. Again, only the data at 90 days are shown since there is little difference in the data at 7 and 21 days. For all three carbon/epoxy systems studied, there didn't seem to be any time dependence effect. System A exhibited moderate degradation in the transverse tensile strength after immersion, but system B and C are not much affected. Results obtained from the interfacial shear test are not presented here, but they are consistent with the transverse tensile test in their indication of reduction in interfacial strength due to moisture absorption effects..

System A has the highest transverse tensile strengths when dry, but it suffered about 17% degradation after immersion. Systems B and C have lower strength when dry, but they don't seem to suffer any degradation after immersion. The moderate strength loss of the system A is a result of the moisture–induced interfacial degradation. SEM examinations of both fractured specimens and real–time three–point–bend specimens revealed a difference in the failure mechanism between system A and systems B and C. Latter systems exhibited interfacial failures for both dry and conditioned samples. For system A, there is a transition from matrix cracking to failure at the interface. When dry, the fracture occurred principally in the resin and no preference to follow the interface was observed. Once conditioned, the fracture showed a strong preference to follow the interface. The absorbed moisture degraded the interface in system A, causing a change of the failure mechanism from matrix cracking to interfacial failure, resulting in a degradation in the transverse tensile strength. Systems B and C have relatively weak interface when dry, and absorbed moisture does not have an effect.

Vinylester Matrix Systems

The weight gain in seawater and pressurized seawater for vinylester systems is shown in Figure 2. The moisture gained by 510 vinylester systems is less than that by 411 systems, but the carbon reinforced systems gained more than the glass reinforced systems. In general, the weight gains are higher for samples in the distilled water. It was expected that the 510 resin, having a brominated backbone, tends to absorb less moisture. It was unexpected that the moisture gains for carbon reinforced systems are higher than those of glass reinforced systems, especially for the case of pressurized seawater. It is possible that the carbon fiber reinforced vinylesters have a relatively weak interface, which may provide additional locations for moisture to diffuse and accumulate. A difference between carbon and glass reinforced systems is that the former has a higher fiber content ($V_f = 0.6$ vs. 0.5), thus having more interfaces.

Contrary to carbon/epoxy systems discussed previously, there seems to be a time dependence in the degradation of vinylester systems except system G, which is glass fiber rinforced 510 vinylester. Results of the transverse tensile test are presented as percentage Figure 3. The two carbon fiber reinforced systems have the lowest dry strength, indicating the weakest interface. These systems also exhibited a strong time dependent nature of the degradation process.

The low strength exhibited by the carbon reinforced systems supports previous speculation of a poor interface. The time dependent degradation observed is probably associated with the time dependent degradation of the interface. With post–mortem and real–time SEM examinations, it was observed that the initiation of failure for all of vinylester systems was at the interfaces fro both dry and conditioned samples. For samples conditioned in moisture for longer times, more numerous and diffused interfacial failure sites were observed. This led to premature fracture of samples conditioned for 21 and 90 days.

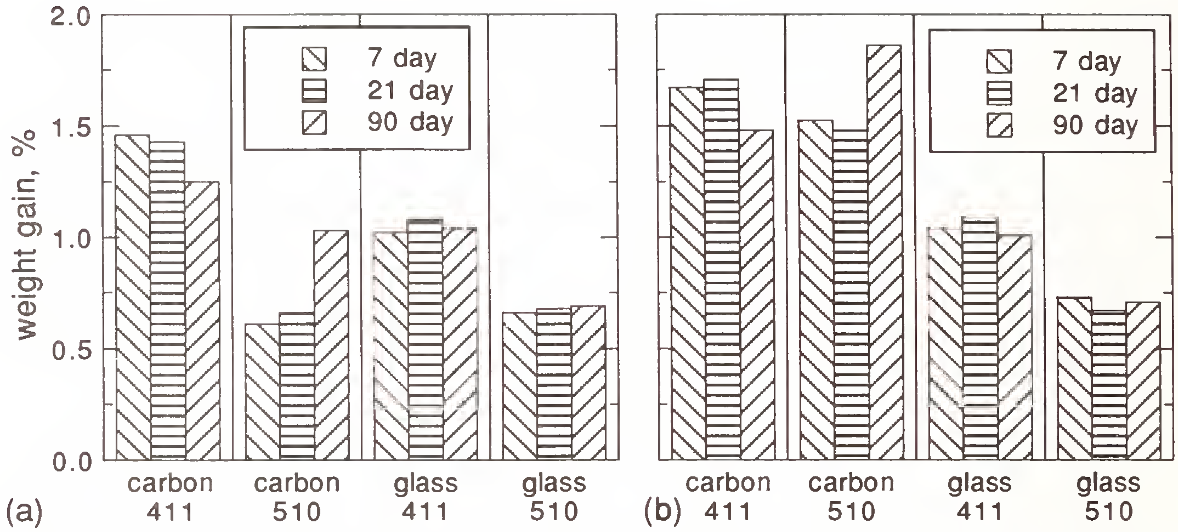

Figure 2. Weight gains for vinylester systems in (a) seawater, and (b) pressurized seawater.

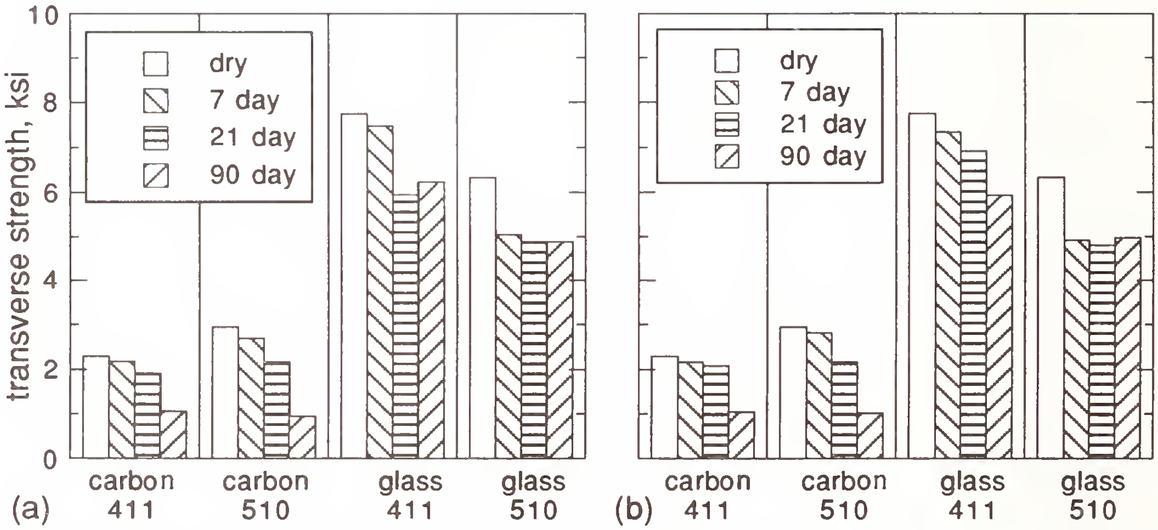

Figure 3. Strength loss of vinylester systems in (a) seawater and (b) pressurized seawater.

Summary

The degradation of polymeric composites made with thermosetting resin matrices have been studied with the transverse tensile test and SEM using samples conditioned in distilled and seawater. A hydrostatic pressure of 3,000 psi only has a minimal effect on the amount of absorbed moisture and degradation. Interface in composites plays a critical role as the moisture–induced degradation is often associated with a reduction in the interfacial strength. Depending on whether the moisture has an effect on the failure mechanism, a system with superior strength when dry may suffer relatively large degradation after moisture exposure. Systems that have relatively weak interfaces and fail in the interface when dry may suffer only a minor degradation. Several systems have been identified wchich showed minimal moisture degradation.

FATIGUE DAMAGE DEVELOPMENT IN EDT SPECIMEN

Materials

The composite system used in this study was the TACTIX 556 resin (Dow Chemical) reinforced with IM–7 (Hercules) carbon fibers. The 556 resin is a low moisture absorption epoxy novolac resin. Quasi–isotropic laminates with a stacking sequence of $[45/0/–45/90]_S$ were supplied. The average ply thickness is 0.0063 inch, and the fiber volume fraction is about 46%, as determined by the acid digestion method. Laminate plate was cut into samples of 9 inches long by 0.5 inch wide for testing. The as–cut sample is referred to as dry sample in this study. Sample edges were polished to facilitate examination under an optical microscope. Unidirectional laminates of 6 and 10 plies and $[\pm45]_{2S}$ laminate were made separately and later used to measure lamina elastic properties and hygrothermal coefficients.

Experimental Procedures

Tabbed samples of 0.5 inch wide $[0_6]$, 1 inch wide $[90_{10}]$, and 1 inch wide $[\pm45]_{2S}$, were used in determining lamina elastic properties of E_L, E_T, ν_{LT}, and G_{LT}. Standard tensile testing procedures were used with T–type strain gages to measure strains.

Coefficients of thermal expansion were also measured with T–type strain gages on $[0_{10}]$ two inch square samples. The transverse coefficient of moisture expansion was measured with a simple fixture that can hold $[90_6]$ samples vertically in a seawater bath. Dial gages of 0.0001 inch resolution were used to monitor the expansion continuously. The weight gain was measured separately with samples cut from the same laminate. Since the moisture expansion in the fiber direction is too small for the dial gage to measure accurately, the coefficient in this direction was assumed to be zero.

The same substitute seawater was used for moisture conditioning and wet fatigue testing. Some of the sample cut from $[45/0/–45/90]_S$ laminates were pre–conditioned to different moisture gains. Edge delamination test (EDT) in fatigue were performed under tension–tension load–controlled mode with a maximum stress of 40 ksi (≈ 40% laminate UTS). R = 0.25 with a frequency of 0.1 Hz, which was selected so that the synergistic effect, if any, of delamination growth and seawater exposure can be characterized in reasonable time periods.

An environmental chamber was built for wet fatigue testing so that the specimens can be tested while immersed in seawater. The testing consists of wet fatigue tests in the chamber with dry samples and conditioned samples of 0.25%, 0.40%, and 0.44% (saturated) moisture gains. Dry fatigue tests were also performed with dry samples (0.0 % moisture).

The polished edges of samples were examined using an optical microscope, which was also used to measure the lengths of cracks on sample edges. Since the crack area across the width of the sample cannot be determined from sample edges, it was measured with an ultrasonic C–scan unit. The crack area was determined by tracing the scanned copies on a digitizing tablet.

Results and Discussion

The lamina elastic properties are listed in Table 1, and the coefficients of thermal and moisture expansion are listed in Table 2. Sample configurations used in testings are also listed. The longitudinal modulus was obtained from a $[0_6]$ laminate that had a slightly higher fiber volume fraction than the $[45/0/–45/90]_S$ laminate. A longitudinal modulus of 18.5 Msi, which gives a calculated laminate modulus close to experimentally measured ones, will be used in later calculations.

The moisture absorption of the $[45/0/–45/90]_S$ laminate is approximately Fickian with a saturation level of about 0.44% of the laminate and a diffusion coefficient of 3.5×10^{-7} in^2/hr. $[0_6]$ unidirectional laminate with slightly higher fiber volume fraction yielded slightly lower saturation level, and the parameters obtained from the multiaxial laminate will be used later.

The dry laminate modulus (E_0) was experimentally determined as 7.16 Msi, which is close to the calculated modulus of 7.19 Msi with E_L = 18.5 Msi. Moisture gain of 0.44% at saturation decreases the laminate modulus about 4% to 6.89 Msi, also obtained experimentally.

The influence of seawater exposure on mode I fracture toughness had been examined by other investigators using double cantilever beam specimen[1], but the experimental results were complicated by the presence of fiber bridging, which enhanced the delamination resistance and can be avoided by using a multiaxial EDT specimen.

Table 1. IM7/556 lamina elastic properties

E_L (Msi)	E_T (Msi)	G_{LT} (Msi)	ν_{LT}
19.8	1.25	0.737	0.345
$[0_6]$	$[90_{10}]$	$[\pm 45]_{2S}$	$[0_6]$

Table 2. IM7/556 lamina coefficients of hygrothermal expansion

α_L (μin/in/°F)	α_T (μin/in/°F)	β_L (μin/in/%)	β_T (μin/in/%)
0.568	22.99	0	2940
$[0_{10}]$	$[90_{10}]$	–	$[90_6]$

Inspection of the fatigued EDT sample revealed that the characteristics of the edge cracking is different between dry and conditioned samples. The edge cracking forms at the –45°/90° interface, in 90° plies and at the mid–plane 90°/90° interface. For dry samples, the dominant mode of cracking is the delamination at the –45°/90° ply interface. These cracks are long and straight, occasionally jump to the opposite –45°/90° ply interface through 90° transverse cracks.

The dominant edge cracking mode of the conditioned samples has switched from the –45°/90° interply delamination to the cracking in 90° plies. The crack path is usually irregular, and it is either at the 90°/90° interface or within 90° plies. The total crack length for these two edge cracking mode as a function of the initial moisture for all samples is shown in Figure 4. The effect of moisture is seen to decrease the delamination at the –45°/90° ply interface, but to increase the crackings in 90° plies.

The extent of crack growth across the width of the specimen as obtained from the through–thickness C–scan is shown in Figure 5 as a function of fatigue cycles. The crack area (A) is normalized against the entire area (A_0). Since the C–scan image is a through–thickness representation of all crackings, it is a representation of the –45°/90° delamination or 90° intraply cracking. It can be seen that the extent of crack growth for conditioned samples is not worse than that of dry samples. Since the initially dry sample tested wet exhibited a crack growth similar to that of the dry sample in the dry test, the moisture effect during fatigue cycling of this system appears to be insignificant.

From the energy standpoint, the suppression of the –45°/90° delamination is expected. The strain energy release rate (SERR) can be calculated using laminate analysis and finite element analysis[9-11]. The effect of cool–down stresses resulting from the cure cycle is to raise the SERR, while the moisture-induced swelling tends to reduce the SERR by relieving the residual thermal stresses. Provided no significant interfacial degradation is present, the reduced interlaminar residual stresses can give a decrease in the SERR required for delamination onset[9,10].

Analysis based on laminate theory that include hygrothermal effects as presented in references 12 was applied to the composite system studied here. The lamina elastic properties and coefficients of hygrothermal expansion listed previously (with E_L = 18.5 Msi) were used in the calculation. The SERR is presented in Figure 6 for the delamination at the –45°/90° interface and the midplane delamination at the 90°/90° interface. The temperature difference was assumed to be –270°F, and the strain was calculated from the laminate modulus with a applied stress of 40 ksi. The –45°/90° delamination has the highest available SERR, followed by that for the 90/90 delamination and that for the 0°/–45° delamination, which is not included in the figure. Non–uniformly distributed moisture was considered.

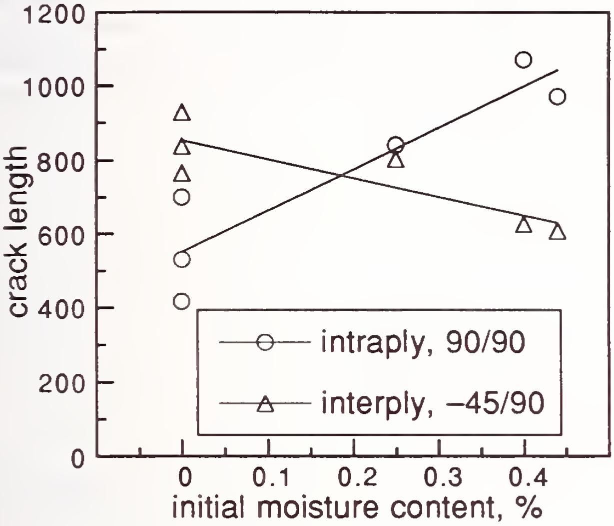

Figure 4. Edge cracking characteristics.

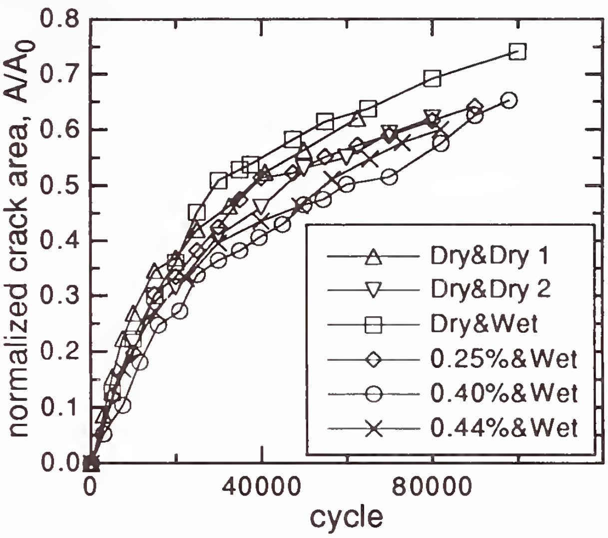

Figure 5. Crack area as a function of cycle.

There is a substantial increase of the SERR when both mechanical and thermal residual curing stresses are considered (shown as M+T in the figure) as compared to considering only mechanical stress (shown as M). If the effect of moisture is also considered (M+T+H), the SERR decreases as moisture content increases. Since the system studied here has a small moisture gain, the effect of moisture is relatively small.

Since load–controlled fatigue tests were used here, the strain increases as the fatigue cycle increases due to the modulus reduction. The SERR calculated shown above is thus the SERR initially available. If the SERR increase due to the modulus drop is considered however, the SERR for the 90°/90° midplane delamination is still smaller than that for the –45°/90° delamination.

For the case of fatigue test with dry sample, the delamination is expected to occur at the –45°/90° interface because the available SERR is slightly higher than that of the 90°/90° midplane delamination. For the conditioned samples, the delamination at the –45°/90° interface is retarded because the SERR available is less from the stress relieving effect of the moisture–induced swelling. But the SERR for the 90°/90° delamination also decreases when the swelling effects are considered, thus the edge cracking in the 90° ply can only occur when there is a moisture–induced degradation of the 90° ply.

The edge cracking mode switch observed is very similar to that observed by Lee[12] who studied the effect of different fiber type on the SERR for edge delamination onset. As the delamination switched from the straight interply failure to the zig–zag intraply failure, the SERR decreases. He concluded that the fibers with lower interfacial strength required less SERR and produced irregular intraply failure. Since there is only one composite system used in this study, the observed edge cracking mode switch should be a result of a lowering of the interfacial strength caused by the seawater absorption.

The absorption of seawater caused the degradation of the interfacial strength for the system studied here and the SERR required should be less when there is moisture present. However, the overall growth of cracking is slightly less for tests with pre–conditioned samples, as shown in Figure 5. There can be two explanations for this contradiction. The first is that the intraply cracking has larger crack area due to its irregularity and zig–zag pattern. A second possible reason is that there are indications of fiber bridging for the 90° intraply cracking. As observed on the specimen edges, the 90° intraply cracking often produces loose fiber ends and bundles.

Summary

For the carbon/epoxy composite laminate studied, the seawater exposure has no adverse effect on the growth of fatigue edge cracking. Moisture tends to decrease the available strain energy release rate. Seawater exposure does seem to cause degradation in the interfacial strength but this degradation leads to edge cracking mode switch. The overall resistance to edge crack growth of the pre–conditioned sample is enhanced by the seawater exposure due to a combination of moisture–induced stress relief and edge cracking mode switch.

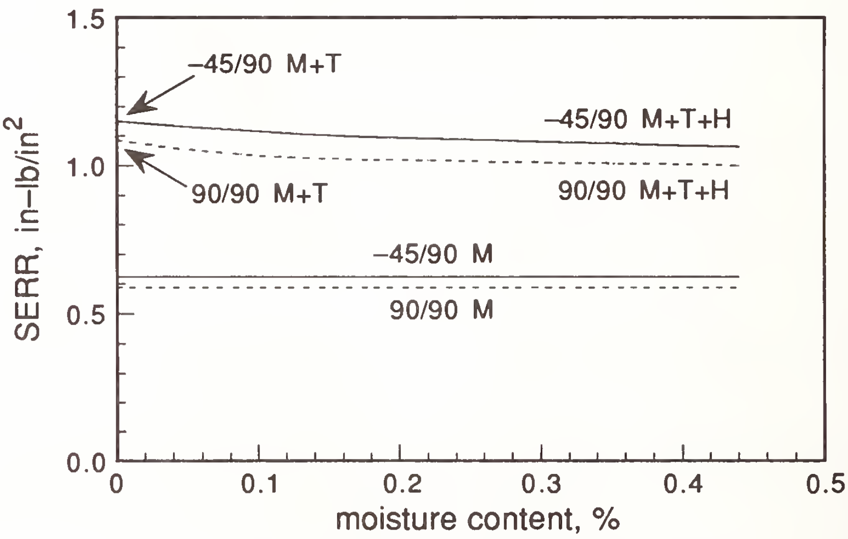

Figure 6. SERR as a function of moisture content.

STRESS CORROSION CRACKING OF GLASS FIBERS

Materials

The composite systems used in this study were E–glass and S–glass fiber reinforced epoxy resin, which is based on EPON 828 resin. Filament wound tubes of [90/±35/90] with an integral rubber liner were supplied (Brunswick Composite). The tube has additional layers of hoop wound on both ends, and a low modulus epoxy resin was later cast on both ends to prepare the tube for testing. Microscopic inspection of the tube cross section revealed a high void content (≈6%), which is a result of the wet–winding manufacturing process used. Tubes were not conditioned before testing.

Experimental Procedures

Since the primary goal is to study the stress corrosion cracking of glass fibers, it was decided to conduct open–ended tube test. In the testing, pressure was introduced into the tube, which was allowed to slide on the pressure seal, creating only the hoop loading. The pressure was held constant, and this is similar to the creep test in which the tube can be submerged in seawater while under pressure.

Results and Discussion

Only preliminary data was obtained at this point, and the result is shown in Figure 7. For the pressure ranges studied, no difference was observed for tubes tested dry or wet.

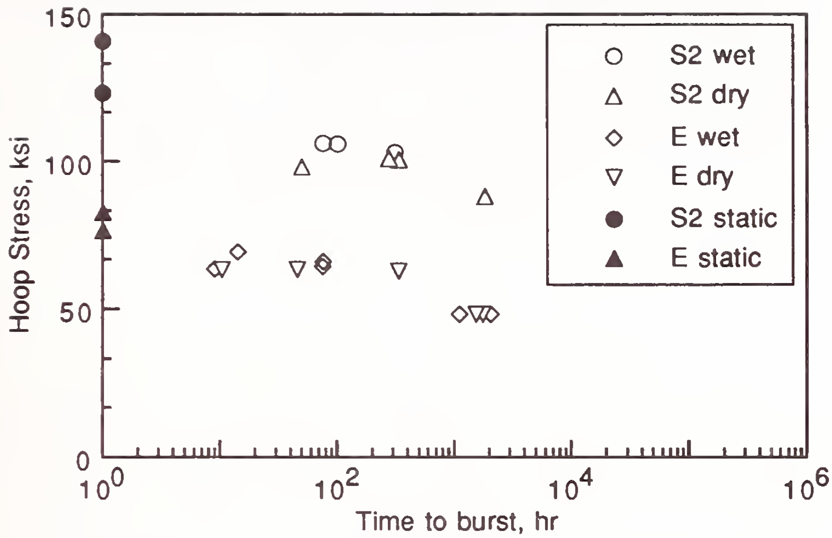

Figure 7. Time to burst at different pressure levels.

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INFLUENCE OF SEAWATER ON TRANSVERSE TENSILE PROPERTIES OF PMC

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INTRODUCTION

Polymer matrix composite (PMC) materials are candidates for use in off-shore and marine structures because they offer substantial weight reduction, good fatigue resistance, and low susceptibility for corrosion compared to metals. It is, however, recognized that the marine environment, Fig. 1, presents some unique challenges due to the presence of numerous ionic species and micro-organisms and long exposure times.

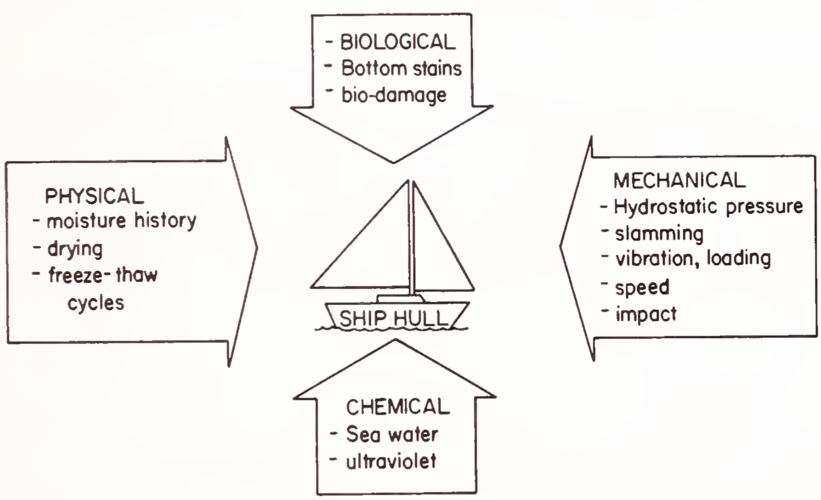

Figure 1 **Typical marine environments.**

When a polymer matrix composite (PMC) is subjected to water, potentially any of the three major components of a composite, viz, fiber, matrix and interface, Fig. 2, may be affected once water penetrates the interior [1]. It is generally accepted that glass and carbon fibers do not absorb water and remain unaffected by water [2]. Polymers, however, absorb water to an extent governed by the network structure (thermosets), or the degree of crystallinity and polarity of the molecules (thermoplastics) [3]. The interface may be a weak link for the integrity of a composite material and has recently been the subject of substantial attention [4-9].

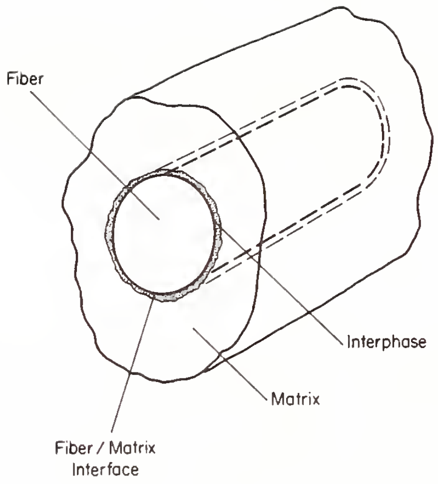

Figure 2 **The three components of a composite material, fiber, matrix and interface.**

It is the objective of this paper to review some recent work on marine environmental effects on PMC performed at Florida Atlantic University [10-12]. Distilled water and seawater were considered. To monitor matrix and interfacial degradations due to water uptake, unidirectional composites were subjected to transverse tension after immersion. Experimental results were compared with micromechanical predictions.

EXPERIMENTAL

Materials and Testing

Carbon/bismaleimide (BMI)-epoxy, E-glass/epoxy, E-glass/polyphenylsulfide (PPS) and carbon/epoxy, Table 1, and neat PPS were examined. Panels with $[0]_8$, $[90]_{16}$ and $[\pm45]_{2s}$ stacking sequences were laid up and processed according to the appropriate specifications, see Table 1. Carbon and glass fiber volume fractions were determined according to ASTM standards D3171 and D2584, and the void content was determined from a quantitative image analysis [13].

Table 1 **Composites examined in the experimental program. V_f = fiber volume fraction.**

FIBER	MATRIX	PROC. TEMP. °C	V_f
G40-800 Carbon	5245 C BMI-Epoxy (thermoset)	177	0.55
NCT-301-2G150 /108 Carbon	Epoxy (thermoset)	130	0.55
E-Glass	5216 Epoxy (thermoset)	140	0.53
E-Glass	LG40-70 PPS (thermoplastic)	330	0.53

As can be noticed, Table 1, the fiber volume fractions of the various composite systems are similar. The void content did not exceed one percent for any of the composites and may be neglected.

Environmental Conditioning

Several specimen geometries were prepared for immersion in distilled water and natural seawater at room temperature (RT,20±1°C) and 35±1°C. The salt concentration of the seawater was approximately 3.5 %. To maximize the water uptake, the specimens were immersed with the cut edges exposed. The total soaking periods were 4600 and 4800 hours for the 25.4 x 229 mm coupons, and 5000 and 5200 hours for the 50 x 100 mm neat PPS and composite panels at 35°C and RT, respectively. To monitor the uptake of water, quantified by the moisture content, M, the specimens were periodically removed from the tanks, dried with absorbing paper and weighed on an Analytic Balance accurate within ±0.0001 g.

Transverse Tensile Testing

Transverse tensile testing of the composites was performed after 4800 hours of immersion at 35°C in distilled water and seawater. The specimens were immersed without endtabs and strain gages to avoid deteriorations of the bonding and gage performance due to water absorption. End-tabs and strain gages were attached prior to testing using M-Bond 200 adhesive.

RESULTS AND DISCUSSION

Water Absorption

Table 2 lists the moisture contents reached at the end of the immersion periods. Only the PPS neat resin and glass/PPS immersed at 35°C were fully saturated. Carbon/BMI-epoxy, and glass/PPS at RT were close to saturation, while glass/epoxy and carbon/epoxy were relatively far from saturation.

Table 2 Moisture contents of composites and neat PPS. Soaking time for the 25.4 x 229 mm coupons was 4,600 hours, and 5,000 and 5,200 hours for the 50 x 100 mm panels at 35°C and RT, respectively.

Material	Planar dimensions mm	Moisture Content, % Distilled Water RT	35°C	Seawater RT	35°C
glass/epoxy*	50 x 100	0.63	0.96	0.57	0.94
	25.4 x 229	----	1.08	----	0.97
carbon/epoxy*	50 x 100	0.84	1.13	0.80	1.07
	25.4 x 229	----	1.21	----	1.14
carbon/BMI epoxy**	50 x 100	0.60	0.66	0.57	0.65
	25.4 x 229	----	0.63	----	0.61
glass/PPS	50 x 100	0.17**	0.18+	0.13**	0.15+
	25.4 x 229	----	0.18+	----	0.16+
PPS	50 x 100	0.05	0.02	0.02	0.02

*) not saturated
**) close to saturation
+) saturated

The presence of salt water reduces the water absorption. The large size of the sodium chloride molecules contained in seawater (as well as other ionic species) appears to be limiting the diffusion of water into the matrix. The thermoset matrix composites absorbed more water than the glass/PPS composite. The small water uptake by the glass/PPS composite is attributed to the semicrystalline nature of the thermoplastic PPS polymer where the crystallites essentially are impermeable to moisture. Neat PPS absorbed less moisture than the glass/PPS composite which is explained by moisture transport along the fiber/matrix interface ("wicking)" via the exposed edges. Increased temperature was found to increase the rate of diffusion, but the saturation moisture content was not affected. For carbon/BMI epoxy, glass/epoxy and carbon/epoxy, analysis of the diffusion data indicates that water is absorbed at similar rates perpendicular and parallel to the fiber direction [10,12].

Transverse Tensile Properties

Transverse modulus, E_2 and strength, X_2^T were measured for the dry specimens and after 4,800 hours immersion in distilled water and seawater. E_2 was not significally changed after water absorption except for glass/PPS that lost about 60 % of its dry modulus [10,12], despite its low water absorption, Table 2. The substantial reduction of E_2 is attributed to extensive fiber/matrix debonding induced by water.

Figure 3 shows transverse tensile strengths for the dry and wet composites. All composites experienced large reductions in X_2^T due to water absorption. The least degraded system, carbon/BMI-epoxy, lost approximately 30 % of its dry strength. For glass/epoxy and carbon/epoxy the strength reductions ranged from 55 to 65 %, while glass/PPS lost 85 % of its dry strength implying a severe degradation of the fiber/matrix interface. Within the scatter in transverse strength, seawater and distilled water are equally severe.

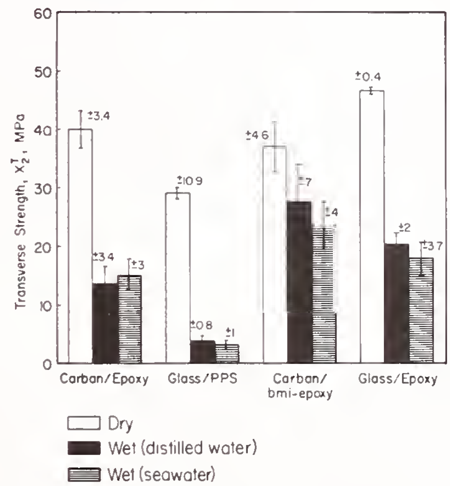

Figure 3 Dry and wet transverse tensile strengths.

SEM observations of transverse fracture surfaces of the dry composites displayed resin adhering to the fibers [10,12] which indicates adequate fiber/matrix adhesion. The fracture surfaces of the wet specimens displayed numerous bare fibers and a wide variation in depth which indicates severe degradation of the adhesion between the fiber and the matrix due to penetration of water. The substantial transverse strength losses observed thus appear to be due to interfacial degradation by water absorption.

ANALYSIS OF TRANSVERSE MODULUS AND STRENGTH

Micromechanical analysis of the transversely loaded composites investigated in the experimental program was performed using finite element analysis and the Cooper-Kelly Model [11,14].

Finite element models were constructed of representative volume elements (RVE) of the composites assuming a simple square packing geometry. Fiber volume fractions of 0.50 and 0.60 were considered in order to encompass the experimental range of fiber volume fractions. The RVE was submitted to loading and boundary conditions representative for transverse tensile loading.

The initiation of a fiber/matrix debond was predicted by using a quadratic interfacial failure criterion,

$$\left(\frac{\sigma_r}{R}\right)^2 + \left(\frac{\tau_{r\theta}}{S}\right)^2 = 1 \qquad (1)$$

where τ_r and $\tau_{r\theta}$ are the radial and shear interfacial stresses, respectively, and R and S are the corresponding interfacial strengths in tension and shear. A debond is thus expected to initiate when the left hand side of eq.(1) reaches unity.

A failure hypothesis may be defined by assuming that transverse failure of the composite occurs at the externally applied stress $\sigma_2 = X_2^T$ when the failure criterion, eq. (1), is satisfied. Such a failure hypothesis may be most appropriate for brittle matrix composites with a strong fiber/matrix interface where debonding is expected to lead to ultimate failure [11,15].

In composites with a weak interface and/or ductile matrix, the transverse strength is expected to be more closely linked to failure initiation in the matrix. Failure of the matrix was thus also investigated using the von Mises failure theory [11] and the Cooper and Kelly Model (CKM) [14],

$$X_2^T = \sigma_m\left[1 - \sqrt{\frac{4V_f}{\pi}}\ \right] \qquad (2)$$

where σ_m is the tensile strength of the matrix, and V_f is the fiber volume fraction. This equation is valid for completely debonded fibers. If the tensile strength of the fiber/matrix interface is incorporated, the CKM is modified to

$$X_2^T = \sigma_m\left[1 - \sqrt{4\frac{V_f}{\pi}}\ \right] + \sigma_i' \sqrt{4\frac{V_f}{\pi}} \qquad (3)$$

where σ_i' is the average tensile stress necessary to separate the fiber from the matrix. Notice that an upper bound estimate, $X_2^T = \sigma_m$ is obtained when $\sigma_i' = \sigma_m$.

In the micromechanical analysis of fiber/matrix debonding, the interfacial strengths (R and S) are required. Experimental methods for determination of such data are not readily available, and ideal bonding was assumed by taking the interfacial tensile and shear strengths as the matrix tensile and shear strengths. Moisture swelling coefficients for the BMI-epoxy and the exopy matrix composites were assumed to be the same as for 3501-6 epoxy, $\beta = 3.2 \times 10^{-3}/\%M$ [9]. The moisture swelling coefficient for PPS has not been published, and micromechanical analysis of wet glass/PPS was therefore not performed.

Failure prediction was performed for each composite by calculating the fiber/matrix interfacial stresses due to cool-down to RT from the processing temperature, Table 1, combined with the actual moisture pick-up after immersion, Table 2. Because of the similar degradations experienced in distilled and seawater, we considered only distilled water.

Correlation with Experimental Results

The transverse modulus of the composites could be predicted from finite elements with good accuracy both in the dry and wet states [11] which indicates that the elastic properties of the constituent fibers and matrices and the modeling are appropriate. The predicted transverse stress levels corresponding to debond initiation and matrix failure generally decreased with increased amounts of absorbed moisture which is in agreement with experimental trends, but because of the ideal fiber/matrix bond assumption and a matrix strength that is assumed to be unaffected by water absorption, the predictions tended to exceed the experimentally observed strengths. The CKM assuming a weak fiber/matrix interface was generally over-conservative. Comparison between the CKM and experimental strengths indicate a fiber/matrix interfacial tensile strength about half the matrix tensile strength for the dry thermoset composites, while the wet thermoset and dry and wet thermoplastic composites suffered from very low apparent interfacial strengths (0-20% of the dry matrix strength).

SUMMARY

Degradation of transverse mechanical properties of polymer matrix composites subjected to water environments have been discussed. Transverse tensile loading was selected because the transverse properties are sensitive to degradations of the fiber/matrix interface and matrix.

It was found that the amount of water absorption is not a reliable indicator of the degradation of the composite. In fact, the glass/PPS composite showed the least water absorption, but lost most of its transverse properties. All composites absorbed somewhat more distilled water than seawater, but distilled water and seawater degraded the properties similarly. Predictions of the transverse modulus were in overall agreement with experimental data, but strength predictions based on fiber/matrix debonding and matrix failure were less reliable. This is in part attributed to the lack of appropriate strength data for the matrix and interface. More reliable predictions would require a complete experimental characterization of matrix and interfacial properties (dry and wet). The accuracy of the strength predictions may also suffer from the assumption of a regular (square) microstructure. Failure may actually initiate locally in a region of closely packed fibers.

Currently, research in this area is extended to investigate the influence of water exposure on interlaminar shear strength and delamination toughness [16,17].

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ASSESSING THE GLASS EPOXY INTERFACE AFTER ENVIRONMENTAL EXPOSURE

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INTRODUCTION

One of the major uncertainties in the use of glass-epoxy composites in the offshore is the resistance of the material to the most ubiquitous of offshore environments: water. The effect of water on epoxy based composites has been quite well characterized in aerospace applications. As a result of the recognition that water indeed has a deleterious effect on the service life of these composites, mechanical testing in so-called hot wet environments is *de rigeur* in the qualification of these materials in the aerospace industry. This recognition has to a large extent also driven the development of semicrystalline thermoplastic composites due to their excellent environmental resistance

However, this aerospace experience is of limited use when designing offshore structures. While the aerospace environment involves moisture exposure of intermittent relatively short duration at elevated temperature, the major offshore applications will involve ambient temperature exposure for periods up to 30 years. The offshore community therefore needs to generate its own set of data to address the issue.

Characterizing this environmental effect is complicated by the fact that in glass reinforced composites water degrades the fiber, plasticizes the matrix and weakens the interface. Therefore, all three effects need to be characterized.

This paper is a brief summary of work which has taken place at Exxon Research and Engineering Corporate Research Labs in the development of a means of studying and isolating the effect of water on the epoxy-glass interface.

EXPERIMENTAL

The epoxy used in these experiments consisted of DER 331 mixed in stoichiometric proportions with Jeffamine D230 hardener. The glass fibers used were from Owens Corning, and contained an epoxy compatible sizing.

Two micromechanical test methods designed specifically for interface strength measurement were evaluated. The first test, the microbond technique[1], involves the formation and curing of resin droplets on glass fibers. The fiber/ droplet is suspended at one end from a force gage, and the filament is gripped by a microvise. The microvise exerts a downward force on the droplet during contact, at which point either shearing of

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the droplet occurs or the fiber breaks (Figure 1). In the former case, the droplet size, as well as the force at which the droplet is sheared is recorded .

The second test which was evaluated was the fragmentation test.[2] In this test, a single fiber is embedded lengthwise down the center of a tensile dogbone specimen of the epoxy, in this case containing a one inch gage length. The specimen is pulled on an Instron machine until fracture, and the number of fiber fractures as well as the length of each fragment was measured (Figure 2).

In an important modification of the experiment, fiber breaks were monitored in situ using acoustic emission apparatus. Using this method, the exact stress at which individual fiber breaks occurred could be measured. The importance of continuous monitoring is described by Wagner et al[2] as a means of determining the strength of the fiber at the critical length. This data is important for conversion of the data into interfacial shear strength values.

In a critical addition to the test, debonded lengths were measured using optical microscopy after failure in the test. The significance of this measurement will become apparent in the subsequent discussion.

Testing was mostly done after water exposure for various times at 95C. This severe temperature condition was chosen in order to maximize the environmental effect on the interface.

RESULTS AND DISCUSSION

Microbond data for unexposed droplets, and droplets exposed to water for 24 hours at 95C are shown in Figures 3 and 4. It is readily apparent that although the test is appropriate to gauge interface integrity in unexposed systems, in exposed samples the glass fiber invariably broke before shear in the droplet. Similar results were obtained when samples were exposed to water at 65C. As a result, it was determined that the microbond test cannot be used to gauge interfacial shear strength as a function of exposure to moisture in these systems under these conditions.

Results of the fragmentation test when run and interpreted conventionally leads to the same conclusion. Figure 5 shows no apparent change in fragment length as a function of immersion time.

The reason for the anomalous microbond and fragmentation results can be attributed to the fact that the environmental exposure affects the strength of the glass as well as the interface. The weakening of the glass results in fiber failure in the microbond test. In the fragmentation test, the weakening of the fiber results in a balancing of the effect of a

---

weaker interface with the lower fiber strength. According to the Kelly-Tyson equation, interfacial shear strength is defined by:[3]

$$\tau = \frac{\sigma_f}{2}\left(\frac{d}{l_c}\right)$$

where σ_f is the fiber strength, d is the fiber diameter, and l_c is the measured fragment length.

Fragment length is a both an inverse function of interfacial shear strength and a direct function of fiber strength. Since both these changes are happening simultaneously during water exposure, this relation becomes an equation with two variables. Measurement of fragment length is therefore an insufficient gauge of interfacial shear strength under these conditions.

If the fragmentation specimens are examined under the optical microscope after testing (Figure 6) one would see that there is in fact a very significant trend as a function of immersion time. In the unexposed state, fracture of glass is accompanied by matrix cracking in the shape of a bow tie at the point of fracture. However, after exposures as short as 30 minutes, one begins to see fiber-matrix debonding on either side of the fiber break in addition to the matrix cracking. After about 10 hours, one sees only the debonding, without the matrix cracking, while after 300 hours, one can see regions of debonding even where there are no fiber breaks.

It would therefore appear that in the case of environmental exposure, a shift of emphasis in data interpretation is warranted. Instead of measuring fragment length, a much more appropriate way to interpret the data in the test would be to measure the length of the debonded regions.

Referring to Figure 7, we consider a relatively brittle single fiber, embedded in a more ductile, infinitely sized polymer matrix. A tensile stress is applied to the composite parallel to the fiber until the fiber breaks sequentially arise, from the weakest fiber site to progressively less critical flaw sites. Only the portion of the process that takes place in the linear elastic region of the tensile test is considered. It is assumed that a fiber break is accompanied by the simultaneous formation of a debonding region on both sides of the fiber break, as has in fact been observed experimentally. This region is very small in the presence of a good interfacial bond, but can be very large for weakly bonded systems. The length of the debond is L_d on both sides of the fiber fracture, and the fiber stress, σ_f, which is zero at the fiber break site and is considered negligible in the debond region, builds up along a region of total length (counting on both sides), until the average fiber stress level σ_f* is recovered. Such stress build up is assumed to be near, for simplicity, as in the Kelly Tyson approach., implying a constant shear in the build up zone. As a result of the fiber fracture, the strain energy in the fiber length $L_d + \delta$ prior to the break is transformed into an energy contribution necessary for the formation of interfacial debonding.

Therefore, the strain energy in the debond region before debonding plus the strain energy in the stress recovery zone is equal to the energy to break the fiber plus the energy to debond the fiber in accordance with the following relation:

$$\frac{\sigma_f^{*2}}{2E_f}(\pi r^2 L_d) + 2\left[\int_0^{\delta/2} \frac{(\sigma_f(x))^2}{2E_f}\,dx\right](\pi r^2) = \gamma_f(2\pi r^2) + \gamma_{if}(r\pi L_d)$$

where E_f and r are the Young's modulus and fiber radius respectively. Referring to Figure 7, the stress profile along each of the stress build up zones is $\sigma_f(x) = [x/(\delta/2)]\sigma_f{}^*$. Inserting this in the integral above, and rearranging, the following equation results:

$$\gamma_{if} = A + (B/L_d)$$

where:

$$A = (r\sigma_f{}^{*2})/4E_f$$

$$B = r\{(\delta\sigma_f{}^{*2})/(12E_f) - \gamma_f\}$$

Equation 2 gives the interfacial energy in terms of the fiber parameters $\sigma_f E_f$, γ_f, and r, of the stress transfer length δ, and of the stress level $\sigma_f{}^*$ at which the fiber breaks and associated interfacial debonding occur. The value of $\sigma_f{}^*$ should, ideally, be determined by continuous monitoring of the fragmentation experiment.[2,4,5] The fiber parameters, E_f, γ_f, and r are known either from the literature or via measurements. The stress transfer length δ varies with the applied stress (or strain) level, and may be estimated from the photoelastic pattern surrounding a fiber break, or it may be accurately measured by more sophisticated techniques such as microscope Raman spectroscopy.[6] Note that, unlike the classical fragmentation test procedure, the aim of which is the calculation of an interfacial shear strength based on saturation data, the present analysis is based on measurements taken from that part of the fragmentation test that takes place far below the saturation limit. This has the advantage that it allows the testing of composite materials systems in which the strains to failure of both fiber and matrix are relatively close to each other, and therefore never reach saturation in a fragmentation test. Using the proposed new approach, their interfacial adhesion may be quantified at the condition that a measurable amount of debonding is present. Note that: (i) the constant A is the limiting value of interface energy when very large debonded length are present; (ii) strongly bonded composites give rise to short debonded lengths and thus very high interfacial energies, which in turn cause the composite to fail by matrix fracture at the fiber break site, rather than by interfacial failure there.

It is important to realize that the theoretical scheme presented here is only approximate, and (at this point of our research program) only points to a possible direction for a reinterpretation of the fragmentation test in terms of energies rather than of stress. Some of the approximations involved are the following:

- The energy balance analysis in Eq. 1 compares energies before and after the fracture of the fiber and of the interface over a certain length. A more strictly correct analysis, which would instead involve the *incremental* growth of a debonded crack along the interface, is currently under investigation.
- Eq. 1 does not account for the energy that is dissipated into the possible formation of matrix damage around the fiber break just prior to interfacial debonding (for example, the formation of matrix cone-like breaks, or of matrix yielding), as well as for the energy due to the fiber breakage that is dissipated into acoustic waves. Also, as previously mentioned, all pre-existing fiber stresses (such as residual thermal of fabrication stresses) are not included for simplicity.
- The debonded region is assumed to be frictionless although in most composites stable debonding most probably occurs with increasing load precisely because of the presence of such frictional forces.

The results in Figure 8 thus shows the fragmentation data, reinterpreted in light of the interfacial energy criterion, involving the measurement of debonded lengths.

CONCLUSION

The microbond test is apparently inappropriate for gauging moisture effects on the epoxy-glass interface (at least under severe conditions). In contrast, the fragmentation test is indeed an effective means of assessing the effect of water on the fiber matrix interface, but only if microscopic assessment of debond length is included in the analysis. An advantage to this approach is the fact that it enables determination of interfacial adhesion for composite systems which never reach saturation in the fragmentation test.

The development of this test method is but one step in joint activities between Exxon Production Research, Exxon Research and Engineering and Imperial Oil Limited to assess the reliability of composite parts in the presence of moisture and hydrocarbon environments.

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FIGURE CAPTIONS:

1 Schematic of microbond test

2. Schematic of fragmentation test

3. Microbond test results before moisture exposure

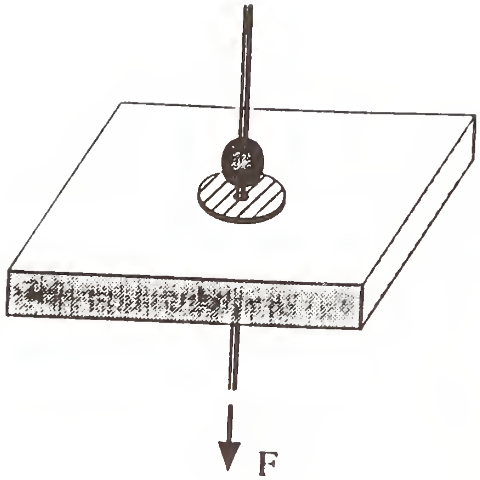
4. Microbond test results after moisture exposure

5. Fragment length versus water immersion time at 95C

6. Optical microscope appearance of specimens after environmental exposure and fragmentation testing

7. Fiber break and interface debonding in the fragmentation test. Applied stress is parallel to the fiber, also showing tensile stress in the fiber around the break site.

8. Interfacial energy versus immersion time in water at 95C



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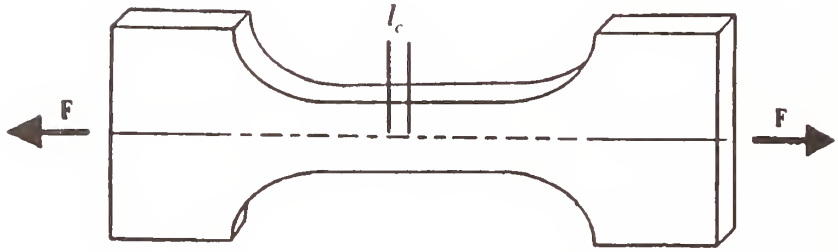

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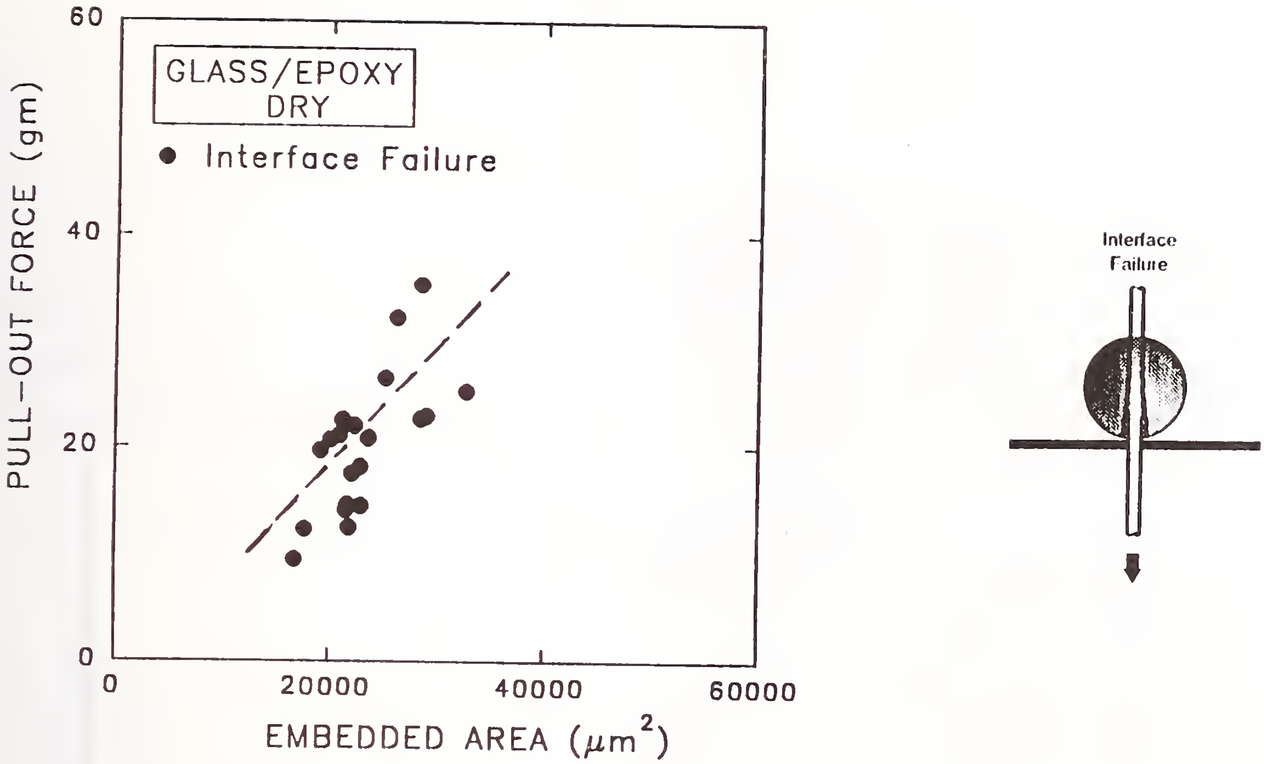
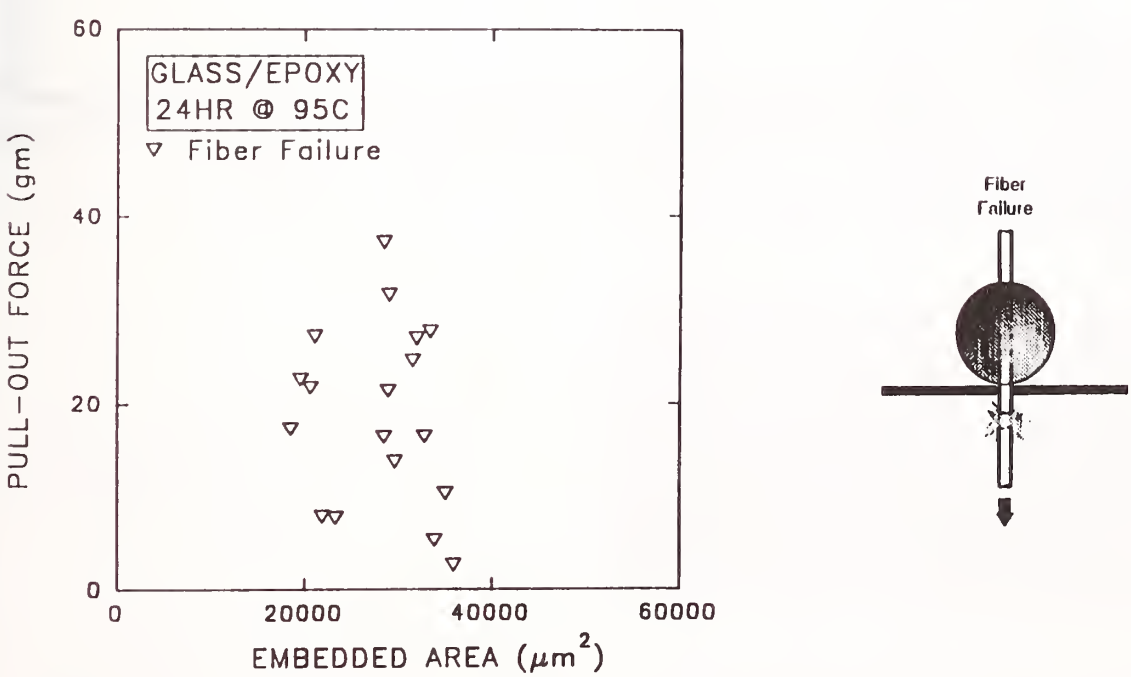
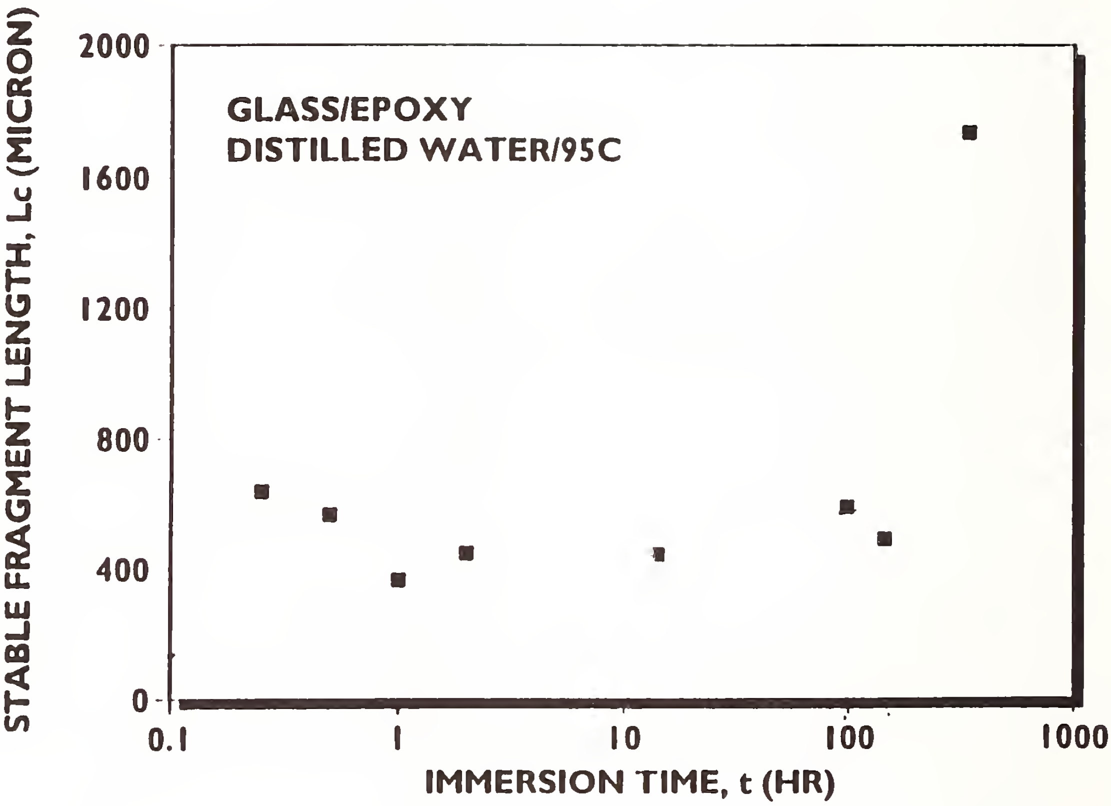

GLASS/EPOXY
DRY
Interface Failure
PULL-OUT FORCE (gm)
EMBEDDED AREA (μm^2)
0
20
40
60
0
20000
40000
60000
Interface
Failure

3

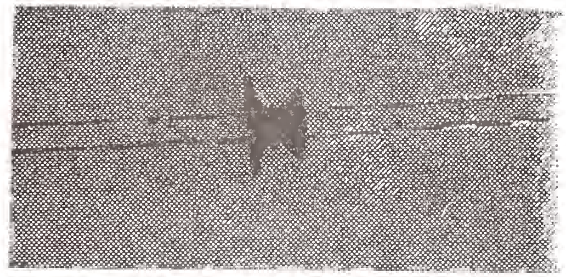

GLASS/EPOXY
24HR @ 95C
Fiber Failure
PULL-OUT FORCE (gm)
EMBEDDED AREA (μm^2)
0
20
40
60
0
20000
40000
60000
Fiber
Failure

4

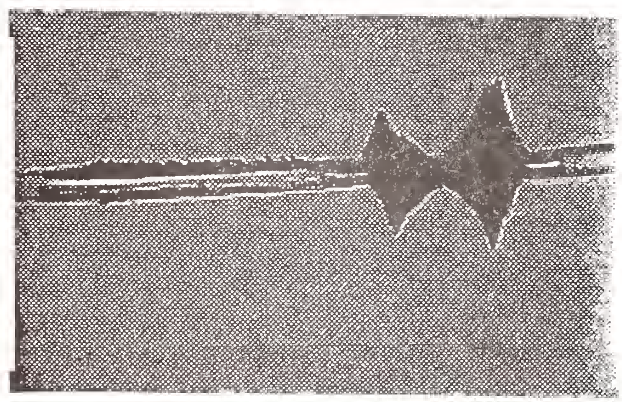

GLASS/EPOXY
DISTILLED WATER/95C
STABLE FRAGMENT LENGTH, Lc (MICRON)
2000
1600
1200
800
400
0
0.1
1
10
100
1000
IMMERSION TIME, t (HR)

5

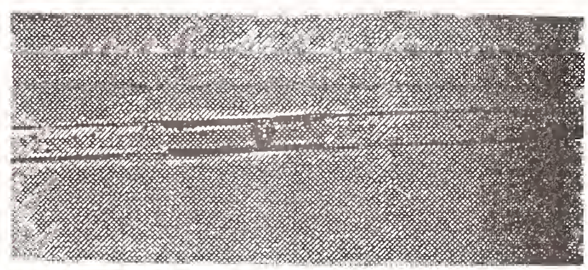
Dry state
Matrix failure
No interface failure



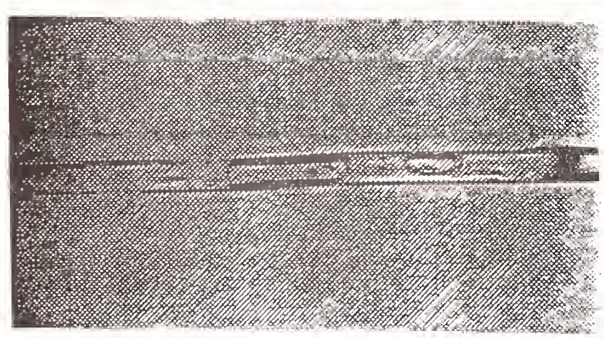
Short immersion times @ 95C
Fiber failure
Matrix failure
Interface debonding



Medium immersion times @ 95C
Fiber failure
Interface debonding

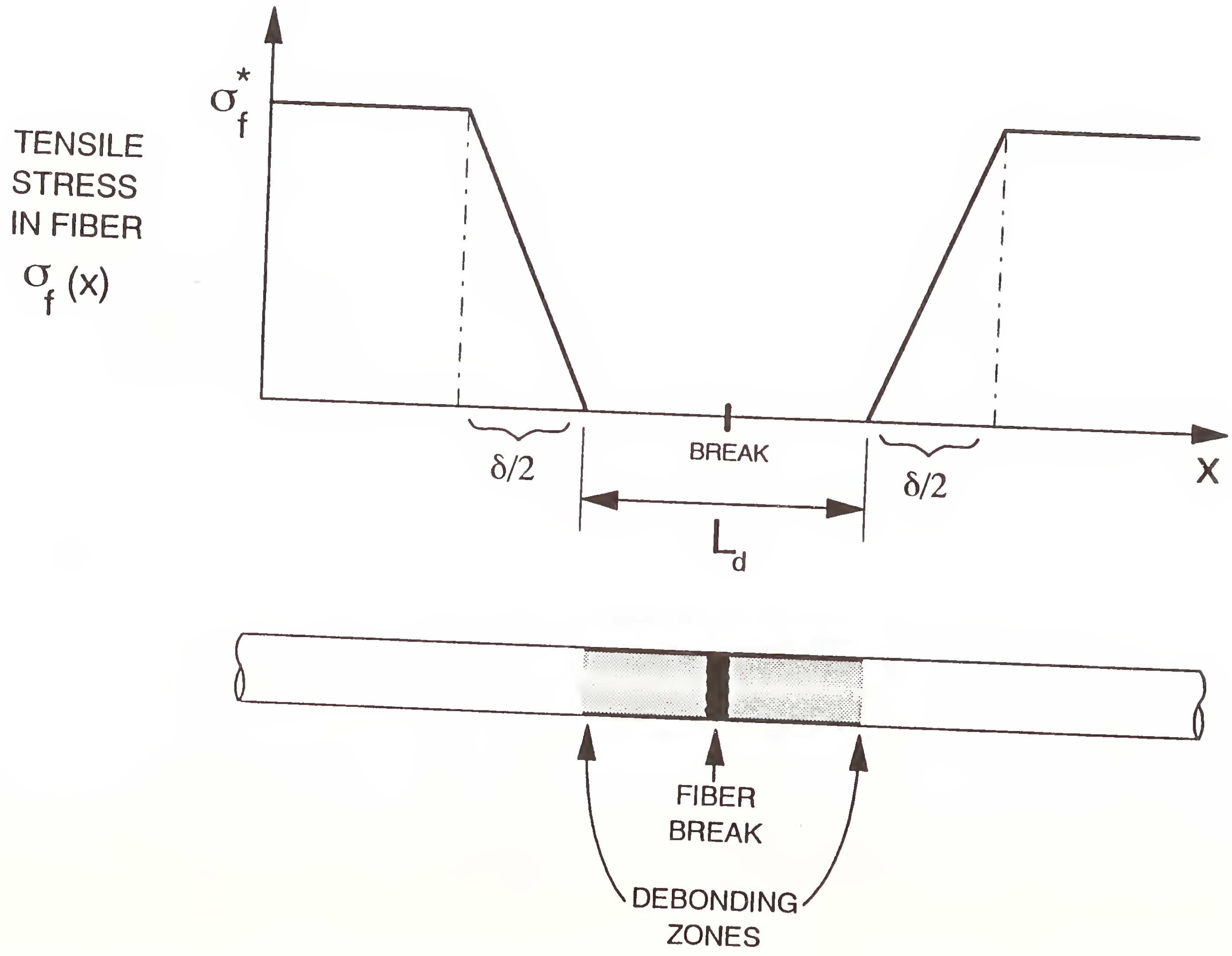


Long immersion times @ 95C
Interface debonding

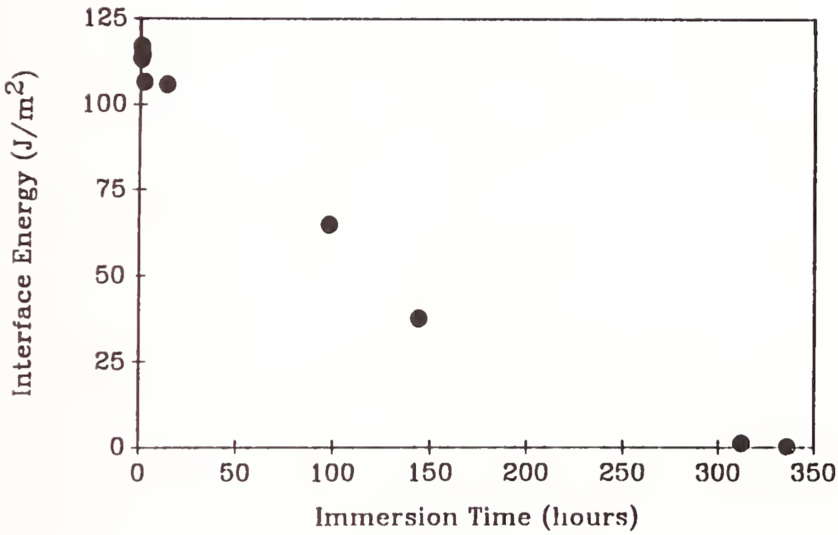


6

7



TENSILE
STRESS
IN FIBER
$\sigma_f(x)$
σ_f^*
$\delta/2$
BREAK
$\delta/2$
X
L_d
FIBER
BREAK
DEBONDING
ZONES



Interface Energy (J/m^2)
125
100
75
50
25
0
0
50
100
150
200
250
300
350
Immersion Time (hours)

8

Analysis-Based Design Tools for Offshore Applications

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ABSTRACT

Design of filament-wound pipes for many applications for offshore engineering have been driven more by manufacturing and empiricism than by micro-macromechanics analysis tools. As demand of strength and durability increases for more critical services in piping and vessels, predictability of deformation and failure modes becomes indispensible. Computer simulation of the physical processes of manufacturing, loading and environmental conditions is the first step in developing a rational basis of design. A few approaches to these issues will be outlined in this paper. In particular the case of the grid/frame structure would be a natural extension of cylindrical structures for future offshore applications.

BACKGROUND

The use of composite materials in aerospace vehicles has been acceptionally successful for the last twenty years. As applications move from secondary structures to primary ones, comprehensive database, design and manufacturing methodologies are available. Growth in aerospace structures has accelerated to include horizontal and vertical tails of Boeing 777, and dramatic applications in high bypass engines for B-777 and beyond.

Other industries are trying to follow the model of the aerospace industry in their introduction of composite materials to their products. Windmill rotor blades, rollers and drive shafts are examples of reliable applications of composite materials. Others are emerging. Offshore applications require no fundamentally different performance. Safety, cost effectiveness, resistance to fire, 30-year life, certification, maintenance and others are common to nearly all industrial applications. The phycial size of the offshore however is a challenge. Again, if we can understand the fundamental physical behavior we can design and manufacture whatever is needed.

SPECIFIC TASKS

We would like to propose specific tasks in support of offshore applications. Most of these are derived from aerospace applications and can be easily adopted to the environments and requirements of offshore situations. These tasks are generic in nature and can be equally applied to cylindrical and structures in general.

- Piping Design

Piping and cylindrical vessels are easy to analyze either as a thin or thick wall construction. Externally applied forces and moments are also easy to analyze. Process parameters that includes the curing stresses, matrix nonlinearity and interfacial strength can all be modeled, by for example an integrated micro-macromechanics analysis, and optimized accordingly. The presumption that there is a complete chaos in predicting the weeping strength of a pipe as material/process parameters change appears to be unwarranted. Even the linear analysis will point to the optimum wrap angles that would be best to increase the weeping and burst pressures. Guessing without the guidelines from analysis would be hopeless.

Prediction of long term behavior has been developed for many years. Viscoleastic models for solid propelants are available and should be used to design and interpret test data for creep, stress relaxation and reliability.

Test coupons often present an issue. For pipes subjected to internal pressure, we would recommend a ring specimen loaded hydrostatically with internal or external pressures. This may provide the most reliable test method. We have used rubber O-rings as the medium to exert the pressure. This is easy to do and can generate hundreds of data points.

- Joints

Bonded and bolted joints are unavoidable and must be modelled, tested and designed. Again, modern analytic modelling is available. The key in our approach is to include the progressive failures of the adhesive layer, interface and individual plies. We are not aware of many existing models that have the progressive failure capability. Once the static performance of the joints are understood, we can then extend it to long term behavior through time dependent modelling like that used in the propelant technology. Again our attempt is to minimize empiricism. Predictability depends on the understanding of the failure modes. Plotting and analyzing test data are at most a point design approach. We need modelling and confirming tests before we can have a theory. Joints, fittings, pipes and vessels can be treated by the same approach, with different geometries and boundary conditions. Thus an investment in the fundamental behavior will pay dividends for different applications. Material/processing engineers often take a different viewpoint from the mechanics oriented engineers. To gain confidence in composite materials, we must learn to work with one another.

- Effects of Defects, Damage and Repair

With a progressive failures capability, user-friendly finite element analysis tools are available to model the following:

Manufacturing defects: nonuniformity, voids, wrinkles, debonds, gaps, laps and surface blemishes.

Operational damages: impact, puntures, delaminations, indentations, scratches, corrosion and fire.

Repair: strength and stiffness recoveries from bonded plugs and patches, and bolted doublers.

With this effects of defects tool, which is formated for use by non specialists, a consistant, rationally derived accept/reject criterion of composite structures can be established. Again, modelling is the key to this tool. With modern computers, we have made great progress using this approach. The aerospace companies have supported this enthusiastically.

GRID/FRAME STRUCTURES

Beyond pipes and vessles, the next frontier of composite structures may be grid/frame structures. We hope to achieve competitive performance and cost targets for these structures for high volume civilian applications. We plan to adhere to the following approaches:

- To use GFRP and CFRP in unidirectional format (not laminates) to form flat, curved and cylindrical configurations as the primary load-carrying structures

- To use organic matrix unidirectional tapes with on-line or in-situ consolidation (without bagging and autoclaving)

The traditional use of multidirectional laminates for composite materials have several intrinsic weaknesses:

- Lower in-plane properties than longitudinal properties
- Low interlaminar strength
- Labor intensive layup process
- Costly bagging and autoclaving operations
- Costly and inefficient joining

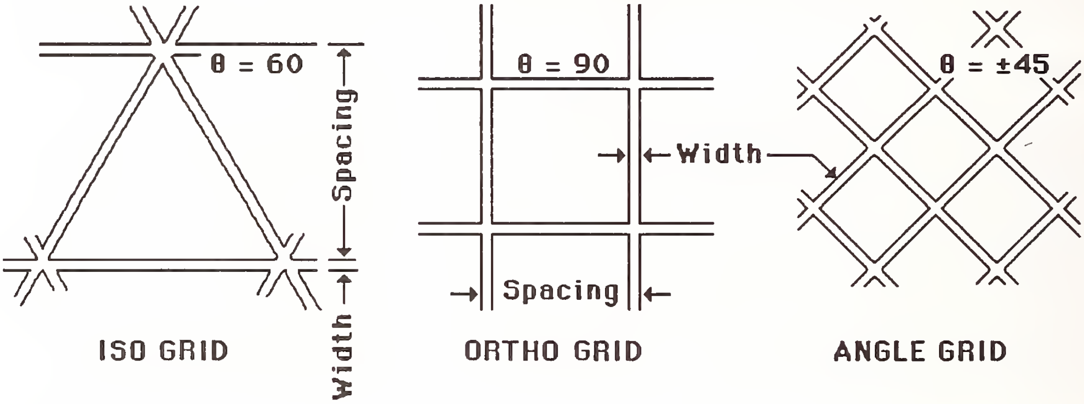
The most challenging task is to translate the exceptional longitudinal properties of composite materials to useful structural forms. The potential of composite materials can increase substantially if we can assemble structures with a minimum reduction in the longitudinal properties.

Pultruded sections are normally unidirectional and thus have the maximum stiffness and strength. Sections however are not complete structures. Joints are often needed to combine pultruded sections by mimicking steel structures. Only a small portion of the total longitudinal properties are translated into the final structures.

Sandwich panels are most efficient in flexural rigidity and are relatively easy to produce. The face sheets are made of laminates which again utilize only a portion of the unidirectional properties. The panels are often made by hand, susceptible to moisture incursion, and difficult to inspect and repair.

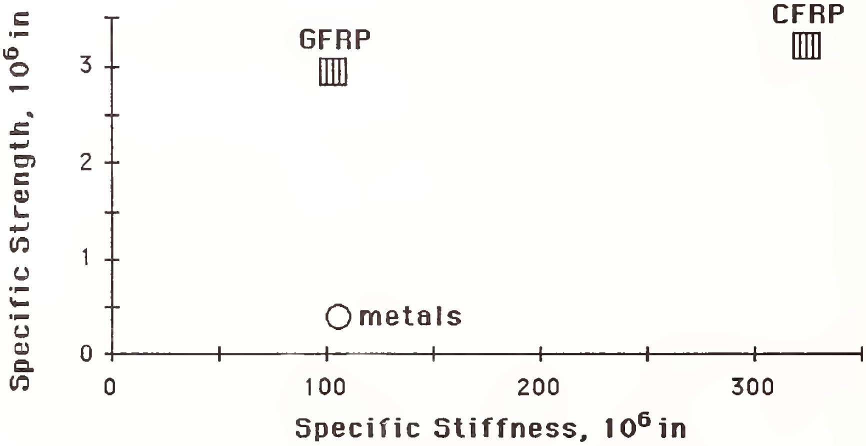
Stiffened panels are also made of laminated composites, difficult to assemble, not amenable to automation, and not easy to repair.

Three examples of the grid structures are shown in the figure below:



The advantages of grid structures are many:

- All ribs are unidirectional and are intrinsically stiff, strong and tough. It is nearly indestructible. The traditional specific stiffness and strength comparisons, shown below, are valid for grid structures:



Thus even GFRP can be used to compete with steel and aluminum! They have the same specific stiffness, and many times the specific strength.

- Grid structures are damage tolerant. Like in a "Chinese torture" strain to failure is many times that of laminates. The ribs are unidirectional and thick, and test data show that the ribs and joints do not delaminate.

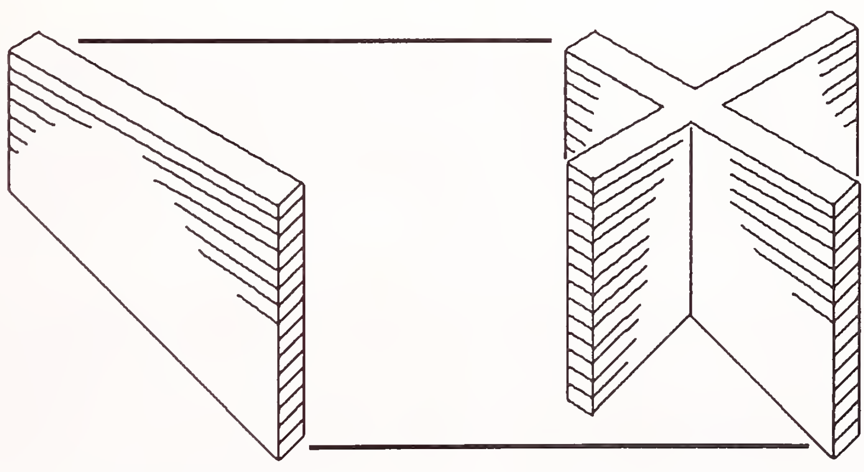
• Continuous filament winding or tape placement process has been demonstrated for grid structures. The speed of on-line consolidation for thermoplastic composites is rapidly increasing. There is no theoretical limit how high the rate of consolidation can reach. For thermosetting composites, in-situ curing without bagging and autoclaving is also possible. The cost of processing will be lower than the cost of material, which is normally difficult to achieve with the conventional thermosetting process.

• Grid structure is open and modular. Inspection will be easier than sandwich panels. Repair can also be modular; e.g., replacing unit cells.

TECHNICAL BARRIERS

To date grid structures have seen only limited applications. Examples include civil engineering (space) structures, W.W.II English bomber Wellington's fuselage, and, more recently, the horizontal stabilizers of Airbus A330 and 340, and an USAF space structure. With the exception of the AF structure, the remaining designs are difficult to fabricate and do not utilize the superior longitudinal properties of modern unidirectional composites. Using on-line or in-situ consolidation, it is feasible to continuously produce a grid structure. This approach that allows automation is fundamentally new. The key to success lies in the mold design and the interlaced joint shown in the figure below.

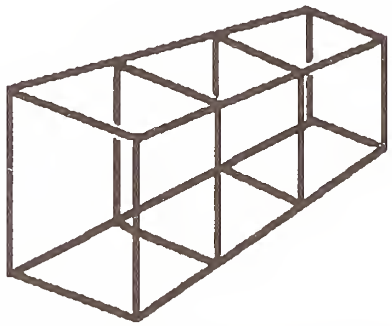
The intersecting or interlaced ribs provide the opportunity to fully utilize all the unidirectional properties. The success of the joint (having a smooth transition) has been demonstrated in thermosetting plastic composites. This needs to be demonstrated in thermoplastic composites using the on-line consolidation fabrication. The damage tolerance of the interlaced joint has been demonstrated. Reduntant load paths appear to be present in this structure.



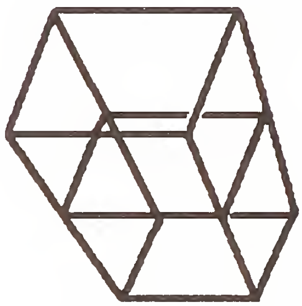
Unidirectional rib **Intersecting ribs**

Another barrier is the design and fabrication at joints (connections), openings and concentrated load introduction points. These issues are different but not more difficult than those with any structure.

The proposed grid design is to eliminate mechanical joints at the rib intersections. Not only can efficiency of the grid structures increase, automated manufacturing is now feasible. The same seamless design will be applied to frame structures, examples are shown below:



Trailer/container



Platform

For offshore applications, we see grid/frame structures for floors, housing, and other load bearing situations. Test data have demonstrated the phenomenal resilience of the grid structure under static loading. Redundant load path is the primary factor for this outstanding character. It is anticipated that dynamic resilience and long term performance will be equally superior to the conventional stiffened panels and shells. This structural concept, for example, is being considered for the containment ring of a new generation of gas turbine engines that is over 10 feet in diameter. With automated manufacturing capability, cost of structures is expected to be the lowest of all composites manufacturing. We are therefore very optimistic about the future of grid/frame structures.

CONCLUSIONS

We would like to combine the experience of aerospace and offshore engineering to face many challenging problems. We believe that analytic tools are critical to bring safe and cost effective structures to use. There are no fundamental limitations of composite materials for such applications. In fact, composite materials may be the only option that is available to meet the requirements of future offshore applications.

It is important to invest in the relevant technolgy in modelling, testing, manufacturing, assembly and maintenance of composites components and systems. An agressive program that would bring industry, government and academia can lead to important applications in a very short time. The risks are low and the payoff can be beyond our fondest dream.

COMPOSITE APPLICATIONS IN OFFSHORE OPERATIONS

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Introduction

The properties of polymeric composites, including low density, excellent corrosion resistance, high static and fatigue strength, low maintenance and low life-cycle cost, clearly demonstrate that composites are desirable materials of construction for offshore uses. The polymeric composites of interest here are mainly fiber-reinforced thermosetting resins; the fibers being glass (mainly E-glass) and carbon; and the resins being vinylester, polyester, epoxy and phenolic. The material cost per pound of polymeric composites is higher than steel. When composites are not used for or viewed upon as providing needed enabling technology, the initial cost of composite components could be of major concern in offshore applications. The cost of glass fiber reinforced components can range from $2-5/lb. When carbon fiber is needed to improve structural performance, the cost of composite components will be significantly higher. For viable offshore applications, components must be made economically by low cost manufacturing processes such as filament winding, pultrusion, resin transfer molding, or contact molding and from the lowest cost resins and fibers.

A brief discussion on the status of topside and below water surface applications is given below. Some issues relating to the design and performance rating of FRP line pipes are presented with the objective of stimulating thoughts and discussion on the design of composite components for offshore operations.

Topside Applications

Glass fiber composites are used for piping, grating, process equipment and a variety of other applications on topside offshore structures (Table 1). In addition to the benefits that can be derived from using composites as mentioned earlier, other motivations for topside uses include reduce initial cost, eliminate corrosion problems, improve safety and reliability, and ease of installation. Topside applications of composites are generally perceived to be technically feasible. Component and system design are within existing capabilities and field experience is gaining in existing installations. Topside uses can also benefit from a long record of proven performance in otherwise comparable installations onshore. Nevertheless, it is recognized that the differences in performance requirements between land-based and offshore installations can be significant and may influence design, material selection, installation and cost.

The impact of composites on the initial cost of offshore installations cannot be realistically estimated without giving considerations to such issues as specific design and performance requirement, and cost of corrosion protection, transportation and installation, for examples. For floating platforms, where weight savings could potentially yield large cost savings, an estimate of the relative economic advantage of composite components can be obtained by calculating the cost of composite per ton of replaced steel. Simply,

$$C(\$/\text{ton steel replaced}) = 2000*(1-X)*A - 2000*X*M - 2000*B$$

Table 1. Potential Polymer Composite Applications On Platforms

Platform Topside
- Vessels
- Tanks
- Process Equipment

- Pressure Piping
- Fire Water Piping
- Sea Water Intake Piping
- Utility Piping
- Drain Piping
- Equipment Enclosures

- Decks
- Equipment Skids
- Grating
- Handrails
- Ladders
- walkways/Stairways
- Cable Trays
- Crew Quarters
- Blast Walls
- Electronic Cabinets
- Helidecks
- Flare Blooms

- Bumpers
- Escape Devices

TLP Below Water Surface
- Production Risers
- Riser Stress Joints
- Tendons
- Mooring Cables
- Floatation Modules
- Buoys

Drilling
- Drillpipe
- Drilling Riser
- Core Tubes
- Choke and Kill Lines
- Riser Fairing

where

C = cost of composite component (before installation) which replaces one ton of steel
X = weight saving with composite in %/100
M = incremental payload cost, $/lb
A = cost per pound of composite, $/lb
B = cost per pound of replaced steel, $/lb

Putting C and B equal to zero in the above equation, the percentage of weight savings at which sufficient incremental payload cost is realized to pay for the cost of the composite component is given by:

$$X(C=B=0) = A/(A + M)*100\ \%$$

Table 2 shows the percentage of weight savings that could contribute to the total cost of the composite component for various combinations of incremental payload cost and composite component cost.

Table 2. (% Weight Savings at which Weight Saved Pays for Component)

	A($/lb)				
	2.5	5.0	10	15	20
M($/lb)	X(%)				
2.5	50	67	80	86	89
5.0	33	50	67	75	80
10	20	33	50	60	67
15	15	14	40	50	57

If the cost of the replaced steel component is included, cost break-even can be achieved at lower weight savings than those shown in Table 2.

Despite the benefits that can be achieved with composites, several issues need to be addressed in order to further increase the use of composite components on platform topside. Regulatory requirements and their implications concerning fire safety and reliability of composite installations need to be clarified and understood. The likelihood and consequences of accidental impact on the long term performance of composite components such as gratings and piping, for examples, are of concern and need to be accounted for in the design of composite components. A rational approach will need to be developed for using/extrapolating test results from laboratory scale test to assess the effect of impact loadings on full scale structures. Replacement quidelines will also need to be established. For new applications, extra initial efforts spent on training, system design, specifications, joining requirement and qualification, equipment testing and inspections, for examples, will ensure satisfactory installations. Further, development of uniform industry specifications for design, manufacturing, testing and quality control will help to expand the applications of composites on platform topside.

Below Water Surface Applications

On floating platforms, such as tension leg platforms, possible applications below the water surface include such components as tendons, risers, and mooring systems, for examples, (Table 1). In these applications, the impact of composites on platform cost and performance is obtained mainly through weight reduction and/or lessening cathodic protection. A system approach is usually required to realize the full benefits of using composites. Carbon fiber, glass fiber, and kevlar fiber all appear to have a place in these applications. In contrast to topside components, actual field experience for below water surface applications is limited.

Composite tendons and risers are, in general, structurally more demanding than topside components. Dimensions, loading requirements and design features will set these components apart from other prior offshore applications. A substantial effort in various areas including design, engineering, connection, terminations, procurement, risk assessment, qualification, fabrication, NDT, transportation and assembly will be needed to demonstrate the acceptability of composites as engineering materials for these critical components. Tendons and risers will probably not be used without some forms of full-scale testing, qualification and verification. Unfortunately, the time required for component development is usually not available within most deep water projects. For entry in these applications, these composite components will probably need to be ready at the start of a project.

In view of the high development cost for below water surface applications, industry cooperation on composite component development appears very desirable and should be encouraged. Evidence of broad interest could stimulate composite suppliers to commit themselves to product development and encourage regulatory agencies to establish the appropriate guidelines, standards and specifications.

Some Related Issues

As mentioned earlier, to increase the use of polymeric composites in existing potential applications and to expand their use into more demanding operations, uniform standards and specifications in component design, performance requirements, ratings, dimensions, fabrication, quality control, risk assessment, transportation, installation and repair will need to be established (for both onshore and offshore applications). Uncertainties in product long term performance must be reduced and ability of product to resist damage in field conditions must be increased through proper design and material selection. Prudence must be exercised through proper training and understanding of composite characteristics to avoid unnecessary premature field failures. On the other hand, excessive conservatism will needlessly increase cost and price composite components outside the competitive range of conventional steel constructions.

FRP line pipes are used extensively in both onshore and offshore applications and will be employed here to illustrate some of the elements discussed above. Despite a long record of proven applications, the allowable service temperature and pressure for these components are still commonly determined by empirically derating manufacturer's pressure and temperature ratings. It is obvious that such a practice will inevitably incur potential penalty on the initial cost of the components and in some cases lead to rejection of the product in favor of the cost of steel construction. However, this is usually done to avoid uncertainties and variations in product long term performance and to ensure continued service without failure. Results of a recent study (Ref. 1) clearly show that a wide disparity in product long term performance could exist between measured values and calculated values based on manufacturers' published data. The urgent need to reduce uncertainties in product long term performance through uniform and rational rating (testing) methods is evident. A performance-based purchase specification for FRP pipes and fittings based on API Specification 15HR and 15LR is recently proposed (Ref. 2). This specification is aimed at ensuring that products will survive long term service at rated operating conditions with a minimum known strength margin.

In addition to reducing performance uncertainties through the use of uniform rating methods and specifications, products need to be improved to meet increasingly demanding operating conditions. This will require an understanding of the relationship between product design and the failure mechanisms that control the performance of the product. For FRP line pipes, the onset of weeping or leakage is an indication of the loss of serviceability of the product. The convoluted path(s) of matrix cracking and ply delamination in the pipe wall controls weeping and should be addressed in product design and performance evaluation (Ref. 3).

For illustration, Tables 3 and 4 show the calculated room temperature stress distributions in principal material directions for different layers of two identically rated FRP line pipes subjected to a rated pressure of 800 psi. Tables 5 and 6 show the corresponding calculated stress distributions at 150 °F. These calculations are based on the assumption of linear elastic behavior. Resin properties and fiber volume fractions are also assumed to be the same for both line pipes. It is recognized, however, that with the assumed fiber angles and ply thicknesses used in the calculations, these line pipes may not truly represent the commercially available products. However, the results shown in Tables 3-6 can be used, at least qualitatively, to bring out several important issues. Some of these issues are discussed below.

It is quite obvious from the stress distributions that weeping in both pipes (A and B) will be governed by the matrix dominated properties of the composites. Even though the pressure ratings of the two FRP line pipes are identical, their through thickness stress distributions in the matrix phase of the composites are quite different. To understand the merits of the two different designs and identify opportunities for product improvement, an appropriate failure criterion for matrix cracking together with some progressive failure propagation mechanisms must, therefore, be used to properly evaluate the performance of these two FRP line pipes. This may require some research and development effort to study the onset of weeping in FRP line pipes.

<u>Table 3</u>

Stress Distributions* (psi) in Pipe-A at Room Temperature

Ply #	Longitudinal Normal	Transverse Normal	In-Plane Shear
1	13090.7	2228.8	-6.5
2	7871.0	3110.8	-152.3
3	13507.6	2174.7	1.9
4	7861.5	3129.7	-173.7
5	13965.4	2117.0	10.9
6	7851.9	3152.1	-197.1
7	14468.7	2055.3	20.7

Table 4

Stress Distributions * (psi) in Pipe-B at Room Temperature

Ply #	Longitudinal Normal	Transverse Normal	In-Plane Shear
1	9874.6	2289.0	-175.7
2	10071.6	2254.9	188.7
3	10190.3	2234.8	-211.1
4	10407.5	2199.3	226.4
5	10550.5	2177.4	-251.1
6	10791.0	2140.3	269.1

Table 5

Stress Distributions * (psi) in Pipe-A at 150 °F

Ply #	Longitudinal Normal	Transverse Normal	In-Plane Shear
1	14376.0	1057.9	-217.7
2	9474.3	1863.7	70.0
3	14584.7	992.5	-207.6
4	9453.6	1837.7	52.7
5	1423.7	924.0	-197.0
6	9432.7	1814.2	34.0
7	15096.4	852.4	-185.9

Table 6

Stress Distributions * (psi) in Pipe-B at 150 °F

Ply #	Longitudinal Normal	Transverse Normal	In-Plane Shear
1	10883.3	1554.7	244.4
2	11093.2	1484.5	-252.5
3	10975.5	1469.6	228.5
4	11195.1	1398.8	-234.5
5	11098.0	1381.6	209.3
6	11329.7	1310.1	-213.1

Table 7

Stress Distributions * (psi) in Pipe-C at 150 °F

Ply #	Longitudinal Normal	Transverse Normal	In-Plane Shear
1	11477.5	885.4	520.1
2	11723.2	819.6	522.2
3	11610.6	814.6	544.5
4	11865.6	748.9	548.8
5	11774.0	742.2	572.8
6	12040.6	676.6	579.7

* planar stress distributions at mid-plane of each ply

For both FRP line pipes (A and B), the magnitudes of the matrix dominated stress components at 150 °F are lower than those at room temperature. If the matrix dominated properties of the pipe composites are not significantly affected at 150 °F, it is likely that the short term hydrostatic strength of these FRP line pipes at 150 °F could be at least equal to if not greater than the short term hydrostatic strength at room temperature. Test results given in Ref. [1-2] on some FRP line pipes seem to support the above observation. Hence, if the recommended long term pressure ratings of these FRP line pipes are based on short term hydrostatic strength, this might lead to the erroneous conclusion that temperature has no effect on the pressure rating of the pipes. However, test results do indicate that the long term performance of FRP line pipes is strongly dependent on the test temperature. Therefore, the combined effect of time and temperature must be included in determining the long term performance of FRP line pipes.

To design for long term performance, the long term rupture characteristics of the matrix dominated composite properties in the intended service environment must be properly accounted for. These long term rupture characteristics are, in general, not easily determined and usually not readily available in the design phase of the products. Hence, a rational approach to determine the long term performance of FRP line pipes through testing will need to be established to minimize the need to excessively derate the performance of FRP line pipes. These test results together with calculated stress distributions such as those given in Table 3-6 could then be used as an engineering guide to improve product design, qualify component variants of similar design and fabrication, and for the selection of resin matrix for different applications. For example, Table 7 shows that a slight change in the fiber angle of the FRP line pipe in Table 6 (pipe B) can lead to a significant change in the ratio of the transverse normal stress component to the in-plane shear stress component. If test results also indicate that an improvement or reduction in the long term performance of the FRP line pipe is also obtained, then by adjusting this stress component ratio, improvement in long term performance can be obtained for a family of products of similar design and fabrication.

It is important to point out that the above brief discussion on design and performance of FRP line pipes are constructed solely for the purpose of stimulating thoughts and discussion on improving composite component design and performance for offshore/onshore applications. It is by no means comprehensive and other factors that could impact the final design are not included in the discussion. It is imperative, however, to fully utilize the design know-how gained and accumulated in other composite applications to successfully improve and expand product design so as to encourage further use of composites for offshore applications.

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Flammability and Fire Safety of Composite Materials for Offshore Operation

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Introduction

There are many possible potential fire scenarios on an offshore platform. Two different types of fires are possible: an open fire caused, for example, by a spilled fluid; and fire in a compartment, possibly started by cooking in a crew compartment. Since the use of composite materials as replacements for steel on offshore platforms is gradually increasing, fire safety issues might become more critical due to the combustible nature of composites. Since composite materials are generally more difficult to burn themselves than the polymer resins they contain, the initiation of fire on these materials by a small flame, such as a match flame, is extremely difficult and therefore, they would not likely be the first material ignited. However, if a nearby fire becomes large enough to emit sufficient amounts of heat and thermal radiant flux, neighboring composite materials could be ignited and sustain combustion, contributing to the spread of the fire. Even if a composite material did not burn under such conditions, it could experience sufficient heat input to cause thermal degradation of a part of the polymer resin leading to delamination and weakened structural strength. Here it will be assumed that the fire is not initiated on the composite material. However, if there is a fire nearby, the issue of whether or not a composite material does ignite and burn or experience loss of structural strength is the desired information.

A schematic illustration of the fire safety of any system utilizing composite materials (including offshore oil platforms) is given in Fig. 1. At first, potential fire scenarios can be considered which may expose available composite materials on a platform to heating. The characteristics of the fire such as heat release rate and thermal radiant flux can be calculated using currently available fire models. Then, using the applied heat load from the assumed fire scenarios, the fire performance of specific composite materials can be evaluated using fire growth models having as inputs fire properties measured by modern bench scale test methods. A similar approach can be applied to assessing the strength of the composite material exposed to the fire. The results would indicate whether the composite materials ignite and have flames spread over them, and to what degree their structural strength is weakened. Using these predicted results, a design company could determine the trade-offs between material and suppression system costs and allowable damage level. For example, momentary ignition but no flame spread and no structural damage might be a permissible option. This paper briefly describes the current level of knowledge and predictive capability for various fire scenarios, such as open fires and a fire in a compartment. Modern bench scale flammability test methods are briefly described and a calculation of fire spread over a vertical composite wall in a compartment made of a composite material is described using the measured flammability properties of the composite material as inputs to a fire growth model.

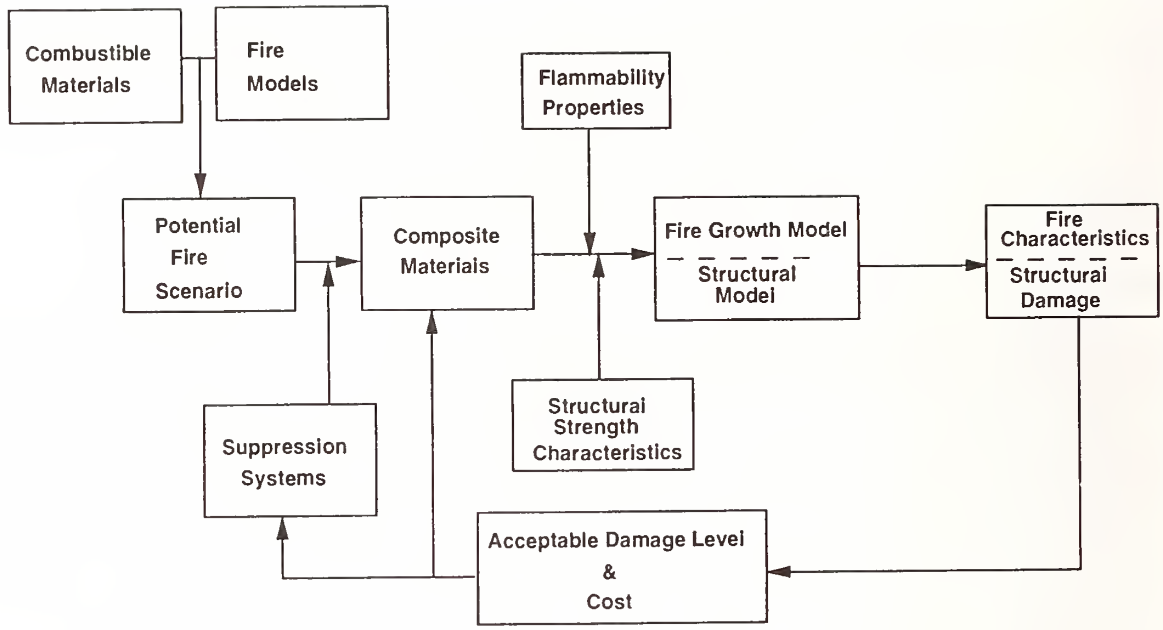


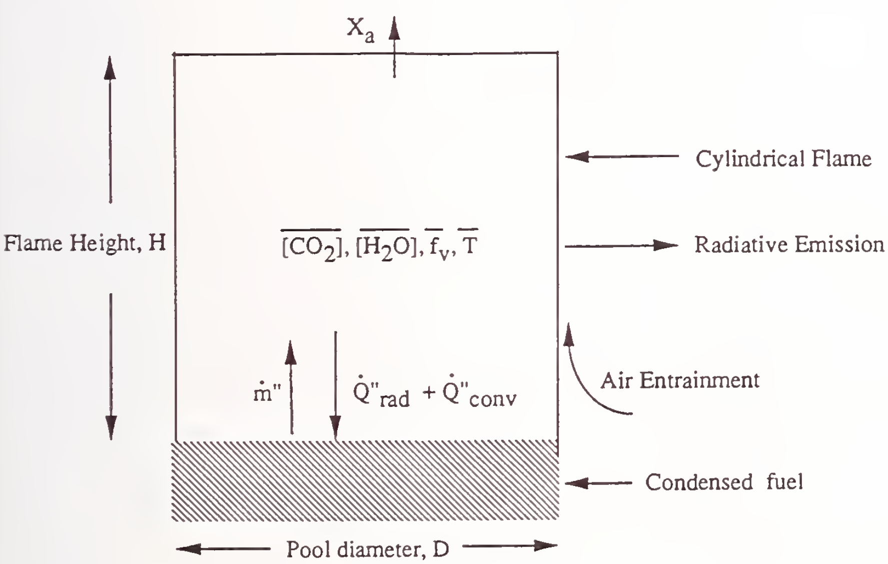
Figure 1 A schematic illustration of a fire safety approach

Open Fire

The global aspects of the combustion process of an open pool type fire are reasonably well understood. A small fraction of the total heat release from the flame (about 1-2%) is fed back to the pool surface by radiation and convection. Radiative transfer is the main energy feedback process for large diameter (roughly above 10 cm diameter) hydrocarbon pools except for alcohols with small molecular weights. Typically, approximately 30% of the heat release from the combustion of hydrocarbon fuels is emitted from a flame as thermal radiation. However, this value tends to decrease with an increase in a pool diameter when the diameter becomes large, for example, about 3 m for heptane and 2 m for kerosene [1]. This decrease is probably caused by trapping of radiation due to soot blockage. An increase in the size of the flame increases the heat release rate which in turn increases radiant flux emitted in all directions from the flame. Therefore, when a flame becomes large, such as in the case of an oil well blowout, a radiant flux from the flame may be sufficient to ignite remotely located combustible materials and contribute to their continued burning. An infrared emission spectrum from the combustion of a crude oil shows a broad emission band from particulates in the flame superimposed with CO_2 and H_2O emission bands. Fuels containing aromatics tend to generate more particulates thus the emission spectrum would be dominated by the broad band emission from soot and consequently, the radiated fraction of the heat release tends to be higher than 30%. On the other hand, small alcohols such as methanol do not generate a large quantity of particulates and the emission spectum is dominated by molecular emission bands of CO_2 and H_2O and thus conversely, their radiated fractions of heat release are roughly 15-20%. It appears that there are no significant differences in radiated fraction of heat release between buoyancy driven flames (for example a pool flame on a spilled fluid) and jet flames (driven by the initial momentum of a fuel flow, such as a blowout flame) [2, 3].

The energy feedback from a pool flame to the pool surface continues to heat the pool, gasifying the liquid fuel which then feeds combustible gases to the gas phase. This coupling between the gas phase and the condensed phase determines the burning rate of the pool flame and also the heat release rate. Thus, the liquid pool fire is a complex, coupled combustion process.

The above combustion process has been described by two different types of models; a global algebraic model and a solution to the set of partial differential equations describing the underlying conservation laws. The global approach is based on a single spatially uniform flame temperature with a specified or calculated emissivity of the flame or more precisely the soot volume fraction in the flame [4]. The flame temperature is specified or calculated from a global energy balance among heat release and heat loss by emitted radiation and cooling by the entrained ambient temperature air into the flame (dilution). A schematic description of this idealized pool flame is shown in Fig. 2. The radiative feedback rate is calculated using the mean beam length approximation [5] which is based on flame height and pool diameter. The combustion efficiency and the radiated fraction of heat release are also needed inputs in the calculation. Typical results of the burning rate of heptane and crude oil are shown in Figs. 3 and 4 as a function of pool diameter. In these figures, point symbols represent experimental data measured by different researchers and the lines are calculated results. The calculated results for heptane pool flames appear to be in reasonable agreement with the experimental data but the calculated results for crude oil underestimate the mass burning rates significantly. This discrepancy might be caused by uncertainty in the thermal properties of the crude oil, given their unique composition. The heat release rate and radiation flux



Inputs:	Calculate:
Combustion Properties	Flame Height, $H_f(Q^*)$
X_a	Air Entrainment, $M_a(H_f)$
X_r	Flame Temperature, $T_f(M_a, X_a, X_r)$
f_v	Mean Beam Lenght, $L_m(H_f, D)$
	Gas and Particulate Emissivity, $E(f_v, r, T_f)$
Fuel Properties	Radiative Heat Transfer, Gray Gas Approximation $\dot{Q}''_{rad}(T_f, L_m, E, f_v)$
H_c	Convective Heat Transfer - Stagnant Film Approach
H_g	
Stoichiometry, r	
Condensed Phase Emissivity	

Figure 2 A global pool burning model

from these flames to an outside target (for example a composite material) can be calculated from the model.

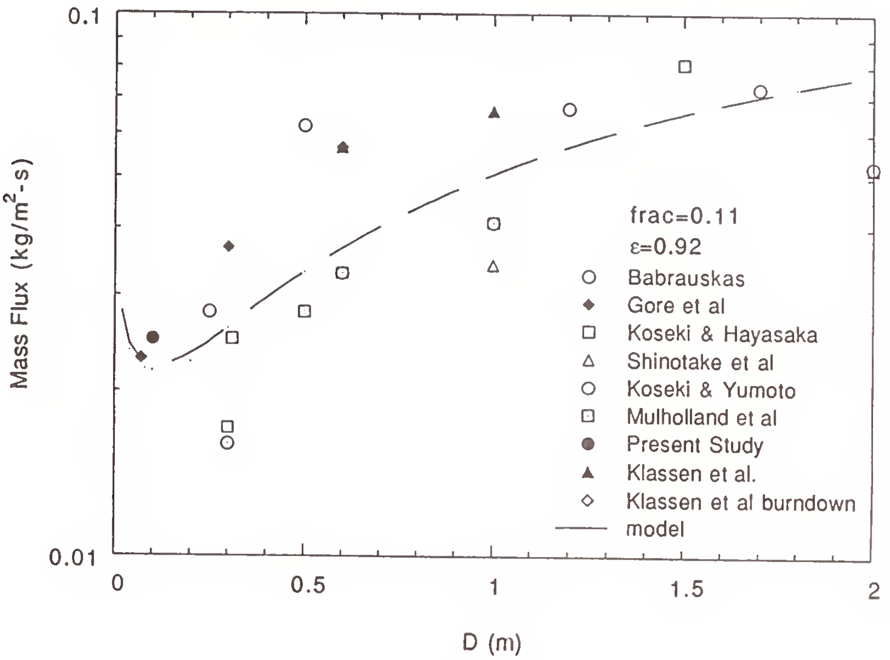


Figure 3 Heptane burning rate

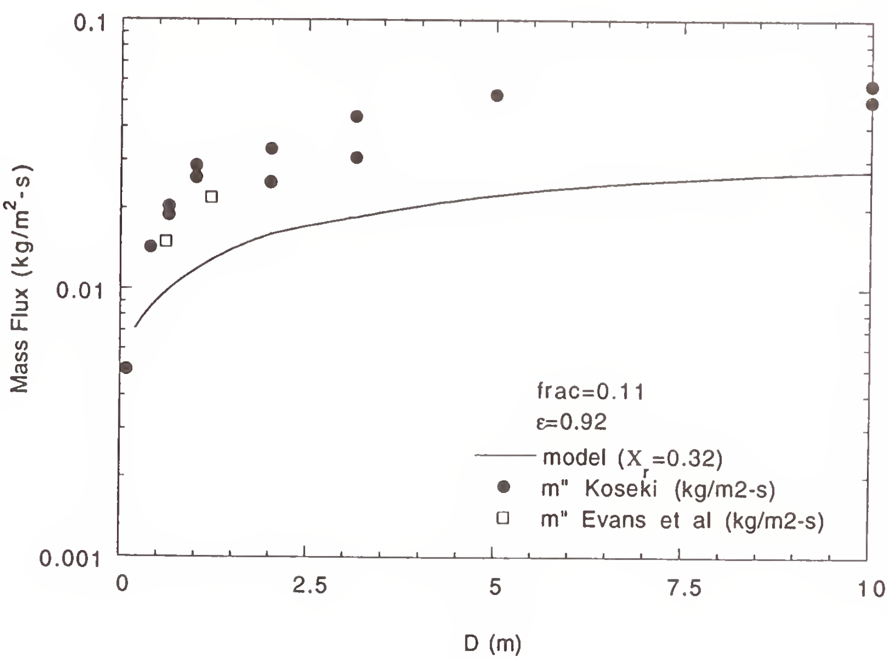


Figure 4 Crude oil burning rate

The second approach is based on solving partial differential equations based on continuity, momentum, energy and species concentrations (so called field equation modeling). Such models contain quite complex equations and require a numerical analysis. Still, the complexity and limited understanding of the underlying processes require approximations. One often used approximation for solving these equations is the k-ε turbulence model to describe the turbulent flow field by using a description of the turbulent kinetic energy and its dissipation rate [6]. One advantage of this approximation is that several codes are commercially available. However, they often need some modification such as the inclusion of soot in a radiative transfer calculation to calculate a specific problem. The codes also require a considerable learning period before they can be used effectively. One drawback to the k-ε models is that this approximation smooths the dynamic behavior of pool flames (large fluctuations) and only statistically averaged quantities (mean components) are calculated. A different approach to solving the differential equations is by use of the Large Eddy Simulation method with a Lagrangian thermal elements submodel [7]. This approach breaks the process up into two different scale effects. Phenomena that typically occur on length scales below the resolution limit of the computational grid in simulations of large scale fire induced flows, such as diffusion-controlled combustion and radiative emission, are modeled in the subgrid-scale thermal elements. As an example of this calculation, 2000 thermal elements are convected in a simple flow field constructed from a prescribed vorticity distribution and a pool flame is described by the flow interactions of the thermal elements which are combusting and radiating. Typical results are shown in Fig. 5. Although the flow field needs further improvement to describe fully the pool flame flow field, the results can capture the

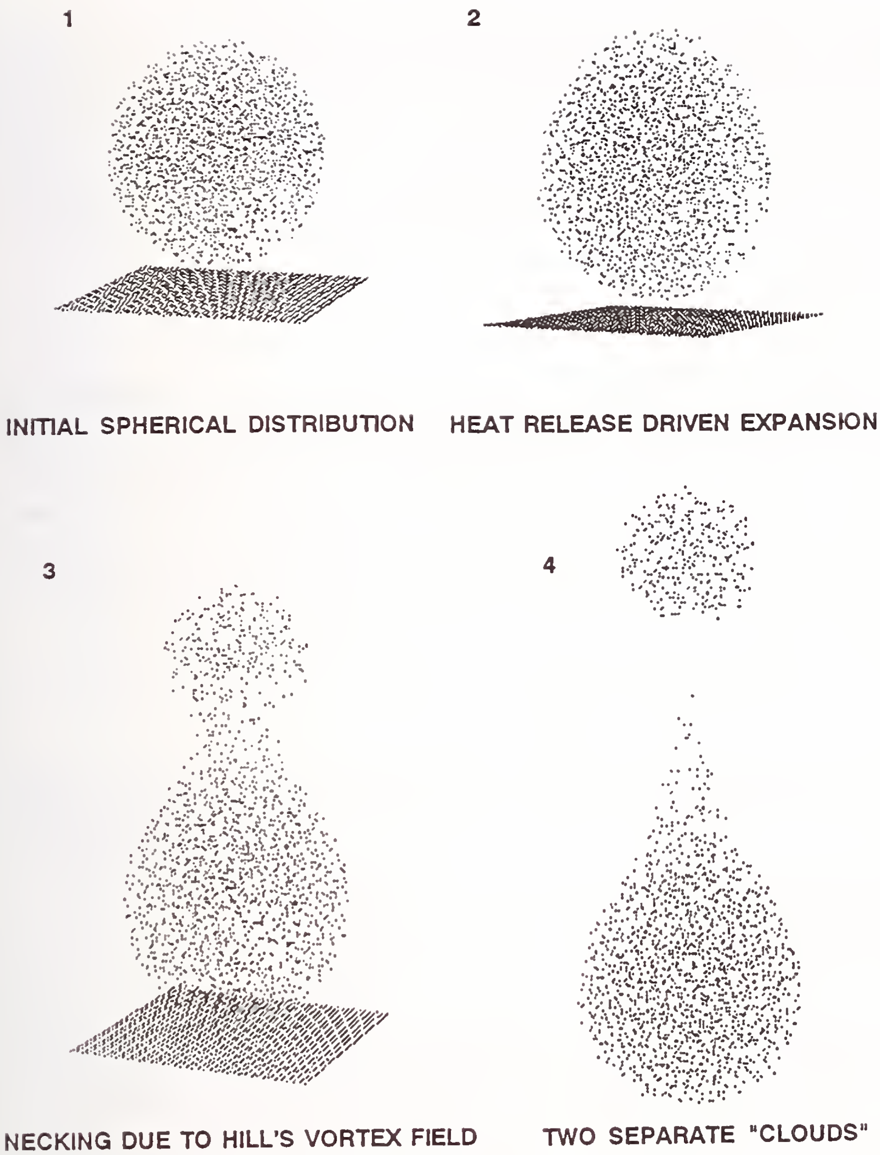


Fig.5 Pool flame by Large Eddy Simulation [7]

dynamic behavior of the pool flame which cannot be calculated from the two approaches previously described (global approach and the use of the k-ε turbulence model). The approach of the Large Eddy Simulation seems promising and may be used more often in the future. Its principal drawback is the considerable computational resources required to perform such calculations.

The effects of ambient winds on open pool fires can be significant. There are often winds on an offshore platform. The effects of cross-winds on pool fires have been only sparsely studied. A rule of thumb that is commonly used is that a 2m/s wind will bend a pool flame by 45°, and the flame tends to hug the ground downwind of the fuel surface to a distance of ~ 0.5D, where D is the pool diameter [8]. This can significantly increase the fire exposure of items downwind, either by causing direct flame impingement, or by increasing the levels of radiant heat flux [9]. Two recent studies obtained flame length correlations with the cross-wind velocity and pool diameter for pool fires of diesel oil [10] and for high velocity gas jet flames [11]. There are few theoretical studies; the most recent study used the k-ε turbulence model to calculate wind-blown pool fire in a large tunnel [12]. More experimental and theoretical studies are needed to understand and characterize the effects of cross-winds on pool flames.

Fire in a Compartment

A schematic illustration of a fire and the fire induced flow field in an enclosure is shown in Fig. 6. The opening on the right side in the figure could be an open window or a doorway, etc. Heat release from the fire acts as a pump to drive combustion products upward to fill the upper part of the compartment. When the stratified layer of combustion products (smoke) becomes lower than the top of the opening, some of the products flow out (flow rate is expressed by $\dot{m}_g$) and fresh air flows into the compartment, satisfying mass continuity in the compartment. The steady-state temperature increase for the upper layer may be approximated by

$$\Delta T \sim C \left(\frac{\dot{Q}^2}{A_0\sqrt{H_0}}\right)^{1/3}$$

where $\dot{Q}$ is the rate of heat release within the compartment, A_0 is the opening area, H_0 is the opening height and C is a constant. When a fire starts inside a compartment, the heat release rate from the fire gradually increases with the spreading of flame. This increases the upper layer temperature as shown in the above equation. A consequence of an increase in the upper layer temperature is an increase in thermal radiant flux from the upper layer to exposed combustible materials. The thermal radiant flux enhances the combustion and flame spread rate of exposed combustibles which increase their heat release rate. This coupling between the upper layer and the combustible materials results in an enhancement of the fire, driving it to the so-called "flashover" condition. The most common

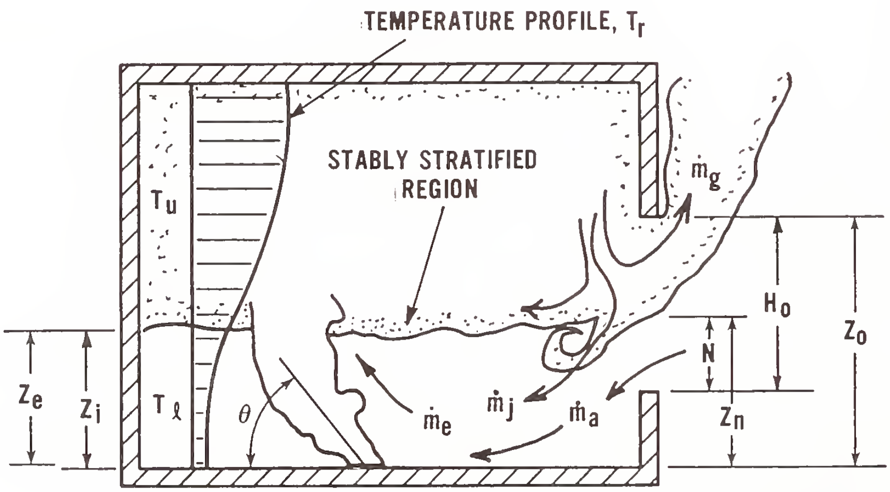


Figure 6 An illustration of fire in a compartment

definitions of flashover are: (a) the transition from a localized fire to the general conflagration within the compartment when all combustible surfaces are burning; and (b) the sudden propagation of flame through the unburnt gases and vapors collected under the ceiling with flames exiting through the opening. Three distinct regions of compartment fire burning, fuel controlled burning, ventilation controlled burning, and flashover region are classified in a plot of burning rate with respect to the opening factor of $A_0H_0^{1/2}$ shown in Fig. 7 [13].

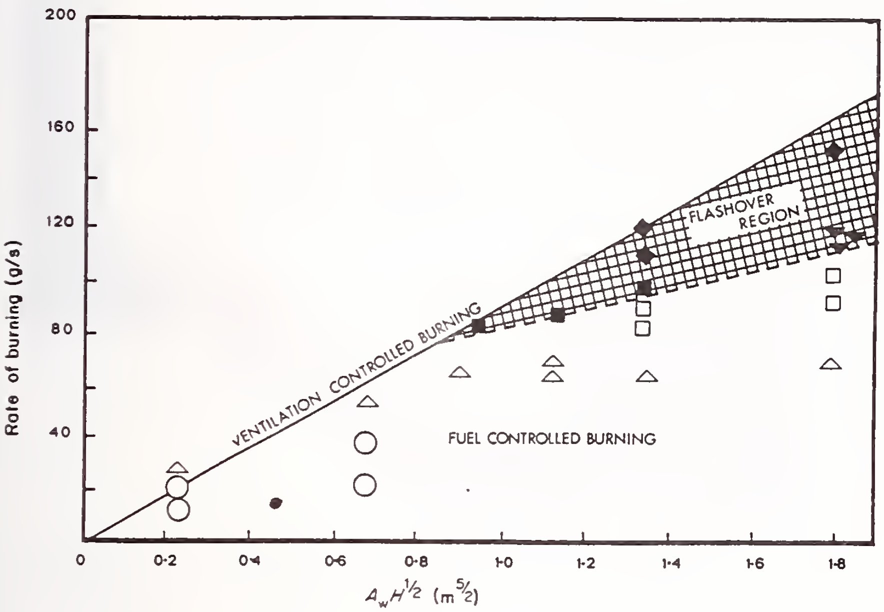


Fig.7 Compartment burning rate as a function of ventilation parameter [8]

Over the last decade numerous computer models have been developed to calculate aspects of fire and its effects in compartments. Two different approaches have been utilized similar to the above open fire cases: Zone modeling is based on the application of mass and energy conservation principles to a homogeneous hot upper layer and a cool lower gas layer in a compartment. Field equation modeling is based on solutions of the three dimensional transient Navier-Stokes equations with the conservation of energy and chemical species equations. The basic equations used in zone models have been derived by Quintiere [14]. There are numerous zone models which differ in detail and in application, but all use basically the same principle. Most of these models use a specified burning rate in the compartment rather than calculate burning rates even though, in general they are coupled with the compartment. Recent field models using the k-ε turbulence model

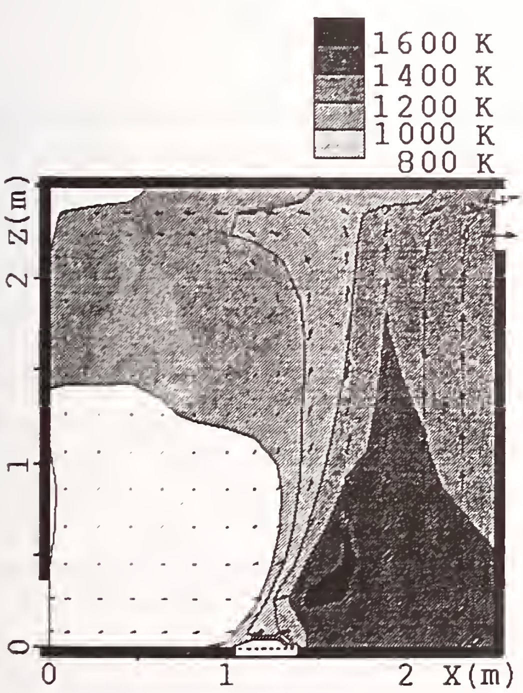


Fig.8 Temperatures and velocities of flame in a compartment [15]

have calculated fire behavior in a compartment including thermal radiation and gas phase chemical reactions [15,16]. The calculated temperature distribution in a compartment from Ref. 15 is shown in Fig. 8. Although these models are usually limited to a single compartment due to the complexity of the required computations, burning behavior and its interaction with the compartment can be described. Another field equation model is based on the Large Eddy Simulation method similar to the model discussed in the open fire section [7]. The calculated dynamic behavior of the movement of hot layers in a complexly shaped of a compartment is shown in Fig. 9. In this calculation, the location of the fire is in a small horizontal compartment next to the large room at the left side and its heat release rate is specified. Although the source of the fire is specified in this calculation, it permits the detailed dynamic nature of the flow to be determined,which cannot be obtained from models using the k-ε turbulence model.

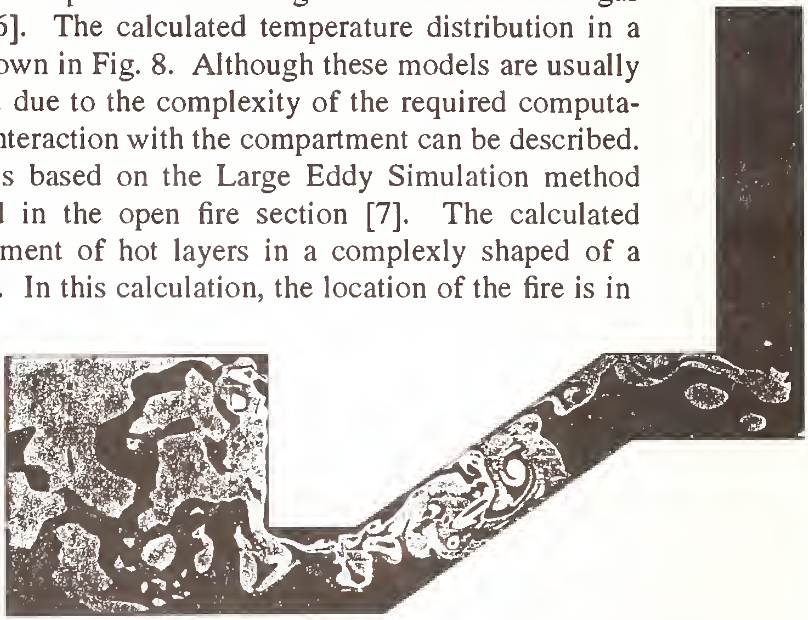


Fig.9 Calculated dynamic movement of hot layers [7]

In principle, the field equation modeling approach is more general. It is only bound by the universality of its turbulence and combustion models, presuming sufficient spatial and temporal resolution is achieved. Nevertheless all computer modeling results need to be examined against experimental data.

Fire Exposure to Composite Materials

Since a typical composite material cannot be ignited by a small flame such as a match, the most likely fire scenarios involving composite materials is the exposure of these materials to a nearby flame, as described above. The approach espoused here is to examine whether a material ignites and burns based on predictions of the performance of that material for various possible fire scenarios. This is accomplished through the use of fire growth models with the measured flammability properties as inputs to the models followed by validation of the results with a limited number of full scale tests. This approach can be applied to composite materials. Such an exercise is demonstrated here. Key flammability properties are piloted ignition delay time, heat release rate, burnout time, and flame spread characteristics (all as a function of external incident flux). The first three properties are measurable with a Cone Calorimeter [17] and the first and the fourth properties are measurable with a Lateral Ignition and Flame Spread apparatus [18], LIFT. The sample size for Cone Calorimeter tests is about 10 cm x 10 cm and for the LIFT test is about 16 cm and 80 cm. The maximum external radiant flux exposure in the Cone Calorimeter is about 100 kW/m^2 and generally tests are performed at various radiant fluxes. A typical heat release rate curve for a glass reinforced polyester sample, GRP, is shown in Fig. 10. A flammability diagram for the GRP sample is shown in Fig. 11 as the combined results obtained from ignition and lateral flame spread tests. Here, the abscissa is the external irradiance, the left ordinate applies to lateral flame spread rate while the right ordinate applies to time to ignition.

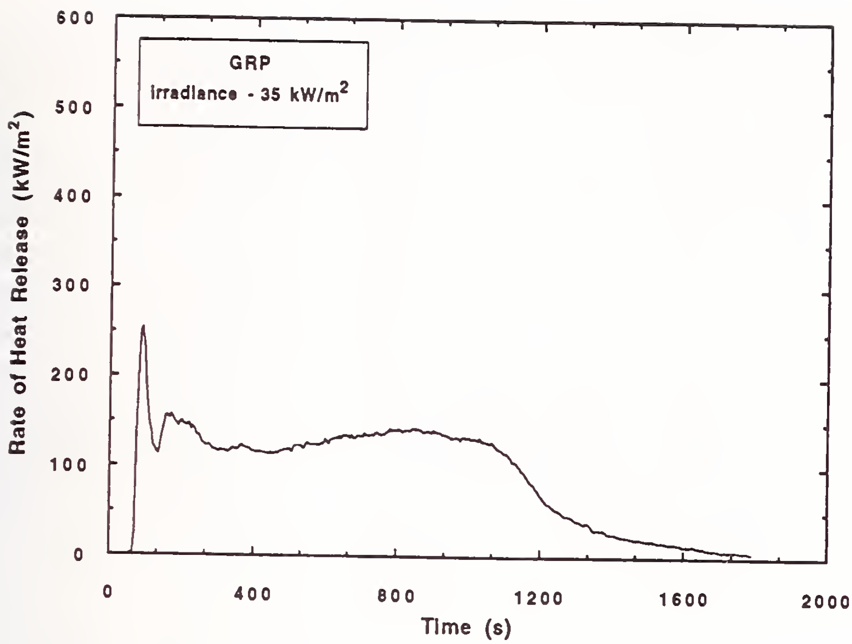


Figure 10. Rate of heat release vs. time for GRP material.

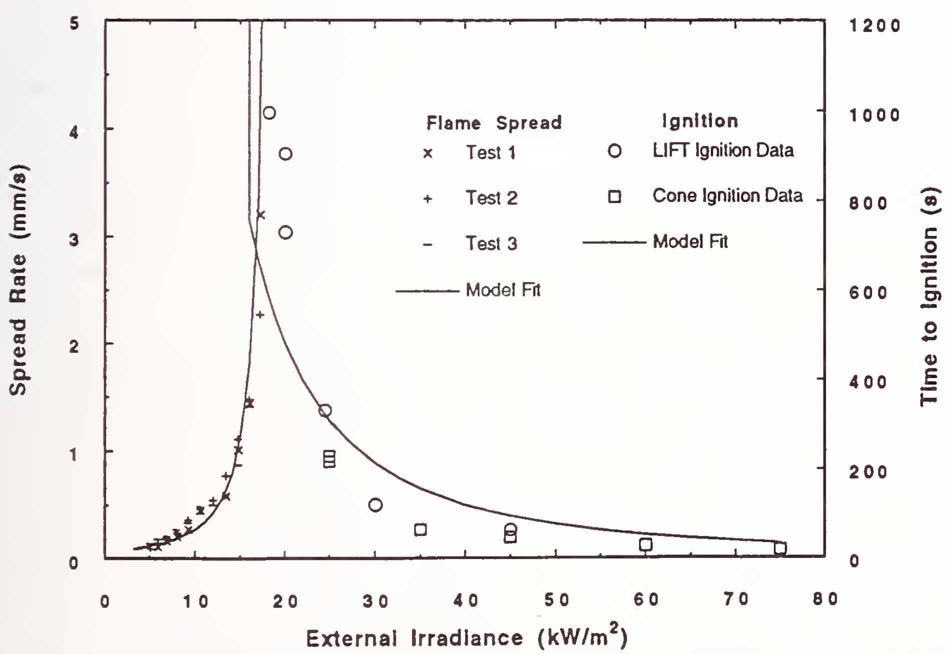


Figure11. Flammability diagram for GRP material. The left ordinate applies to the flame spread rate, while the right ordinate applies to time to ignition.

This plot summarizes the ignition and lateral flame spread characteristics of the material. In general, a shift of both curves to the right would indicate better performance in terms of ignition and flame spread behavior.

One model that yields good predictions of transient heat release rate in a compartment and the time to flashover was recently developed [19]. This model is generalized to handle different sample orientations (wall, floor, and ceiling configuration), but has only been validated for wall and wall plus ceiling configuration. Six basic flammability properties, ignition characteristics, average heat release rate, thermal properties, burn time, lateral flame spread parameter, and minimum temperature to sustain flame spread, are determined from the above results using the Cone Calorimeter and LIFT. The calculation of the fire behavior initiated from a well-calibrated sand burner in a compartment made of the GRP material was made to compare the predicted results with the experimental data.

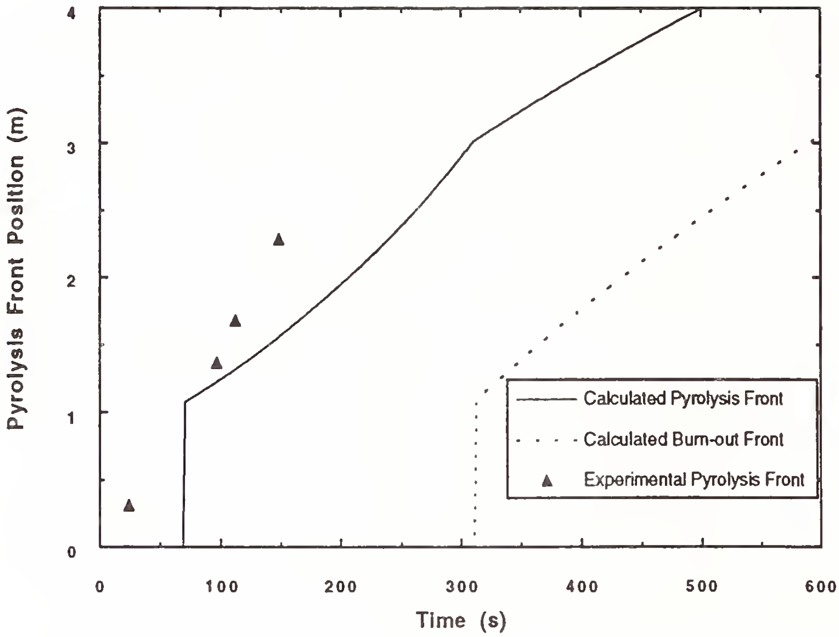


Figure 12. Pyrolysis front position vs. time for the GRP module 200 kW wall fire. Experimental and predicted values are shown. Predicted burnout front position is also shown.

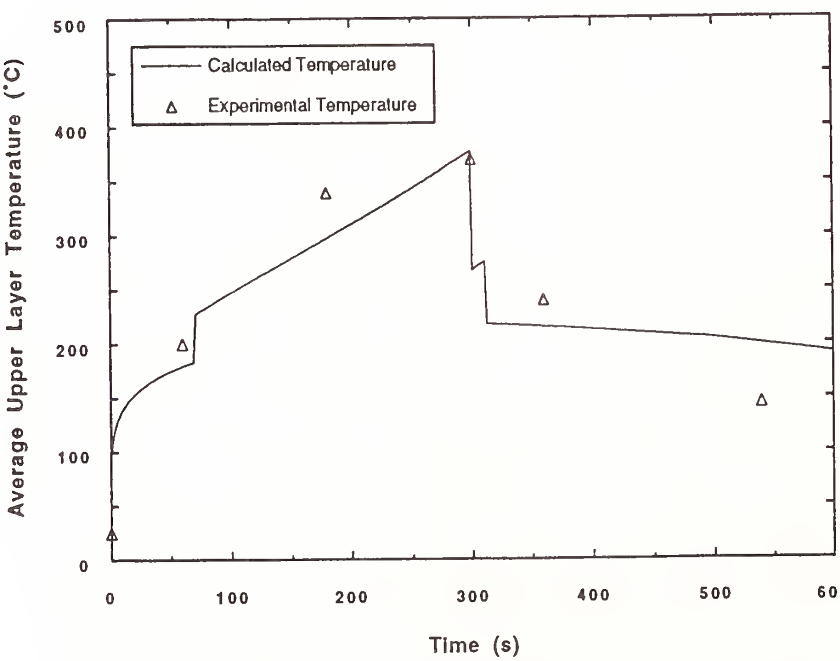


Figure 13. Average upper layer temperature vs. time for the GRP 200 kW wall fire. Experimental and predicted values are shown.

A brief description of the large scale fire tests on the GRP composite material is given here. The composite module was 2.4m high by 2.4m wide by 4.8m long. A dividing wall was installed which formed two isolated 2.4m by 2.4m by 2.4m cubic compartments. A door 0.41m wide by 1.5m high located 0.41m off the base was cut into the wall adjacent to the interior dividing wall. The composite module was formed from 2.4m by 4.8m sheets which were bolted and glued to an internal, steel I-beam frame. The I-beam frame was welded to a steel floor. The room walls and ceiling were comprised of the composite material. One test was performed with a 200 kW ignition source (0.48m x 0.48m propane sand burner) which was placed against an interior wall. The ignitor was on for 300 s. The flame spread up the wall, across the ceiling, and partially down the opposing wall. The model predicts the flame spread up the wall and across the ceiling, but the predicted progress of the pyrolysis front lags the measured progress of the pyrolysis front, as shown in Fig.12. Gas temperatures in the room were obtained from thermocouples spaced evenly from 0.15m to 2.29 m from the floor. The gas temperatures achieved in the upper portion of the compartment provide an indication of the fire severity. The average upper layer temperature as a function of time was obtained from the averaged temperature of two thermocouples at heights of 1.68 and 1.98 m from the floor. The upper layer temperature was calculated from Eq. 1 using the two-zone model as described above with the calculated total heat release from the sand burner and the composite material. The comparison of upper layer temperature history is shown in Fig.13. From time 0 to about 70 s, heat was released only from the sand burner. At about 70 s, the composite material ignited and flame started spread upward as shown in Fig.12 and consequently upper layer temperature increased with an increase in total heat release. At 300 s, the sand burner was turned off and also nearly at the same time the bottom part of the wall burned out as shown in Fig.12. These two events significantly reduced the total heat release and accordingly the upper layer temperature dropped rapidly. The predicted upper layer temperature agrees reasonably well with the experimental results as shown in Fig.13. Further experiments were conducted with different ignition source strengths and locations and generally the predicted results agreed reasonably well with the experimental data even though the model contains a number of approximations.

Summary

The last two decades of active fire research studies have made significant progress in understanding fire phenomena, identifying and measuring important flammability properties, allowing for the prediction of fire growth. It is strongly recommended that off-shore platform users and designers apply the current body of knowledge as much as possible and avoid unnecessary repetitive fire research studies. Of course, certain unique features of offshore platforms, their environment and of composite materials require further study, but the basic principles of fire dynamics can apply to the offshore platform. Also, it is important to use the concept of an overall fire safety strategy such as the use of early detection, suppression system, for a offshore platform instead of relying strictly on composite material performance.

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FIRE, SMOKE, AND TOXICITY RESEARCH WITH COMPOSITE PIPE

A HISTORY OF PAST AND PROPOSED FUTURE WORK BY SPECIALTY PLASTICS, INC., LOUISIANA STATE UNIVERSITY, AND THE U.S. NAVY

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Introduction

Composite pipe has many unique characteristics that distinguish itself from conventional metallic materials and even other plastics. Characteristics such as lightweight, high strength to weight ratio, corrosion resistance, and flexibility all define the products in the composite pipe industry. These unique traits, however, can prove to be a hindrance in the design of composite pipe systems if not properly understood. One characteristic of composite pipe that must be investigated in certain applications is the product's fire characteristics and its smoke and toxicity emissions. This is critical in the design of active fire protection systems. Composite pipe, when properly designed, can have advantages in fire water systems for marine applications over carbon steel, copper nickel, stainless steel, and other exotic alloys.

Louisiana State University and Specialty Plastics, Inc. of Baton Rouge, LA have had extensive experience with the United States Navy in developing advanced composite piping systems characterized by exceptional fire, smoke, and toxicity properties for shipboard applications, and, in general, marine applications. Research work completed to date has included laboratory, bench scale experiments for screening purposes on various resin systems, toxic emissions testing on phenolic, epoxy, and elastomer-modified vinyl ester resins, and bench-scale fire testing on pipe samples. Proposed future work in the area includes standardized testing on advanced composite piping systems both with and without passive fire protection and pilot scale testing of complete advanced composite piping systems, including pipe, fittings, and joints. The goal in these tests are to determine the survivability and performance integrity of the advanced composite pipe system when exposed to possible fire hazard conditions.

Fire, Smoke, and Toxicity Research with Advanced Composites

Fire testing has had an extensive history with fiberglass reinforced plastic products. To reliably substitute composite pipe in fire safety applications where ferrous alloys have long dominated, extensive testing and experimentation must be performed. This ensures a properly designed product adequate for its environment.

One such example of the research performed in this area by Louisiana State University and Specialty Plastics, Inc is a research project entitled "Composite Piping Systems - Phase II." This project was completed under a Small Business Innovative Research (SBIR) Phase II grant for the United States Navy. The principal investigators on the project were Specialty Plastics, Inc. and Louisiana State University of Baton Rouge, LA. However, companies from Acoustic Emissions, Inc. in Conroe, TX to Woodside Offshore, Ltd. in Perth, Australia, participated in the research activities. The goal in this project, in the area of fire resistance and smoke toxicity, was to provide experimental data on fire and smoke for advanced composite pipe. From this, the resin matrix and reinforcement that performed best in the fire, smoke, and toxicity categories were identified and recommended for further study.

Several screening tests were performed under this research project. This included smoke emissions tests, mass loss tests, and toxicity tests. A schematic of the laboratory-scale smoke test chamber used in the screening

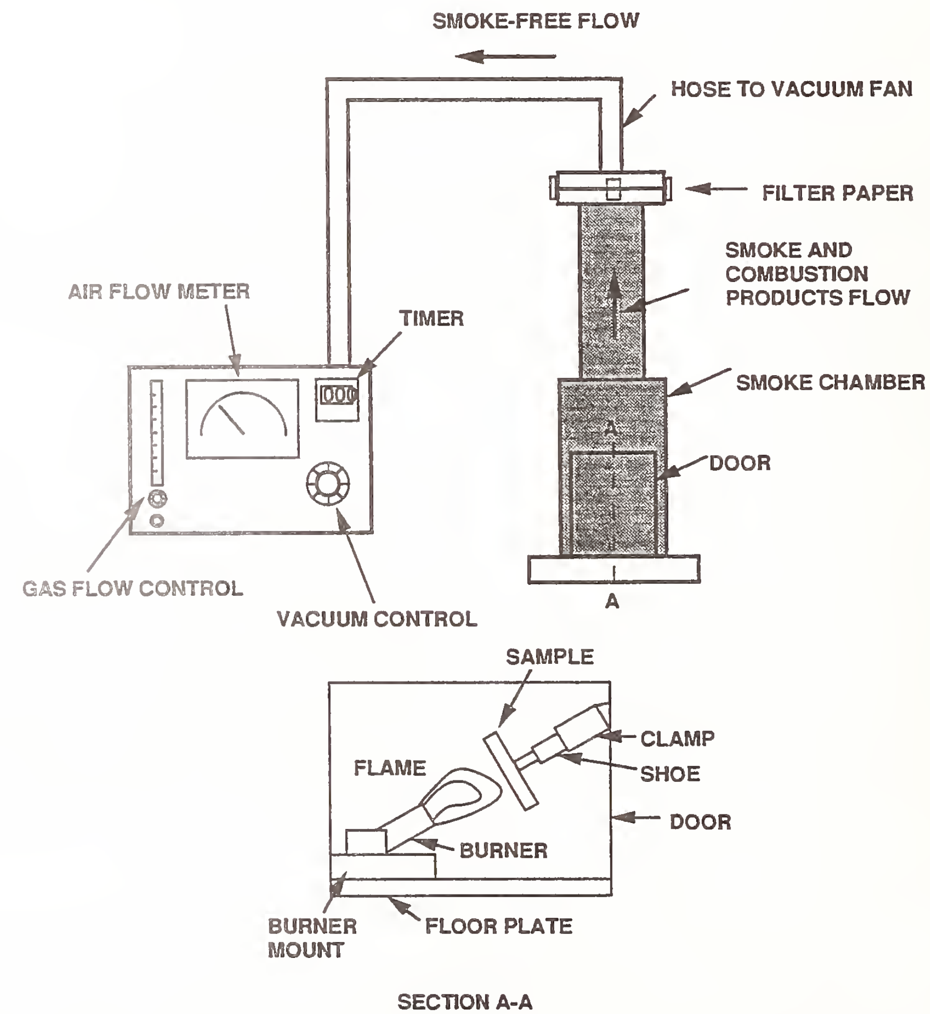

Figure 1. A bench scale smoke test chamber was used to measure the smoke and toxicity characteristics of various resins.

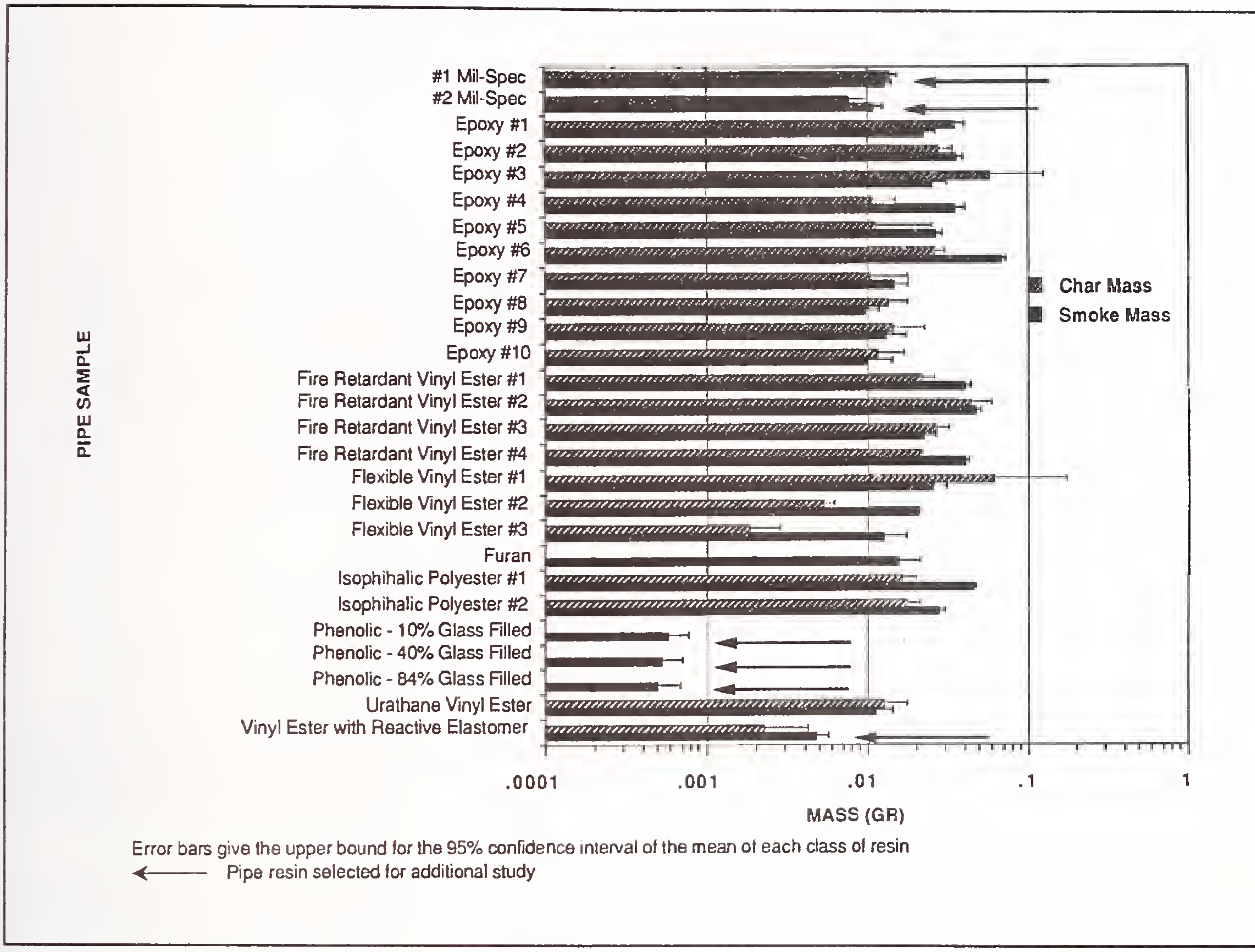

Figure 2. A comparison of the smoke and char mass produced from various resin exposed to flame.

tests is shown in Figure 1. Again, this setup was designed for comparison purposes. Thus, the experimentation needed only to be scientifically reproducible; it did not have to follow existing standards.

The pipe samples (a total of 27 were tested) were burnt using a propane source in an Arapohoe™ smoke chamber for 30 seconds. Weight measurements of the filter paper, sample, and decharred sample were taken after completion of the test. Typical results for this screening test are provided in Figure 2. From the tests it is evident that the phenolic resins are superior to all others in terms of the smoke mass and char mass produced. The elastomer modified epoxy vinyl ester resin also showed excellent results in both categories. Although this resin does not perform nearly as well in the fire category as the phenolics, it has exceptional mechanical and impact properties which the phenolics lack.

Toxicity tests were also performed for screening purposes. The best performers in the smoke test category were further tested in this area for CO, CO_2, and HCN.

Bench scale testing went even further with a laboratory-scale fire test rig. This laboratory level experiment exposed a full-scale pipe sample to fire conditions for a fixed period of time at a fixed temperature curve. Refer to Figure 3. This particular dual wall pipe sample, composed of a vinyl ester resin matrix inner pipe, a polyphosphazene fire retardant foam, and a phenolic resin matrix outer pipe withstood a fire test at 1100°C for one full hour in the dry condition. Typical results from this bench scale test are shown in Figure 4.

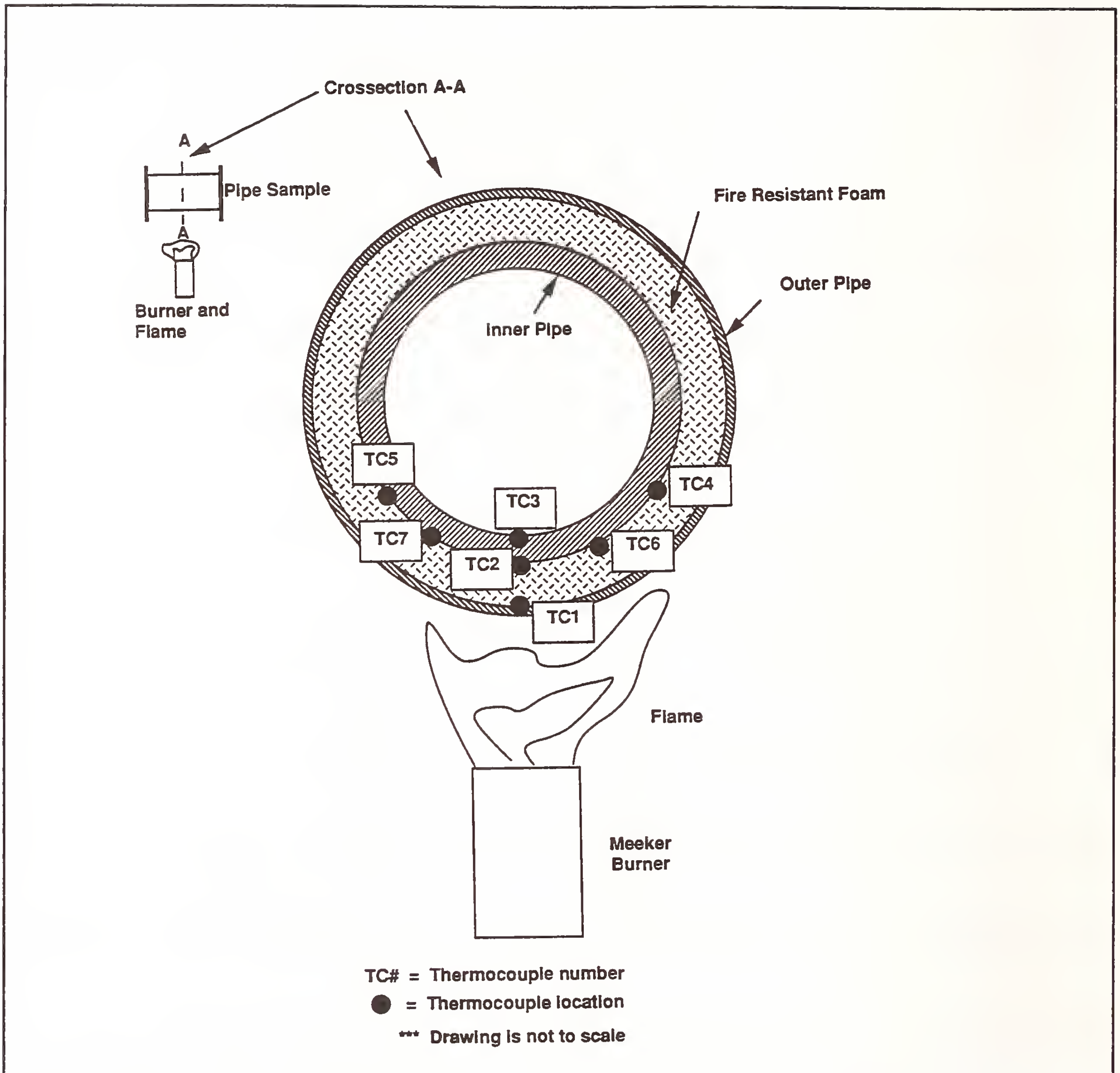

Figure 3. A laboratory-scale fire test rig was used to test various passive fire protection systems for pipe.

Future Work on Fire, Smoke, and Toxicity with Advanced Composites

As stated in its original goals, the research work performed for the United States Navy under the SBIR grant provided only screening results of a few basic materials with the intention of identifying the best materials for further research. Thus, it did not go far enough to prove the acceptability of composite pipe in specific fire applications.

A proposal for a much more expanded series of experimentation on fire characteristics has been presented to the United States Navy by Specialty Plastics, Inc. and Louisiana State University in the form of a separate

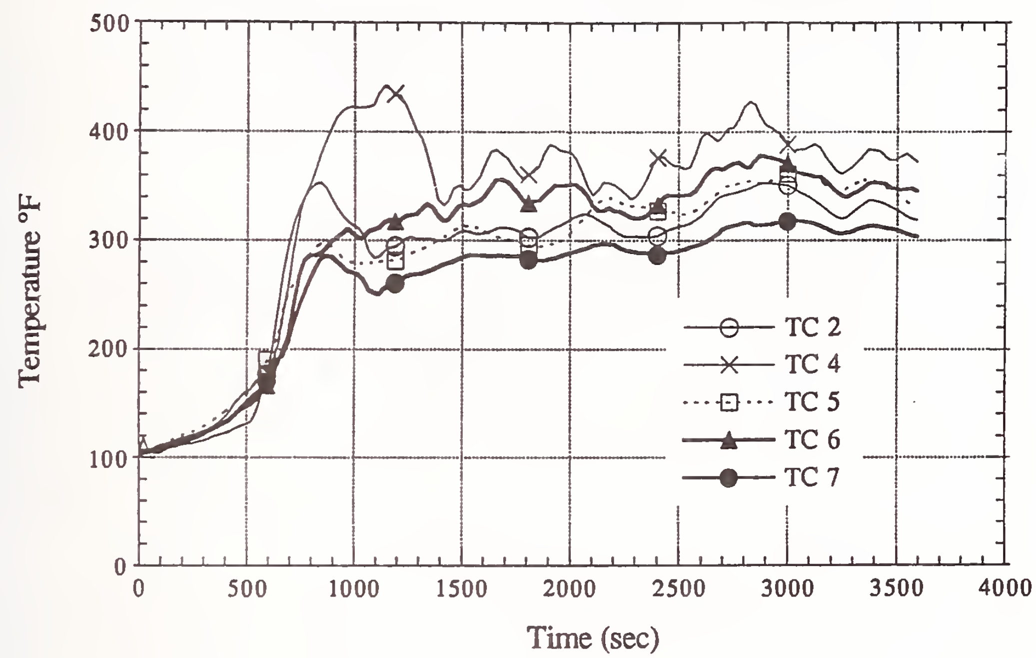

Figure 4. A typical time-temperature curve of a sample tested in the fire rig. This sample was a dual wall sample with no external coating.

SBIR grant. The goals, in the fire category, are to evaluate the fire performance properties of advanced composite pipe systems by performing tests in accordance with ASTM E662 and E162 in addition to pilot-scale fire tests on entire piping systems, including pipe, fittings, and joints.

The proposed pilot-scale furnace is shown in Figure 5. This project, which is a joint venture of industry, the university, and the United States Navy, has been designed to test entire pipe systems and follows the guidelines set by the ASTM F25.13.03 Fire Subgroup and the newly proposed ASTM F1173 standard.

In the proposal, this facility is to be operated by the Mechanical Engineering Department of Louisiana State University in concert with Specialty Plastics, Inc. at the Fireman's Training Facility near the LSU campus in Baton Rouge, LA. The facility's greatest advantages are its flexibility in design and its mobility. The pilot-test rig will have a removable burner system to simulate various fire conditions, will allow pipe, fittings, and joints to be tested, and will be transportable to and from test sites, if necessary. Activity at the test rig will included tests for the U.S. Navy for screening purposes and material selection for ship-board applications, standardized tests for industry participants for screening purposes for offshore and, in genera, marine applications, and research activity for the university.

Benefits of the Proposed Future Work

As stated above, the benefits of the proposed research work in the fire and safety area will benefit all of the participants in the activity. The United States Navy will be able to test piping systems to screen possible candidates for further large-scale tests. The facility will also allow the Navy to compare materials for possible

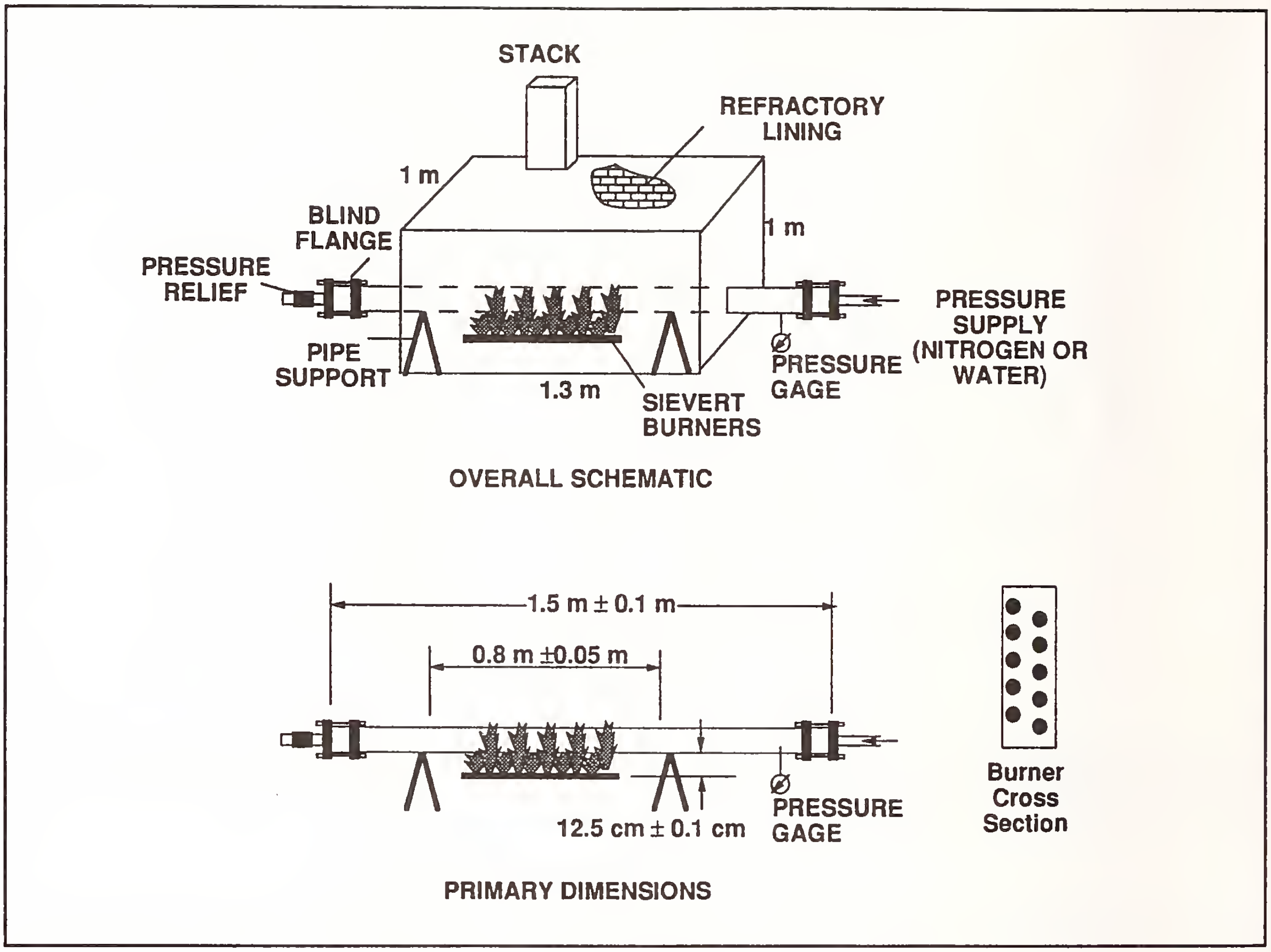

Figure 5. The proposed fire test rig at the LSU Composite Fire Test facility.

use in fire applications for on-board ships.

The industrial partners in the research activity will be able to test their own piping systems for their specific applications to screen composite material systems. The industry participants will also be able to use the facility to test systems according to standards, such as the proposed ASTM F1173 standard. Various piping systems, such as dual wall systems, insulated pipe, and fire-retardant resin based systems can be tested. These passive fire-retardant systems can be compared with unprotected systems for selection of the optimal design for future large-scale testing, if so required.

The university will benefit from the program by participating in research activity. This activity will be for both the U.S. Navy and the industry participants. Corporations can provide grants to the university for specific use at the fire test rig and requires the support of the university in the research and development of advanced composite material systems for fire applications. Likewise, the United States Navy, through the SBIR program, can consult the university for assistance in its research with advanced composites.

Summary

While the research completed in 1991 under the Phase II program achieved many goals in evaluating the fire characteristics of advanced composite piping systems for marine applications, there is a great need for additional research and development to be performed to further investigate the advantages of advanced composite piping systems for fire applications in the marine industry. The proposal for further research and development under the Phase III program continues the progress made in Phase II. Furthermore, the proposed pilot-scale fire test facility provides a hub of research activity that benefits all of the participants, the U.S. Navy, industry, and the university.

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TWENTY YEAR HISTORY OF SUCCESSFUL APPLICATIONS OF COMPOSITE PIPE IN SEA WATER SERVICE

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Introduction

Since the 1950's composite pipe has been considered a viable alternative to carbon steel, stainless steel and copper nickel pipe in sea water applications. The most obvious benefits of utilizing composite pipe for offshore applications is its excellent corrosion and erosion resistance as well as its attractive cost. Case histories exceeding twenty years have been reported in the Gulf of Mexico. A typical example is a water flood system installed by Exxon in Block 16 in 1970. In U. S. Navy tests conducted in the early 1980's, the erosion, chemical, abrasion and fouling characteristics of composite pipe were shown to be superior to copper-nickel pipe. The American Petroleum Institute (API), The American Society for Testing and Materials (ASTM), The International Maritime Organization (IMO), and The Norwegian Petroleum Directorate (NPD), in addition to groups such as the United Kingdom Offshore Operators Association (UKOOA), are all working on standards and guidelines to provide adequate engineering documentation for the expanded use of composite pipe systems. Innovative strategies for promoting University-Industry-Government Co-Beneficial Collaboration are recommended.

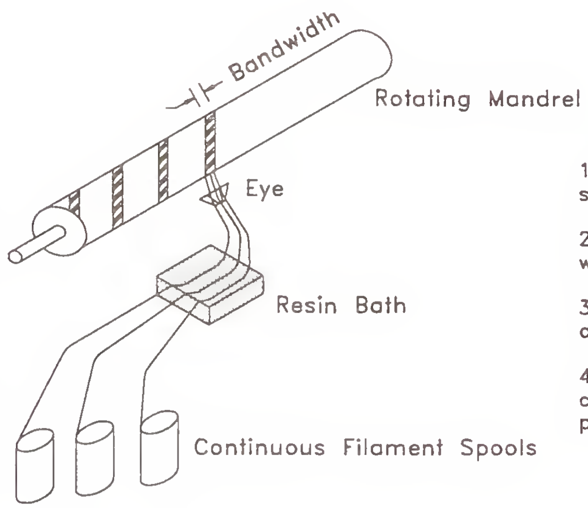
Background

The Composite Pipe Industry grew out of a U. S. Government Research Grant issued during World War II to find a viable alternate to protected steel, stainless steel and other exotic materials which were in short supply. The early applications included well casing and oil field gathering lines. Some of these installations of over thirty years are still in use. Today, composite pipe can be designed to handle hot wet chlorine gas at temperatures up to 250 °F (121 °C) in chemical process lines, down hole tubing to 4000 psi (275 Bar) for marine applications, and chilled water in the world's largest office buildings for cooling systems.

In order to appreciate the design flexibility of these materials one must have a basic knowledge of composites. In Dr. A. Brent Strong's book entitled, Fundamentals of Composites Manufacturing, he provides this definition of a composite, "The combination of a reinforcement material (such as glass fiber) in a matrix or binder material (such as resin)." This definition implies that the materials act in concert --- that is, one helping the other --- hence the term, composite. The matrix (resin) in a fiberglass composite provides protection against adverse environmental effects while the reinforcement (glass) provides the strength.

A standard in widespread use today that describes and classifies one type of composite pipe is ASTM D2996, the Standard Specification for Filament-Wound "Fiberglass" Pipe. This specification covers machine-made (by the filament winding process) reinforced thermosetting resin pipe (RTRP) only, however, it does not address the fittings or joining methods. In spite of this, it is a good standard to assist the user in understanding composite pipe. It describes the filament winding process to manufacture tubular goods by

FILAMENT WINDING MANUFACTURING PROCESS



1. Fibers are pulled at a controlled speed to maximize saturation with the resin.

2. Fibers are pulled under controlled tension for proper weight ratio and to eliminate imperfections.

3. Fibers are placed at the proper winding angle for optimized strength.

4. Fibers are wound at plus/minus degrees until one complete closure is made. This is repeated until the proper thickness has been achieved.

Figure 1. The filament winding method is an automated process where numerical controls are sometimes employed.

winding continuous fibrous glass strand roving or roving tape onto the outside of a mandrel in a predetermined pattern under controlled tension. Refer to Figure 1.

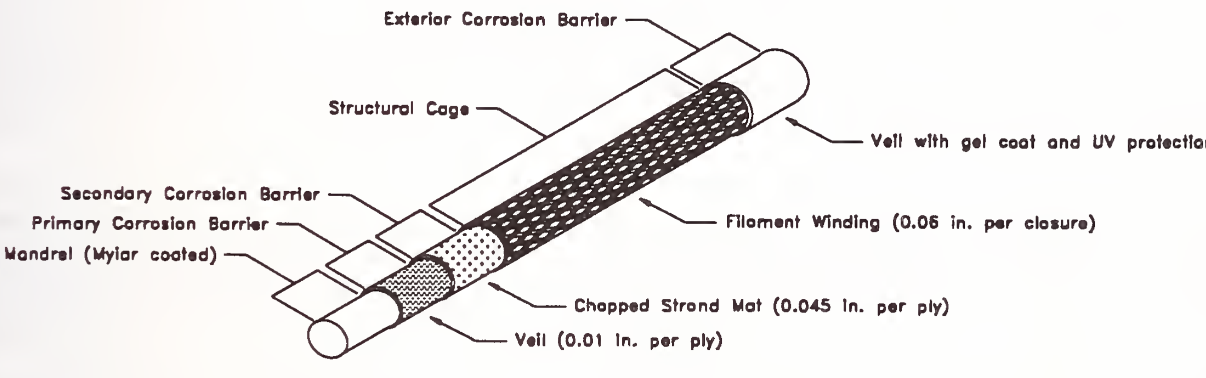
The construction of these products is as follows. The liner is described as the inner portion of the wall exposed to the fluid at least 0.005 in. (0.13mm) in thickness which does not contribute to the strength in the determination of the hydrostatic design basis. It is the reinforced wall thickness, which is the total wall thickness minus the liner and/or exterior coating thickness, which is used in the mechanical calculations. Refer to Figure 2 for the basic construction of filament wound pipe. The user of composite pipe should be familiar with this specification and understand its contents and limitations, prior to designing or specifying a composite pipe system.

Erosion, Chemical, and Fouling Characteristics

In one erosion investigation reported by the Navy, three 2-inch diameter flange piping assemblies, incorporating pipe, elbows, and tees were located upstream and downstream of throttling globe valves in the wide open position. One assembly included both 90/10 and 70/30 copper-nickel spools to serve as a baseline for comparison. Assemblies Number 1 and 2 were operated at 11 and 17 ft/sec respectively for twelve months. Assembly Number 3 was operated at 25 ft/sec for three months.

Seawater temperature, dissolved oxygen content, ph, salinity, and average velocity were monitored during the exposure periods. After one year of operation, final inspection showed no signs of erosion or any other damage to the inside of the composite pipe test spools. The 90/10 and 70/30 copper-nickel test spools, however, showed definite signs of progressive erosion damage. Assembly Number 3 which operated with composite pipe at 25 ft/sec also showed no signs of any damage after a 3-month exposure period.

FILAMENT WOUND PIPE



PRIMARY CORROSION BARRIER

10–20 mils (0.01–0.02 in.) thick
10% glass reinforcement (by weight)
C-Veil or Synthetic veil

STRUCTURAL CAGE

1/16" – 1" thick
Special designs exceed 1" thickness
50–70% glass reinforcement (by weight)
Continuous glass roving

SECONDARY CORROSION BARRIER

0–90 mils (0.00 – 0.09 in.) thick
Special liners up to 480 mils
25% glass reinforcement (by weight)
0.75 or 1.5 oz Chopped Strand Mat

EXTERIOR CORROSION BARRIER

10–20 mils (0.01–0.02 in.) thick
10% glass reinforcement (by weight)
C-Veil or Synthetic veil
Can include UV, gel coat, and/or pigment

Figure 2. Typical construction of filament wound pipe. Materials of construction and tolerances vary from manufacturer to manufacturer.

Chemical resistance tests completed in accordance with ASTM C582 by various composite pipe manufacturers and resin manufacturers conclude different grades of composite pipe can handle a wide range of chemicals. Composite pipe is in services such as gasoline, jet fuel, chlorine, sodium hypochlorite, carbon dioxide, carbon disulfide, fatty acids, hydrochloric acid, nitric acid, sodium hydroxide, sulfur chloride, sulfuric acid, and naturally, sea water, desalination water, waste water, potable water, deionized water, demineralized water, produced water and steam condensate. The designer of composite pipe systems should refer to current resin manufacturer's standards or check with the individual manufacturer for specific recommendations. Temperature resistance is limited to 250 °F (121 °C) in most chemical services. A good source for chemical resistance is the Fiberglass Pipe Handbook published by The Composites Institute of the Society of the Plastics Industry.

Marine fouling tests conducted as far back as 1950 by J. L. Basil for the U. S. Navy at Wrightsville Beach, North Carolina showed that while composite pipe collected marine organisms in quiet seawater, after a 14-month exposure the fouling that occurred was easily cleaned and there was no evidence of attack by marine borers or other marine life. This is to be expected because marine fouling can occur on any non-protected surface which will not leach a metal salt or other agents toxic to marine life. Most resins used in the construction of composite pipe are considered inert to marine life, offering no food value and producing no toxic effects.

Platform operators in the Gulf of Mexico have reported no fouling problems in 12-inch diameter seawater circulating lines operating continuously for approximately five years at maximum velocities of 5 ft/sec. Fouling does occur, however, in lines that are shut down for one-month periods while heat exchangers are being cleaned.

In one of the longest continuous exposures of composite pipe to natural seawater, three fifteen foot sections of 6-inch diameter pipe were installed in the seawater system at the Francis L. LaQue Corrosion Laboratory in Wrightsville, Beach, North Carolina. These sections were removed for inspection in September 1976, after 17 years of service. Inspection revealed that although 1-inch of hard marine fouling had accumulated on the inside diameter (as expected), the inside surface of the pipe was in excellent condition after the fouling was removed. The three sections of pipe were returned to seawater service after cleaning.

If fouling in composite pipe is considered a problem and it is impossible to maintain water velocities above 2 ft/sec. continuous chlorination as low as 0.25 parts per million can completely eliminate all marine growth.

More recent tests completed this past summer in Fort Lauderdale, Florida at a Naval Surface Warfare Center test site concluded composite pipe compared favorably with both titanium pipe and copper nickel pipe in ultraviolet water treatment and ozonation tests. These tests were the result of reports of severe corrosion, erosion, and marine growth blockage of copper nickel (90/10 and 70/30) seawater piping systems on board U. S. Navy surface ships. The final report should be available by the Spring of 1994.

For those of you interested in the API investigation into materials suitable for sea water applications, we suggest you obtain a copy of the current API 14G Document entitled, "Recommended Practice for Fire Prevention and Control on Open Type Offshore Production Platforms". This document, available now, provides a summary of the advantages and disadvantages of carbon steel pipe, stainless steel pipe, copper-nickel pipe and composite pipe in fire water systems using sea water on offshore platforms.

Fire Endurance and Heat Transfer Characteristics

One area of concern regarding composite pipe systems is their characteristics under a sustained fire and/or explosion. Of primary concern is the ability of the pipe to withstand the severe environment which would be present under such a scenario. Obviously, the critical design parameter for fire water systems is for the pipe to be able to deliver quench water to the fire until all personnel are evacuated or the fire is brought under control.

Since many of the resins used in composite components are flammable, it is clear that most composite pipe systems used in offshore applications may need to be insulated and protected from direct fire impingement. Manufacturers of composite components are actively involved in the design and development of new protective coatings which range from simple intumescent coatings to advanced dual-wall configurations.

A distinct advantage of composite pipe, often overlooked, is their inherent resistance to heat transfer. Compared to metallic pipe, the thermal conductivity of composite pipe is substantially lower. This advantage can be significant and should not be overlooked or underestimated as designers make greater use of composite pipe.

To illustrate this qualitatively, consider the following example. Suppose a bare 102 mm (4 in.) pipe is exposed to a fire. Assume that the pipe has a 6.4 mm (0.25 in.) wall thickness and that the pipe is in the dry condition (the most severe condition). For this example we will let the heat load vary from 0 to 1 kW/m^2. Given a heat load and the thermal conductivity of the pipe, one can readily estimate the temperature difference across the pipe using Fourier's Law of heat conduction:

$$T_{outer} - T_{inner} = (Q/k)\,[r_o \ln(r_o/r_i)]$$

where:

Q	=	the heat flux (W/m^2)
T_{outer}	=	the outer pipe skin temperature (°K)
T_{inner}	=	the inner pipe skin temperature (°K)
r_{outer}	=	the outer pipe radius (in this case 57 mm or 2.25 in.)

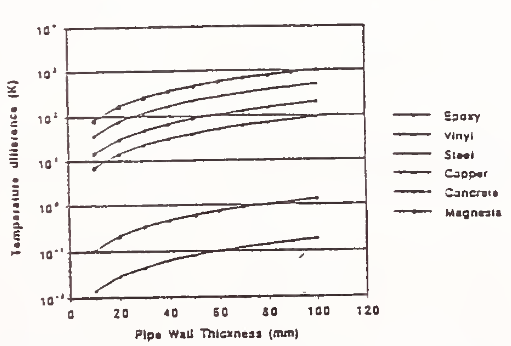


Fig. 9. Effect of Pipe Thickness for Different Materials at 500 W/m^2 Heat Load.

Figure 3. Comparison of different pipe materials under variable heat loads.

r_{inner}	=	the inner pipe radius (in this case 51 mm or 2 in.)
k	=	the thermal conductivity of the pipe (W/m-°K)

Results of this simple analysis for a number of pipe materials are shown in Fig. 3. In the figure, the temperature differences between the outer and inner pipe skin (T_{outer} - T_{inner}) are compared over the range of heat loads shown.

The purpose of Fig. 3 is not to provide absolute data; rather, the graph is meant only for comparative purposes. Note, the smaller the temperature difference, the better the heat conductor. Copper, with a very high thermal conductivity and low resistance to heat transfer, would experience essentially no temperature difference across the pipe under a 1 kW/m^2 (317 Btu/ft^2-hr) heat load. Under the same load a carbon steel pipe would experience a 0.1°K temperature difference.

On the other hand, a composite pipe system with an epoxy vinyl ester resin would experience a 75°K difference while the pure epoxy resin system would exhibit a 20°K difference. For comparative purposes, two insulators are given (concrete at 9°K and magnesia at 100°K). Magnesia is considered a very good insulating material. According to Fig. 3, the composite pipe systems chosen would exhibit heat transfer characteristics bracketed by two good insulators, concrete and magnesia.

Economic Characteristics

There have been numerous studies completed within the past ten years on this subject. A report issued in April, 1987 by the Naval Surface Warfare Center in Annapolis, Maryland stated, "Composite Pipe ranks as the lightest and the least expensive corrosion resistant piping material that can be used in the marine industry." (Conroy, 1987). The current API 14G document states, "The use of fiberglass pipe has the advantages (over carbon steel, stainless steel and copper nickel pipe) of corrosion resistance, lighter weight, lower cost, and ease of installation." Each composite pipe manufacturer can furnish prices for estimating if cost studies are not currently available within your own company.

Naturally, when discussing composite pipe systems, there is a wide range of prices available to the customer depending on his needs. Composite pipe comes in various resin systems, liner thicknesses, wall thicknesses, and joint designs. Flexibility to design composite pipe systems to meet specific or individual piping requirements remains one of the greatest advantages of composite pipe over alloys. Each manufacturer of composite pipe manufactures various "series" or "grades" of composite pipe to meet these specific needs. As with Sch. 5, Sch. 10 or Sch. 40 carbon steel or 304 vs 316 stainless steel or 90/10 vs 70/30 copper nickel pipe, prices vary based on a wide range of variables.

Future Work Proposed by the U.S. Navy in Cooperation with Louisiana State University

The U. S. Navy is interested in an additional series of tests to determine the fire endurance levels of composite pipe in accordance with newly developed IMO Standards and the proposed ASTM F1173 (Epoxy Resin Fiberglass Pipe and Fittings to be Used for Marine Applications) standard currently being revised. Rather than merely test pipe, the proposed facility will be unique since it will have the ability to perform fire tests on the entire composite piping system, consisting of pipe, fittings and joints. The facility will test composite piping systems bare and with protective coatings/jackets. The results of this research effort will provide future designers optimum characteristics for efficient use of materials.

The manner in which the facility is designed will allow Louisiana State University scientists to test under a variety of fire conditions benefiting the U.S. Navy, who is a primary sponsor, the industry participants, and the university. Both the Navy and industry partners will be able to use the facility for screening tests on entire composite pipe systems and to perform tests according to fire standards to evaluate promising composite materials. The university will be able to use the facility as a research hub performing research and development in the advanced composites field.

The estimated cost for such a facility is $100,000, of which $50,000 is expected from U. S. Navy funding. A special Foundation Account has been established at Louisiana State University. Conoco and Mobil Oil have already contributed to the support of such a project. This is a typical example of the "Innovative Strategies for Promoting University-Industry-Government Co-Beneficial Collaboration" that will be needed to keep the American industrial base strong and competitive in the future.

Summary

Composite Pipe, even though around since the 1950's and with over one billion lineal feet of composite pipe in service in the United States alone, is finally becoming the "system of choice" in the offshore oil and gas industry as well as the petro-chemical industry all over the world. In addition to many of the raw materials being products of the american petro-chemical industry, with companies such as Amoco, Shell, Conoco and Mobil being major resin producers along with many others, these materials offer:

- Exceptional corrosion resistance where temperatures are under 250F (121C)
- Low installed cost (no hot work permits required), minimum maintenance (no repainting cost), low life cycle cost with over twenty (20) years case histories in sea water service
- Excellent hydraulic characteristics (C Factor = 150), with resistance to erosion and fouling
- Lightweight (six-inch composite pipe weighs approximately four (4) pounds per foot vs twenty (20) pounds per foot for Sch. 40 carbon steel pipe)
- High strength to weight ratios
- Flexibility of design to meet customer needs

In 1990, the Department of Defense Critical Technologies Plan classified composite materials as a critical technology. The U. S. Congress has provided funding to several federal agencies to foster development of the United States' capabilities in composite manufacturing processes to benefit the Department of Defense and maintenance of the United States defense industrial base.

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ADVANCED COMPOSITES FOR THE OFFSHORE INDUSTRY: APPLICATIONS AND CHALLENGES

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ABSTRACT

Innovations and technological advances are essential to the success of the offshore industry in meeting the challenge of continuing its effort to exploit natural resources in deeper waters. Although the traditional engineering material for offshore structural applications is steel, other materials such as composites are now being seriously considered for several critical applications. The primary motives for using composites are to improve efficiency and reliability, and to reduce life cycle cost. In addition to the current use of composites for vessels, tanks, low pressure piping, cable tray, grating, and fire and blast walls, there are several other applications that are currently under development. These applications include production and drilling risers, riser stress joints, riser tensioners, TLP tendons, drill pipes, high pressure coiled tubing and spoolable flowlines and reinforcement for flexible pipes. However, efficient exploitation of composite materials to satisfy economic or performance requirements is most likely to be successful if an integrated approach is developed to address the currently existing technical, financial and emotional barriers. This paper reviews some critical applications of composites for deepwater developments and identifies the current barriers that must be eliminated to ensure the success of these applications. The paper also presents an approach to eliminate these barriers.

INTRODUCTION

The oil industry is continuing its effort to exploit oil and gas reservoirs in deeper waters (> 1500 ft). Exploration in water depths of 7000 feet (2134 meters) was performed, and Shell's Augur Tension Leg Platform (TLP) was recently installed in 2860 feet (782 meters) in the Gulf of Mexico. In addition, designs for 4000 ft are currently in progress for potential developments in the North Sea and west Africa. Figure 1 provides historical and projected water depth for exploration and production activities. A single deepwater project can easily be a multi-billion dollar capital investment, and the new technology needed to extend current capabilities to the deeper waters of new license areas may lead to expenditures for the novel subsystems measured in hundreds of millions of dollars. New technologies are required to enable the industry to proceed with a significant number of such new projects, particularly under the pressure of low oil prices. Therefore, serious effort was devoted toward the evaluation and the application of innovative approaches to reduce capital and operating costs. Part of that effort involved the use of innovative and cost competitive materials that can improve performance and reduce maintenance costs while increasing reliability, improving safety and providing enabling capabilities beyond those achieved with currently used materials. Advanced polymeric composite materials offer the potential of achieving these goals. The efficient exploitation of composite material is, however, only possible if materials, structural and manufacturing technologies are utilized in an integrated approach. This will ensure greater design flexibility and promotes system oriented solutions.

Composite materials have been receiving much attention in the offshore industry as demonstrated by the many special meetings and workshops held in the U.S., Norway and UK. This interest is motivated by composites light weight, corrosion resistance and excellent fatigue performance. In addition, composites offer a unique advantage because they provide the flexibility for engineering the materials properties to meet the design requirements. Composites can be tailored to achieve specific mechanical properties such as high axial strength and stiffness, or high circumferencial strength and low axial stiffness. They also can be tailored to achieve specific thermal properties such as low thermal conductivity and low coefficient of thermal expansion. In order to ensure the successful implementation and commercialization of advanced composites, development programs must involve the key companies from each element of the supply chain and from engineering contractors and regulatory agencies. The development program must draw on the vast knowledge of the defence and aerospace companies and should include serious economic analysis at key junctures to ensure that the results are truly aligned with the strategic needs of deepwater development.

This paper reviews current and potential applications of advanced composites in the offshore industry. The paper also identifies and presents ways to eliminate barriers that limit the acceptance of advanced composites for critical applications in deepwater developments.

APPLICATION OF ADVANCED COMPOSITES

So far, the main emphasis of potential applications of advanced composites for the offshore industry is focused on high pressure tubular barrier (above 1000 psi pressure) which are either discrete (20 to 80 feet length) for use as drilling and production risers, choke and kill lines, pipes, tubing and casing, or continuous (many thousands of feet long) for use as coiled tubing and flowlines. For the continuous case, the pipes are of relatively small diameters (< 5 inch) and, therefore, can be spooled. These spoolable composite pipes have been proposed for use as coiled tubing, and subsea flow and control lines. High pressure composite coiled tubing (Sas-Jaworsky and Williams, 1994) is currently attracting major attention because it provides enabling capabilities to workover, logging and completion of highly deviated wells. The proposed coiled tubing is constructed of a hybrid composite of glass or aramid and carbon fibers. In addition to conventional composite pipes, several companies such as Wellstream and Coflexip are evaluating the application of composites instead of steel for axial and hoop stress reinforcements for deepwater flexible pipes (Figure 2) to reduce weight which will significantly reduce deck and installation loads. The hoop stress is carried by circumferentially wound flat strips of thermoplastic fiber glass composites and both axial and hoop loads are carried out by composite wires formed into helixes.

There are other applications, that do not fall under the high pressure tubular classification such as TLP tendons that use a strand assembled of many continuous small diameter carbon fiber rods or laminate construction containing carbon fiber rods. The use of composite rods by the oil industry is not new. Fiberglass sucker rods with metallic end fittings have been in service for more than 15 years. Amoco has developed and used spoolable sucker rods in the form of uniaxial carbon fiber composite ribbon (Lea and Winkler, 1994). Composite sucker rods are used because of their light weight and high fatigue and corrosion resistance. There are many other applications, which are not unique to the offshore industry, where primarily fiberglass composites are currently being used on offshore platforms. These include storage tanks, vessels, low pressure pipes, torque shafts, structural parts, seals, grating, fire and blast walls, cable trays, etc. The motives are lower weight, less maintenance and reduced installation costs. As an example, composite cable trays can save 150 to 250 tons of weight on an offshore platform (Chang, 1993).

In this section, the discussion will focus on three applications that are selected because they can be characterized as advanced composites and because they have the highest potential in providing enabling capabilities and in achieving major cost saving to deepwater developments. The tension leg platform (TLP) concept (Figure 3) is the most likely concept to be used for developing large deepwater reserves. The TLP is a buoyant platform connected to the sea bed by vertical mooring lines called tendons, tethers or tension legs. An excess buoyancy over weight assures that the tendons remain in tension for all weather and loading conditions. The platform's mooring permits large motions of surge, sway and yaw under the effect of wind, wave and current, while remaining stiff in heave, pitch and roll. The primary advantage of the TLP concept over other floating production concepts is allowing the well systems to be tied back to the TLP's deck similar to conventional platforms, with the main control valving (Christmas Tree) at the deck level. This provides maximum safe access to the wells for monitoring and remedial work. Currently, there are four TLPs in operation (Conoco's Hutton and Jolliet, Saga's Snorre and Shell's Auger), a fifth being fabricated for installation in 1995 (Conoco's Heidrun) and a sixth in the design stage for installation in 1996 (Shell's Mars). Shell's Augur TLP was installed in 2860 ft (872 m) water depth and Mars will be installed in 2930 ft (893 m)in the Gulf of Mexico. Table 1 provides the principal technical data for Conoco's TLPs. The three key TLP systems that are most affected by an increase in the water depth and, therefore, will be considered in this report are the tendons, production risers and drilling risers.

TENDONS

Tendons are impacted by not only the need for more length but more importantly by the effect of increased length on the platform heave and pitch natural period. It is the current design practice to limit these periods to less than 4 seconds to avoid resonance which is known to increase fatigue loading and may also increase the extreme load. Although this limitation can greatly affect the cost of the carbon fiber composite tendon system for which higher fatigue loads may not constitute a problem because of its superior fatigue resistance, the natural period limit is still imposed because the increased load will affect both the foundation and the connections to the hull. In addition, the current state of the art of hydrodynamic analysis does not allow sufficient confidence in load predictions when the natural periods are increased. Discussions on this issue and how it affects the design of the composite tendons are presented by Salama (1984). The required section modulus (EA) of a single TLP tendon can be estimated as follows (Salama, 1984):

$$E\,A = \frac{4\,\pi^2\,L(W + 0.4\,D)}{g\,n\,T^2} \tag{1}$$

Where:

- E = Elastic modulus of tendon materials, psi
- A = Cross section of a single tendon, in^2
- L = Tendon length, ft
- W = Platform weight, lb
- D = Platform displacement, lb
- g = gravitational constant, 32.2 ft/sec^2
- n = Number of tendons
- T = Heave natural period, sec

An attractive composite tendon solution that has been evaluated is based on the use of a strand constructed from 3 to 5 mm continuous carbon fiber rods as shown in Figure 4. The strand can be terminated, similar to a steel bridge strand, using potted terminations. Other termination concepts such as a loop type can also be considered. The strand is very light weight with a density of 0.044 lb/in^3 (1.22 g/cm^3). The results of static and fatigue properties of terminated 250 tonne 2 inch (54 mm) diameter strand demonstrated outstanding properties (Walton and Yeung, 1987; Yeung and Parker, 1987; Salama, 1988). Table 2 presents a comparison between fatigue performance of the carbon fiber strand and a carbon steel welded tendon. In order to achieve the 4 second design criterion for a Heidrun type concrete TLP in 4400 feet in the North Sea, the required tendon stiffness per corner is about 300 MN/m. Under these condition the maximum stresses in the tendon will be about 20% of the tendon strength if fabricated using P-55 (55 x 10^6 psi modulus) carbon fibers. The utilization if P-120 (120 x 10^6 psi modulus) carbon fibers are used is about 35%. A P-55 carbon fiber composite tendon will have a mass of about 14,000 mT (@ 30 x 10^6 lb). The weight of the fiber alone exceeds 8000 tonnes (@ 18 x 10^6 lb). The cost of this tendon system will exceed 1/2 billion dollars. These numbers demonstrate that there is sufficient business incentive for both fiber and composite manufacturers to support the development of the composite tendon system. This is in addition to the other potential applications for high stiffness composite strands such as suspension bridges, floating islands to support military operations and subsea suspension tunnels. There is also a major thrust by several companies to develop low cost high modulus pitch based carbon fiber (60 to 100 msi). Success of these development will result in an improvement of the strain to failure of these fibers and in bringing their cost down to the range of $10 to $20 per pound. The use of these fibers will allow fabrication of rods that have an elastic modulus much higher than steel. Also, the use of low cost short (few inches long) pitch carbon fibers instead of continuous fibers may result in major reduction in the tendon cost by about 50% without impacting its size and weight. Note that if this system is made of steel the mass of the tendon system will be more than 80,000 tonnes and more than 16 tendons per corner will be required, which may not be practical.

As discussed above, steel tendons may not be technically and/or commercially feasible for large TLPs in deepwater. Even in cases when a steel tendon is feasible, i.e. for small TLPs, the total cost of a composite mooring system can be lower than a steel system and more reliable. The three key components of the cost of a TLP mooring system are the cost of tendons, cost for connections to hull/foundation (e.g. flex joints, top and bottom connectors, tension and inspection monitoring systems), and cost of installation. The costs of the tendons and installation are the most affected by increased water depth. Table 2 provides a comparison of materials and installation costs for both steel and composite tendon for a small TLP in 4000 feet in the Gulf of Mexico. The cost of the carbon fiber strand is very competitive with steel tendons. For a 350,000-lb strand, the cost is 500 to 700 $/ft compared to a steel tendon of the same capacity of about 300 to 400 $/ft. The weight of the strand in air is 6.6 lb/ft compared to 200 lb/ft for steel. The strand diameter is about 4 inches while the steel pipe will be much larger depending on the buoyancy requirement. It needs to be noted that beyond 2500 ft water depth the use of a neutrally buoyant steel tendon is not feasible because of collapse considerations and, therefore, the weight of the tendon becomes an important parameter. Because of the smaller size and weight of the composite tendons, their installation cost will be lower than steel tendons. Installation of composite tendons is feasible using both reeling and towing methods. It is estimated that the installation cost of a steel tendon in 4000 ft of water is in the range of $1000 to $1500/ft while the installation cost for composites is in the range of $500 to $1000/ft. In addition to lower installation cost, it is also feasible to reduce the cost of a tendon system by taking advantage of the composite properties to simplify the top and bottom assemblies and possibly eliminating the expensive flex joints.

In addition to the carbon fiber strand concept, there are other concepts that are attractive candidates for TLP tendons and need to be evaluated. These include high modulus aramid ropes, carbon fiber laminates and composite pipes. Composite pipes which can be fabricated using braided aramid or glass pipes that contain axial carbon fiber rods possess several attractive properties. This concept will be more costly because it will require more fibers, but it offers the advantage of being neutrally buoyant which is a desired property from both weight and installation view points. Installation cost can be very high and a configuration that reduces this cost is desirable. Neutrally buoyant tendons can be towed in one piece and installed. Stranded type tendons can be either towed using flotation to achieve the required buoyancy or reeled. The reeling approach may not, however, be feasible if large diameter tendons are required because of the physical limits of the reel size.

PRODUCTION RISERS

The second important TLP system for which composites represent an optimum solution for deepwater is production risers. Composite risers can not only reduce the required pretension but they may also allow the rigid connection of the riser to the platform, thus eliminating the expensive tensioners. Composite production risers are probably the most mature of composite applications because they have been the subject of several major studies within the last few years. Several major oil companies sponsored a major development and evaluation study of a 9 5/8 inch composite production riser to prove the concept. The study was done during the period of 1985 to 1989 by the Institute Francais du Petrole (IFP) and Aerospatiale. The riser pipe (Figure 5) was fabricated of a hybrid of carbon fiber and S-glass fibers. The pipe could withstand a combined pressure of 15,000 psi and an axial tension of 450 tonne. The pipe was also designed to withstand a collapse pressure of 5400 psi. The study included several static, fatigue, multi-axial loading and damage assessment tests. Major portions of the results have been published by IFP and Aerospatiale (Ordu and Guichard, 1986; Sparks, et. al, 1988 and 1992). As a follow-up to this study, Brunswick, Coflexip, IFP and aerospatiale engaged in a project to reduce the cost of the risers by optimizing the manufacturing process and the design. The design optimization included simplifying the metallic threaded joint (Figure 6), using the lower cost E-glass instead of the S-glass, and changing fiber lay to achieve zero thermal and pressure induced axial strains. Table 4 provides a comparison between steel and composite 9 5/8 inch production riser as currently proposed by Brunswick. Although the cost of the composite riser is higher than steel, the total riser system cost will be lower due to reduction in payload and tensioner costs by taking advantage of the several unique properties of composites. These properties include low density, low axial stiffness, zero coefficient of thermal expansion and infinite bulk modulus.

In addition to the production riser pipe, composites are being considered for other riser components such as taper joints and tensioners. The riser taper joints provide a smooth transition between the flexible riser pipe and the relatively rigid subsea wellhead and thus prevent the overstressing of the riser itself. The currently considered taper joints are fabricated of a hybrid of a steel or titanium riser pipe with a taper outer filament wind wrap of fiberglass and carbon fiber composite. The tensioners are used to compensate for the platform movement and keep the riser in tension under all loading conditions to prevent riser buckling. The tensioner is a non linear spring with high initial stiffness to generate the required mean riser tension followed by a low stiffness to accommodate operating stoke without increasing the riser tension. Currently, the tensioners used are short stoke hydropneumatic motion compensators that are both complex and expensive. Several simpler composite alternatives are being considered including a pipe section that achieves the non-linear behavior by designing the pipe to elastically buckle after certain specified load. So far, none of these systems has been evaluated.

DRILLING RISERS

The third major TLP system that will be considered are the drilling risers. A drilling riser is similar to the production riser except that it has larger diameter (18 to 22 inches as compared to 9 to 11 inches for production risers) and it should be able to be run and retrieved within a reasonable time, i.e. it should have a quick make-up and break-out connections. Also, the drilling riser is designed for shorter service life, 15 years versus 30 years for the production riser. For deepwater TLPs, titanium instead of steel is considered the preferred material for drilling risers. The cost of a titanium drilling riser may exceed $10,000/ft while the cost of a composite riser may be less than half that value. Therefore, several companies including Westinghouse and Brunswick have demonstrated the feasibility and the cost benefit advantage of composite drilling riser pipes and composite taper joints.

BARRIERS TO THE APPLICATION OF ADVANCED COMPOSITES

There are three types of barrier that must be recognized to ensure the required acceptance and the successful applications of advanced composites for the critical offshore applications. These barriers involve technical, financial and emotional issues. While most of the efforts are focused on addressing the technical and financial issues, the emotional issues are, generally, ignored. Emotional issues, while very critical, are more difficult to resolve and, therefore, should be treated very seriously. Both the technical and financial barriers are not unique to composites, they are applicable to any new material. Eliminating these barriers will offer significant opportunities to leverage major benefits for the oil industry with high payoff of potential billions of dollars for the composite industry.

Technology Barriers

As with other materials, there are many factors that must be considered in materials selection of composites. These factors include strength, stiffness, fatigue resistance, creep resistance, wear resistance, defect tolerance, weight, inspectability, repairability, fire resistance, toxicity, environmental degradation resistance, etc. With the current emphasis of the offshore industry on reliability based design, analytical methodologies and sufficient data bases to allow proper risk assessment are important to meet regulatory requirements for both design and manufacturing. The lack of these data is, however, not unique to composites and, therefore, should not serve as justification for not using composites. We only need to reflect on how much money is spent and how many papers are published annually to address technical issues concerning steel such as corrosion, fatigue and welding to conclude that lack of knowledge has never prevented engineers from using steel. But when an engineer trained in steel design and construction attends a composite meeting where needs for further research are being identified, he may mistakenly conclude that design and fabrication of composites are not mature enough for his application. Therefore, the reader should not interpret the technical needs identified in this section as a must before considering the application of composites, but rather as a requirement to improve the capability to optimize composites from reliability and cost view points.

Fortunately, major technical strides have been achieved through the application of composites for aerospace and military applications that can pave the way for the commercial marine applications. Computer programs for detailed stress analysis are well developed. There is, however, a need for design methodology and user friendly composite design software for material tailoring and for assessing multiaxial failure and structural performance under transportation, installation and operational loads. There is also a need to identify loads and requirements for storage, transportation and installation of composite components.

There is a wealth of material performance data for composites. The marine environment may actually be less demanding than current applications for composites. However, composites must be able to survive 20 to 40 years unattended, therefore, data and models to predict long term degradation are required. Although composite components are used as blast and fire walls, there is a major misconception regarding fire and impact resistance of composites. Since composites, unlike metals, allow the fire to be localized and contained because of their low thermal conductivity, fire resistance test methods that are developed for metals may be inapplicable for composites because composites will allow more time for the offshore operators to tackle the fire and/or escape. Also, smoke and toxicity have been areas of concern in the past but with advances in the resin technology and the expanded use of phenolics, this issue should not be of major concern.

Fabrication technology for the simple geometries that are being considered by the offshore industry is relatively mature and requires little capital investment to increase production within a short time. However, there is a need to develop high speed continuous processing technology that addresses manufacturing processes (filament winding, pultrusion, braiding, resin transfer molding and hybrid) for cost effective manufacturing. Manufacturing of composites utilizes many material forms including dry, hybrid fibers, wet, prepreg tape, woven fabrics, preforms. Each of these forms has its own process control requirements such as curing, fiber placement, compaction, consolidation.

Termination of composites remains an area of concern since batch process filament winding manufacturers are limited in length to 30 to 75 ft and, therefore, requiring many connections which are always considered as the weak link in the system if not properly designed. This may not be an issue for a critical applications such as tendons because the strength utilization of the composite is low (@ 20%). Therefore, efficient termination may not be required. Effective terminations for pressure containing systems such as risers are well developed. The effort should be focused on optimization to achieve cost minimization.

Adequate technology and procedures for inspection and quality control are available. However, the development of standard quality control manuals for these techniques is necessary to simplify procurement and certifications. Since marine components are intended to be in continuous service for 20 to 40 years, developments in the area of in-service integrity monitoring using implanted sensors and fiber optics will be valuable to eliminate the need for the expensive removal of the composite components for inspection.

Since the successful application of composites in the offshore industry can potentially result in the annual use of 100's of millions of pounds, environmental issues due to replacement and disposal need to be seriously considered. This may impose some restrictions on materials selection to allow recycling.

Financial Barriers

Because of the high capital investment and the strict certification requirements, selection and implementation of composites is only feasible when the pay-off value is judged to be greater than the cost at an acceptable risk. Therefore, the current use of composites in the offshore industry is limited to applications where the risk is low and the savings are modest. These applications involve low pressure fiberglass water handling pipes and vessels. The reliability of these systems have been clearly demonstrated by many years of successful service in the petrochemical industry.

The breakthrough for composite applications will, however, be realized when large savings can be achieved for high risk components. The large savings can be realized in terms of financial savings as a result of the lower actual or life cycle cost of the composite system, or in terms of revenue generation as a result of the enabling capability of composites, or in terms of both cost and revenue. Although the cost of composite components can be lower than the cost of equivalent components made of a special alloy such as titanium, it will be more than the cost of steel components. Therefore, it is critical to evaluate the application of composites in the context of system performance and functional requirement and not in terms of individual components. Composites can simplify the total system by eliminating expensive components and thus, the cost of the system will be lower even though the cost of the composite component may be higher. Potential applications under this category include production and drilling risers, TLP tendons and high pressure spoolable pipes (e.g. coiled tubing and flowlines). In addressing these applications, it is critical that composites technology be challenged beyond its current state because advances continue to be made on structural concepts, and metal components are evolving. Some of these changes may change the economic equation for composites as it is perceived today.

It must be realized that the financial incentive (cost and revenue) is necessary but not sufficient condition to ensure the acceptance of advanced composites in the offshore industry. Two additional factors must be considered. The first factor is the availability of production facilities to supply the required composite components within the time frame of a project. The offshore usage of composites will involve large scale orders which may be far higher than required by aerospace or military. For example, production risers for a single TLP for 4000 ft water depth may involve more 200,000 feet of 10 inch diameter pipes that require more than 2 millon pounds of carbon/fiberglass composites. Also, a single TLP may require more than 20 million pounds of high modulus fibers for its tendon system which may approach the current world annual production capacity of these fibers. The paradox is how can a project team commit to the concept knowing that the production capacity is currently not available, or how can a manufacturer justify the required investment to develop the necessary production capacity without being awarded a contract? The solution to this problem will require the development of a modular production facility which allows rapid expansion and contraction of the production capacity at minimum cost.

The second factor is prototyping and development of sufficient performance data on full scale components to ensure reliability and give confidence in the safe application of these materials. The cost of such an effort for a single component will be several million dollars. Here lies another paradox: oil companies are not willing to commit the financial resources to develop the required data unless the data will be used on a specific project which is under development. When the project is under development and funds are available, it is practically impossible to consider composites because it would be too late to develop basic data on time to be useful to the project. Although joint industry sponsored programs have been successful in proving the concept of composite production risers, they were not able to attract sufficient participation to generate the necessary funds to optimize both materials selection and manufacturing and to develop the necessary data for commercial applications. There is a need for alliances and consortia because resources are limited and no one company has the necessary skills to succeed. One approach to addressing the challenge may lie in a joint sponsorship of these program by government and industry. Programs such as the Advanced Technology Program (ATP) that is administered by the National Institute of Standards and Technology offers hope to achieve these objectives. Resources from this program is currently being tapped by the University of Houston's Composite Engineering and Application Center for Petroleum Exploration and Production to develop the required information.

Emotional Barriers

There are several factors that contribute to resistance to using composites for critical applications in the offshore industry. These factors can be classified in five basic categories: change of culture, lack of standards, lack of available resources, oil industries' short attention span regarding needs, and oil industries' minimal tolerance of failure.

The application of composites constitutes a change of culture to many engineers. Application of composites places designers who are trained mainly in steel structures outside their comfort zone. It is important to overcome the "can't weld, do not want" mindset. To add to the complications, current design rules do not provide any guidance on use of composites and, therefore, a simple design criteria such as a safety factor becomes a major issue for the designer. This makes it more often easier to ignore the benefits of composites than confronting the design procedure issues. In order to minimize the impact of this barrier, focus should be placed on the few critical components where composites can make major impact on the economics of offshore facilities and design codes for these components should be developed. Developing the design code should be one of the highest priority items.

The perceived lack of standards to allow certification of composites is a major hindrance to composite applications. The offshore industry follows strict guidelines that are being adopted or developed by certifying authorities. The lack of guidelines make some certifying authorities reluctant to give approvals for composite systems by imposing strict interpretation of standards and codes due to the lack of understanding of the material. It must be recognized that not all regulatory bodies react to the application of new materials the same way. Some are much stricter than others. Even in the absence of regulations, the Norwegian Petroleum Directorate (NPD) has been very receptive to accepting innovations when cost efficiency and safety have been demonstrated. As an example, although the Norwegian codes clearly restrict the use of non-metallics for safety systems, NPD was willing to waive the requirement and approve Amoco's request for the use of fiberglass piping for the fire water system on the Valhall platform. This approval was conditional on Amoco performing risk assessment analysis and fire survivability tests, and developing performance based specifications and quality control procedures for manufacturing. Other regulatory bodies may insist that codes of practice and performance data be developed before applications are approved. Therefore, it is very important to initiate early interaction with the certifying authority to provide them with better understanding of composites and to identify the type of date required to alleviate any concern that they may have.

There is a perceived lack of available resources to support the application of composites. Almost all marine design engineers lack training in design of composites. This should not be surprising since very few universities have mandatory course requirement for design of composites for mechanical, civil and marine engineers, while all schools have a mandatory course on steel design. This barrier can be easily addressed if universities make a course on design of composites mandatory for all of its undergraduate engineering disciplines.

The oil industry is reactive with short attention span regarding needs. This statement may be unfair because this may not be unique to the oil industry and also because the oil industry is one of a few industries that can not forecast the price of its product, because it has no control over the forces that influence the price of its commodity. Therefore, when prices are high, interest in deepwater and technologies that support it is high. The interest diminishes when the price of oil falls. However, it is important to understand the reality that it is very difficult to sustain sufficient interest for long term programs to optimize and qualify the design of composite components. Therefore, it is important to focus the study on the few critical systems that can clearly demonstrate composites cost and reliability advantages over conventional systems. Also, it is critical that an accurate definition of the performance requirements for these systems be established and an optimum design be developed before implementing any costly prototype and testing program.

The offshore industry is less tolerant of failure because of the resulting high financial and environmental risks. In order to impact the deepwater developments, composites need to be used in highly critical components such as tendons and risers where failure of these components can be very expensive. A failure of a tendon system may jeopardize a multi-billion dollar investment and a failure of a riser system may result in major spill with its environmental and safety hazards. Therefore, it is imperative that the system reliability be demonstrated to clearly show that a composite tendon or riser system is more reliable than a steel system.

CONCLUSIONS

1. The technology currently exists to effectively apply composites for several critical deepwater components such as TLP tendons and production and drilling risers.

2. In order to take full advantage of the tailoring and special properties of composites and therefore optimize the cost of composite systems, it is necessary to develop a clear definition of system functions and to avoid the temptation to use composites as substitutes for steel components and thus subject them to the same constraints.

3. The current use of composites is limited not necessarily by technical and financial barriers but rather by emotional barriers which must be clearly identified and addressed. These emotional

barriers include issues such as change of culture, lack of standards, lack of available resources, lack of long term commitment, and fear of failure.

4. Although composites provide enabling capability for deepwater development, their use will only be justified on an economic basis. Therefore, economic benefits must be clearly demonstrated. Recent studies have shown that the use of composites for tendons and risers will make it both technically and financially feasible to extrapolate the water depth of existing TLP structures to two to four times the water depth.

5. Although tendons, production and drilling risers constitute critical systems, emphasis should be directed toward the optimization of the tendon system because it offers the most potential for major saving. In comparison, the cost of a composite tendon system for 4000 ft TLP may exceed $600MM, while the cost of fifty production risers may be less than $80MM and the cost of a composite drilling riser may be around $30MM. Also, while the concept of composite risers is well established, the concept of tendons represents an area where innovations can be made. Tendons will also benefit greatly from advances in high modulus pitch based carbon fibers, high modulus aramid fibers, thermoplastic resins and innovative manufacturing methods.

6. Since offshore applications will require large quantities of composites on an infrequent basis, it is critical to develop a modular production facility to allow the rapid expansion and contraction of production capacity at minimum cost. The impact of the fluctuation in demand may be reduced if the lower cost of fibers and fabrication generates large new markets.

7. There is a need to establish a comprehensive program to develop the required data to quantify component and system reliability and to establish certification guidelines. Since financial resources are limited and no one company has the necessary skills to succeed in developing composites systems, there is a need to form alliances and consortia.

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TABLE 1
PRINCIPAL TECHNICAL DATA FOR CONOCO'S TLPS

Project Location First Production	Hutton UK, North Sea 1984	Jolliet Gulf of Mexico 1989	Heidrun Norwegian N. Sea 1995
Water Depth	150 m	536 m	350 m
Recoverable Reserves (est.)	200 MMBO	40 MMBO	750 MMBO
Design Production Rate	100 MBOPD	35 MBOPD	200 MBOPD
Number of Wells slots	32 (10 pre-drilled)	20 (all pre-drilled)	58 (9 pre-drilled)
Total weight, Incl. risers	48,500 tonnes	12,150 tonnes	258,000 tonnes
Displacement at MWL	63,300 tonnes	16,600 tonnes	288,000 tonnes
Tendon Pretension at MWL	14,800 tonnes	4,450 tonnes	30,000 tonnes
Pretension/Displacement	0.23	0.27	0.104
<u>Tendons</u>: Number Outside Diameter Thickness Min. Yield Strength	 16 260 mm 92.5 mm 120 ksi	 12 609 mm 20.6 mm 65 ksi	 16 1118 mm 38 mm 70 ksi
<u>Columns</u>: Number Diameter Column Centers	 6 17.7 m (4 corners) 14.5 m (2 centers) 78 m (length) 74 m (breadth)	 4 12.2 m 42.7 m	 4 30 m 80 m
<u>Pontoon</u>: Height Width	 10.8 m 8.0 m	 7.0 m circular	 13 m 16 m
Draft at MWL	33.2 m	24.1 m	77 m
Height, Keel to main deck	68.9 m	52.7 m	133 m (approx.)

TABLE 2
COMPARISON BETWEEN FATIGUE STRENGTH OF WELDED STEEL PIPE AND CARBON FIBER STRAND WITH POTTED TERMINATION

Component	Cyclic Stress, ksi	Life, cycles
250 tonne (560,000 lb), 54 mm (2 inch) diameter carbon fiber strand with potted termination. (extrapolation: 5 inch rope has a 3,600,000 lb strength)	Max: 125 Min: 43 Range: 82	2,000,000 + (No Failure)
X60 steel pipe, 24 inch (609 mm) O.D. and 0.8 inch (20 mm) thickness. (3,600,000 lb yield load)	Max: 32 Min: 3 Range: 29	300,000 (Failure)

TABLE 3
COST ESTIMATES FOR 4000 FT TLP TENDON IN GULF OF MEXICO (TENDON STATIC STRENGTH = 4,000,000 LB)

	Steel Pipe	P55 Carbon Composite Strand
Weight in air, lb/ft Weight in water, lb/ft	200 100	8 3
Material Cost, $/ft	300-400	500-700
Installation Cost, $/ft	1000-1500	500-1000

TABLE 4
COMPARISON BETWEEN WEIGHT AND COST OF 9 5/8 INCH STEEL AND COMPOSITE PRODUCTION RISERS

	Steel Pipe	Composite Riser
Weight in air, lb/ft Weight in water, lb/ft	42.8 37.3	12.7 6.0
Material Cost, $/ft	70 to 90	150 to 200

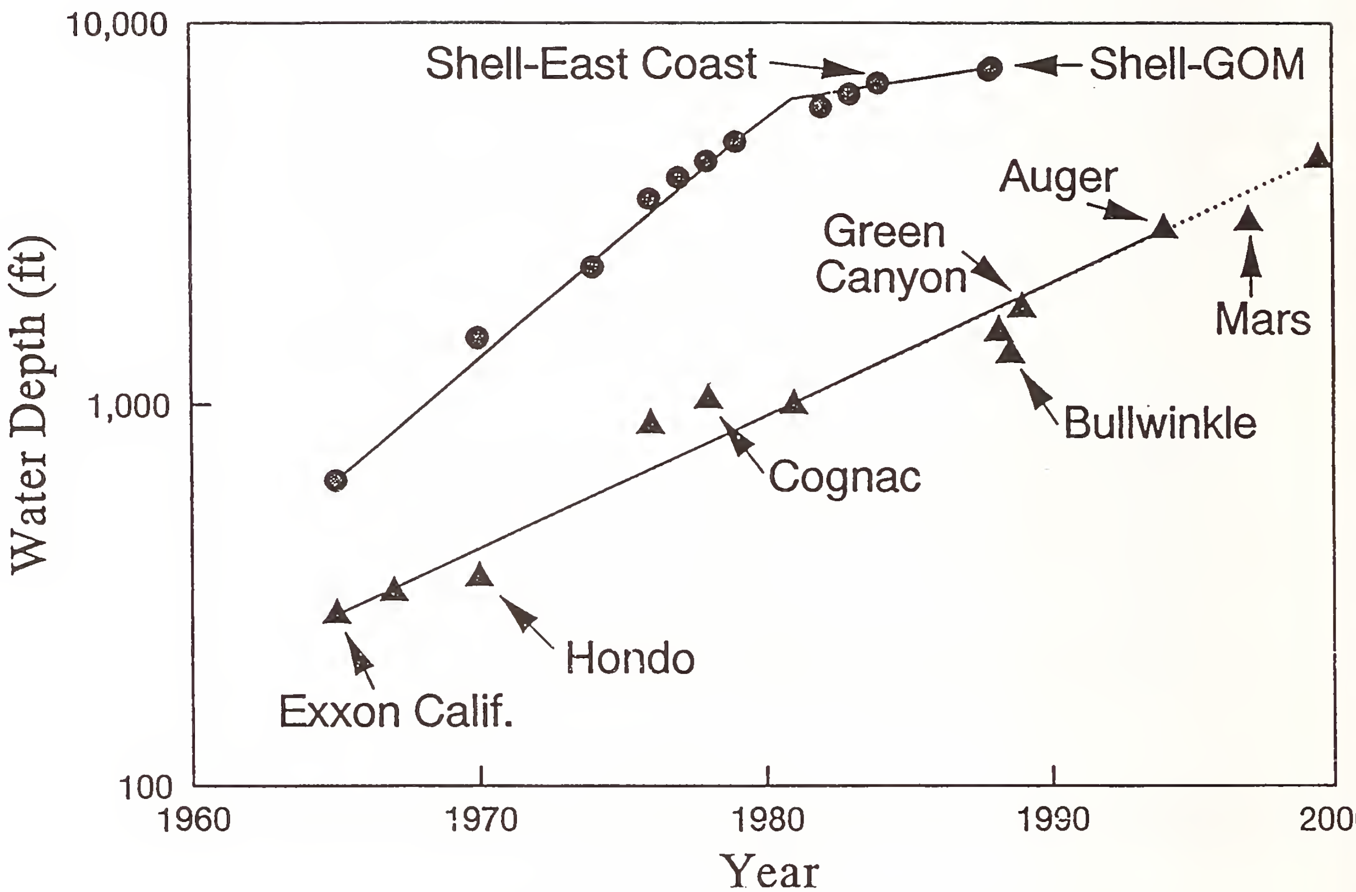

Figure 1. Historical and Project Water Depth for Exploration and Production Activities

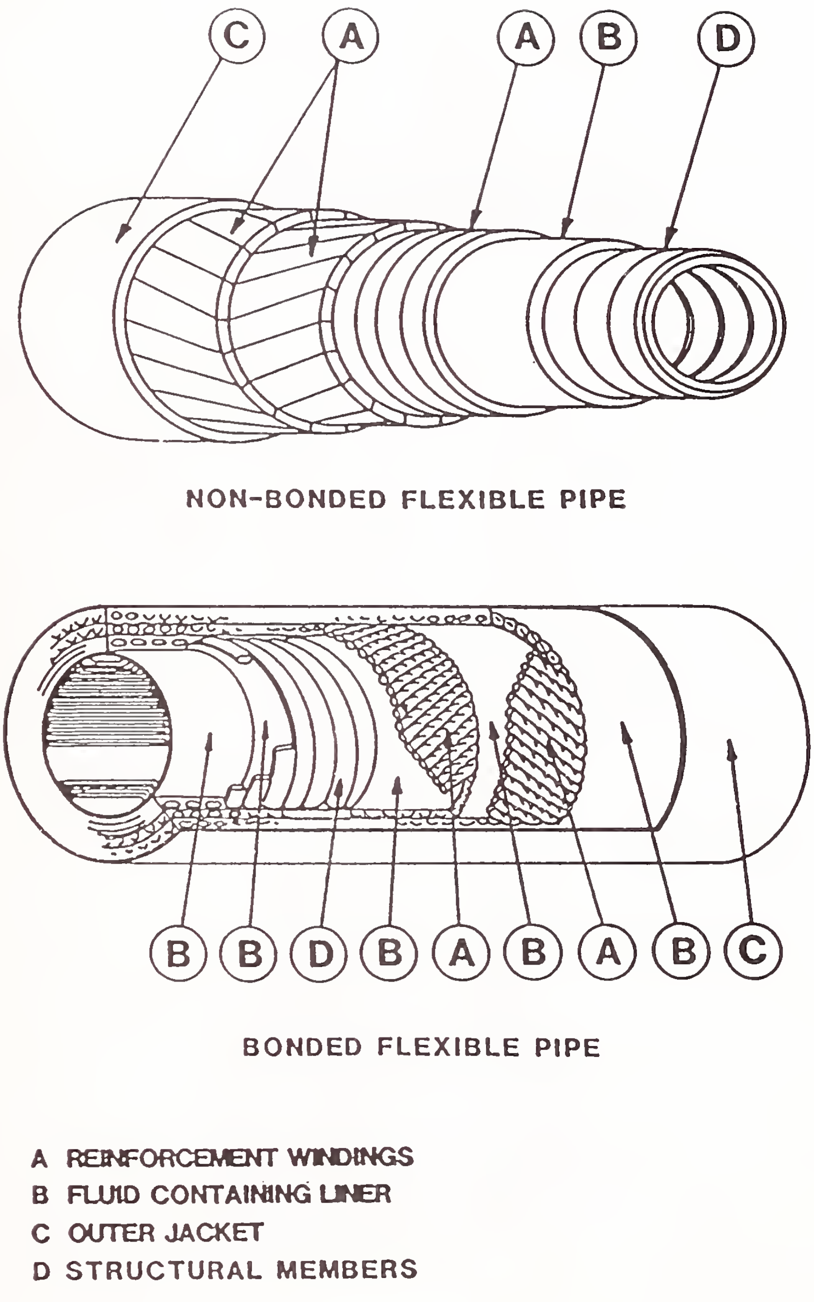

Figure 2. Construction of Flexible Risers

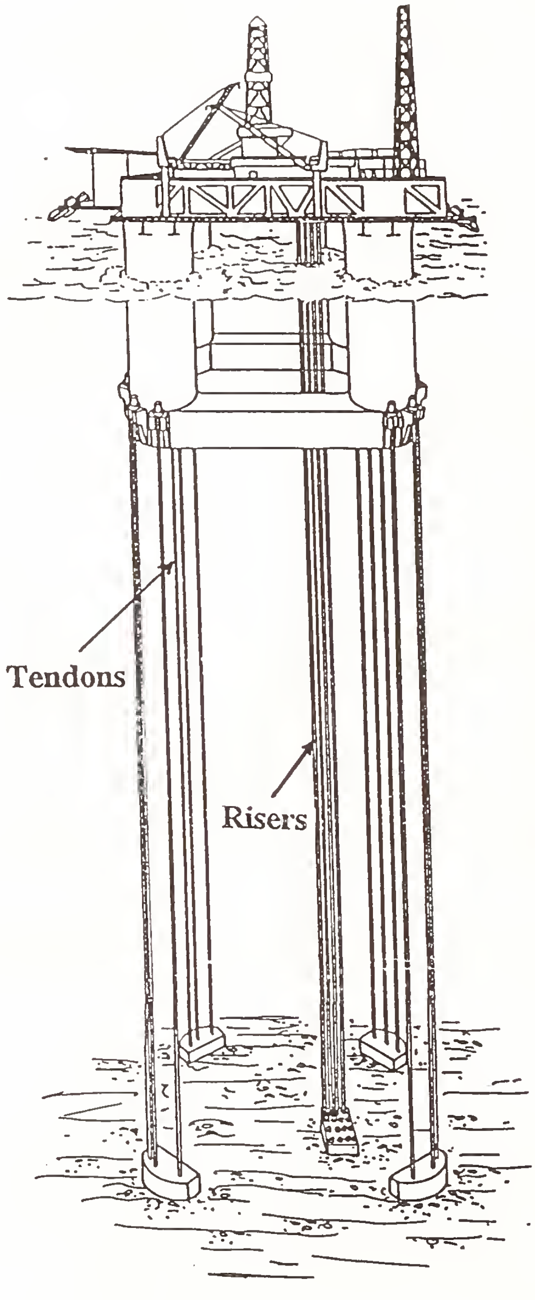

Figure 3. Some Applications for Composite Materials for TLP Components

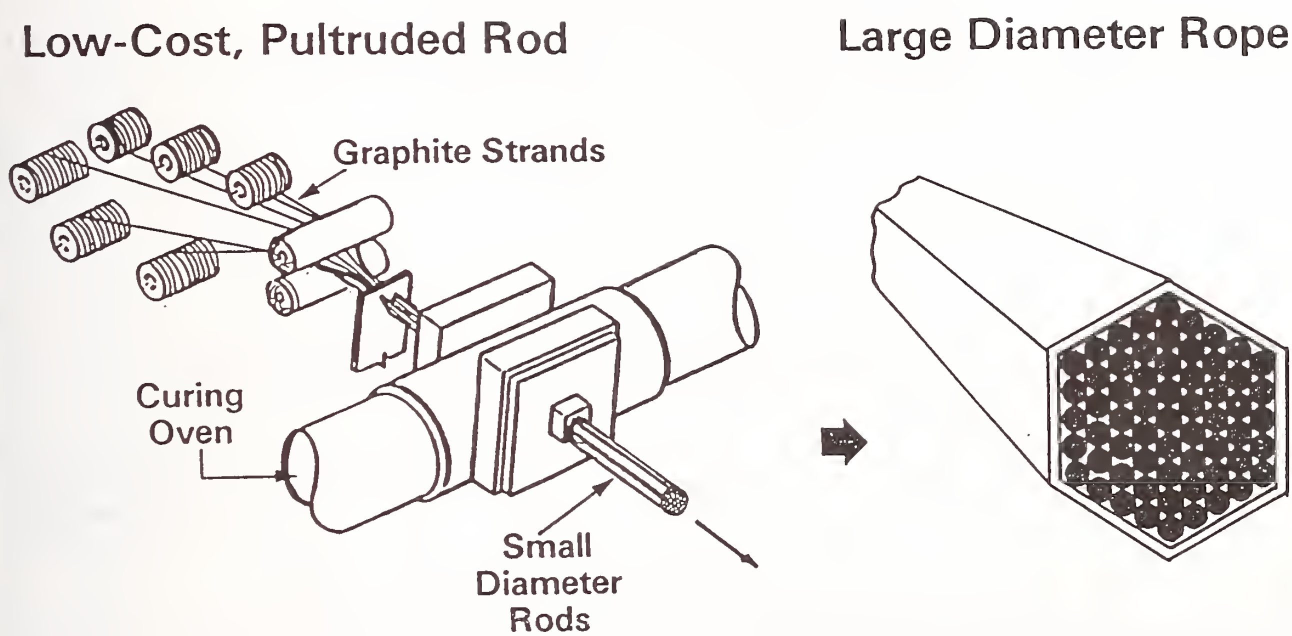

Figure 4. Proposed Composite Strand as TLP Tendon

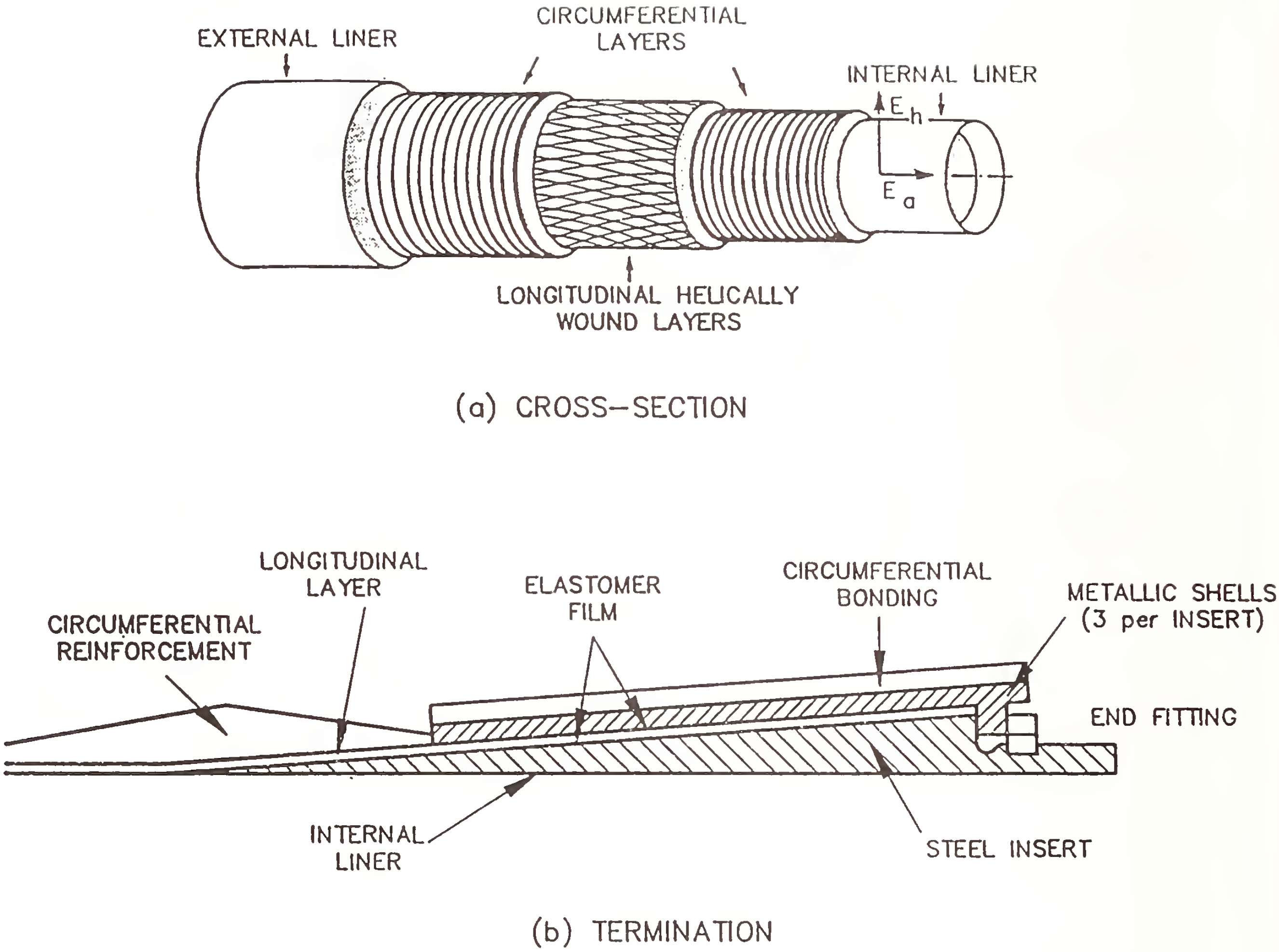

Figure 5. IFP-Aerospatiale Composite Riser Design

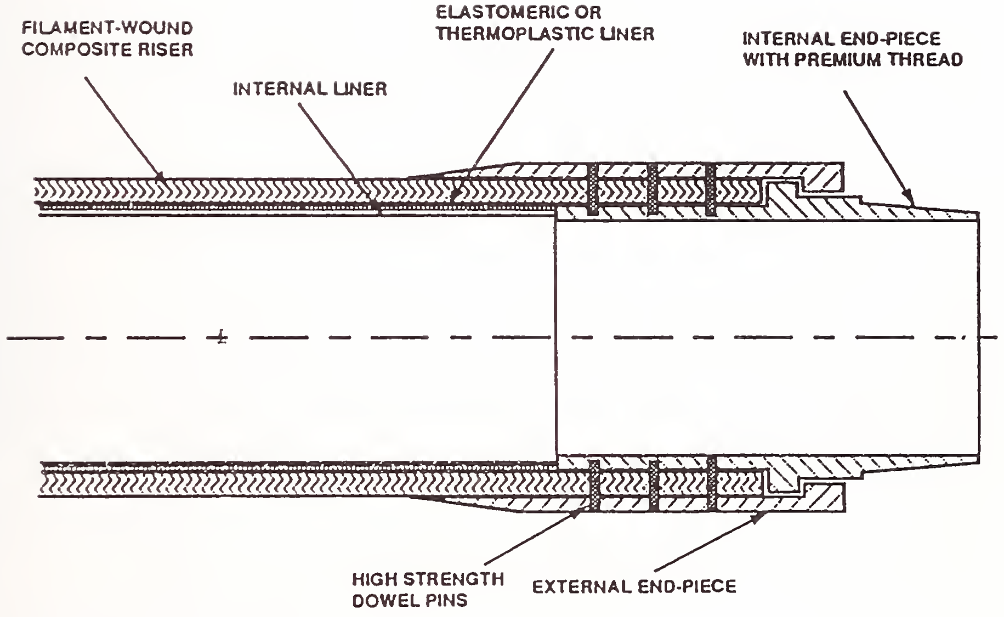

Figure 6. Brunswick Composite Riser Design

USING COMPOSITE MATERIALS TO PROTECT VULNERABLE EQUIPMENT AGAINST JET FIRES

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Introduction

When the use of fibre-reinforced plastic (FRP) composite materials on offshore facilities are discussed, concerns about fire resistance are often cited as an impediment to wider use. It is therefore perhaps a little ironic that one early use of these materials has been as passive fire protection (PFP) for vulnerable equipment.

As a result of the Piper Alpha disaster in July 1988, the catastrophic consequences of jet fires on an offshore platform were tragically realised [1]. This sharply focused attention on the need to ensure that vulnerable equipment on an offshore installation is adequately protected against jet fires.

Shell Expro, who operate in the North Sea on behalf of Shell and Esso, decided to provide, where necessary, passive fire protection to vulnerable equipment and structures. The most severe fire event to be protected against was considered to be an impinging jet fire from a high-pressure gas leak. In the absence of any recognised test for jet fire resistance, a series of full-scale demonstrations has been carried out to provide assurance that candidate PFP systems would provide protection in the event of a jet fire [2].

Two primary examples of such protection using FRP composite materials are enclosures for topsides emergency shutdown valves (ESVs) and protective systems applied to tubular elements (jacket members or risers). This short paper describes jet fire demonstrations carried out on these two systems and the findings that led to their installation offshore. Other candidate systems were also tested and these, together with the supporting research, are described in reference 2.

Jet fire demonstrations

The jet fire used in these demonstrations represents only one realistic event, but its selection was underpinned by extensive research into the nature of jet fires.

The flame, an ignited 3 kg/s, 60 bar release of natural gas, engulfed the specimen. Figure 1 is a photograph taken during one of the tests. The discharge orifice, a 20 mm hole, can be seen to the left of the picture, 9 m away from the specimen.

The required test duration was two hours; owing to a limited gas supply, the mass flow rate had to be reduced to 2 kg/s after the first hour.

ESV enclosures

To comply with regulatory requirements [3], topsides ESVs have been installed on all of Shell Expro's oil and gas risers in the North Sea. An additional requirement is that the ESV and its actuator shall, so far as is reasonably practicable, be protected from damage arising from fire, explosion and impact.

Figure not available at press time

FIG. 1 - A jet fire demonstration in progress

Figure not available at press time

FIG. 2 - The FRP composite emergency shutdown valve enclosure

Fire protection was to be provided by enclosures and one candidate system, Figure 2, was fabricated from FRP composite sandwich panels retained around the ESV by inner and outer steel frames.

The enclosure tested contained an 18-inch ball valve and was mounted horizontally between two, epoxy intumescent coated, pipe spools. A dummy actuator was also fitted to the valve and in this test it was protected by a metal foil insulation system. The basic specimen configuration and its orientation to the jet flame is shown in Figure 3. Thermocouples were attached to the valve, the actuator, the inside of the enclosure and the inside of the pipe spools to monitor temperatures.

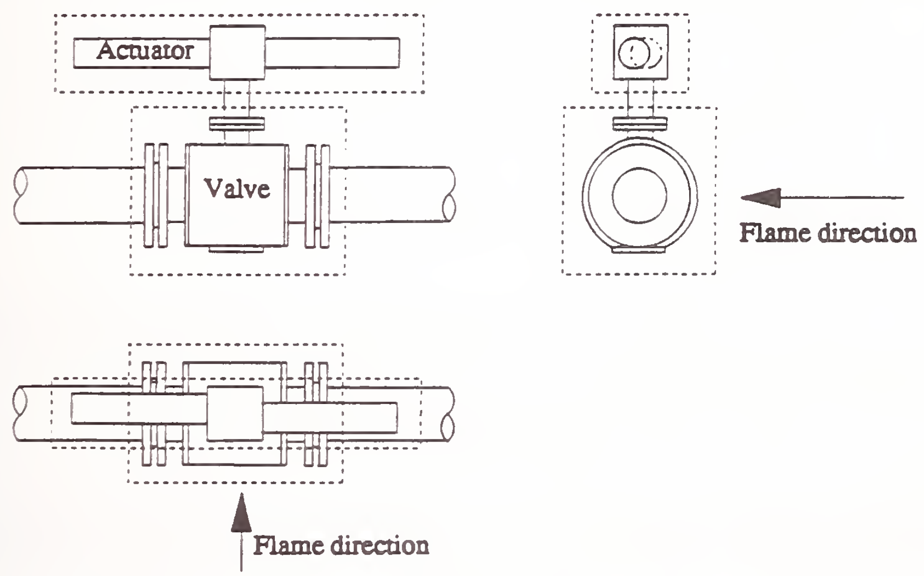

FIG. 3 - Configuration of the valve enclosure used in the jet fire demonstrations

For these two-hour demonstrations, a maximum temperature limit of 300°C was set for the valve. This was based on maintaining the integrity of the particular valves chosen. A different limit might be required for other designs or operating conditions.

In practice, the valve actuator must be capable of closing the valve within the first 15 minutes of a fire. Having closed the valve, the actuator is no longer a critical component, although it may provide a heat path into the valve body. For the demonstrations, a maximum temperature for the actuator of 100°C was the only limit set. This was based on the operating limit of the actuators used by Shell Expro and a different limit might be required for other designs.

Figure 4 shows the temperature record at selected points on the valve and actuator. After two hours' exposure to a jet fire, the maximum temperature of the valve remained below the 300°C target value, commensurate with safe functioning of the ESV.

In comparison, another enclosure tested, comprising insulation encapsulated in stainless steel, did not provide the required thermal protection to the valve.

FRP panel enclosures have now been installed offshore by Shell Expro.

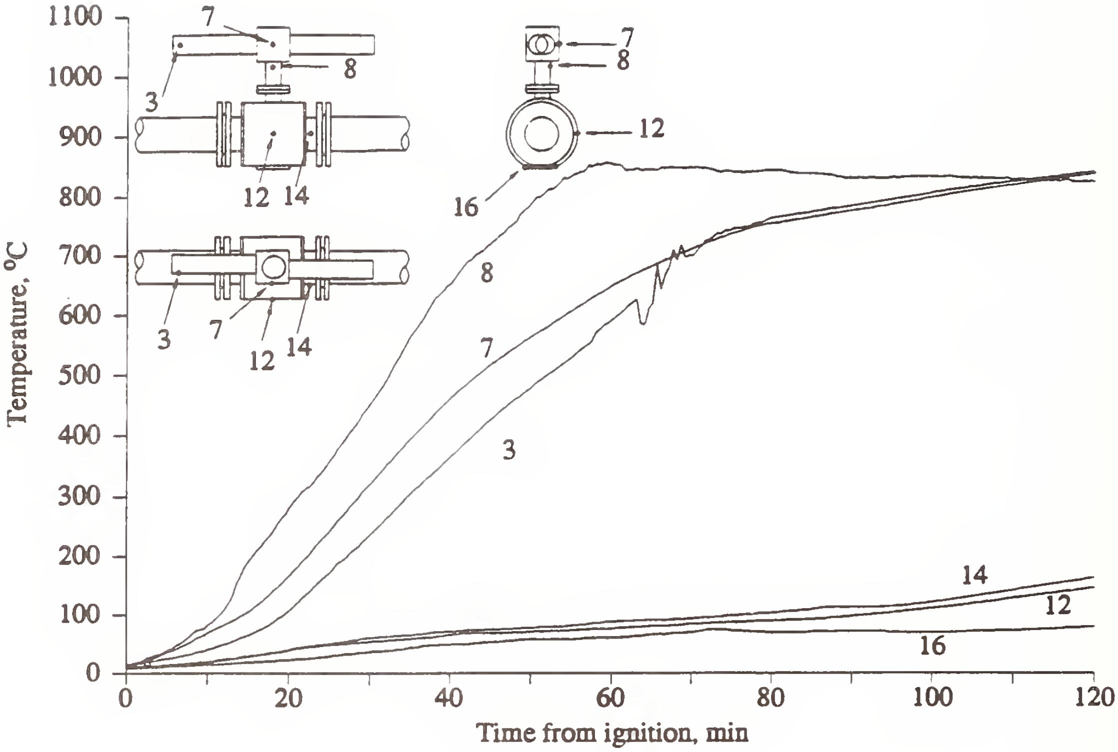

FIG. 4 - The temperature response of the valve in the FRP enclosure and the actuator in the all-metal enclosure

Tubular protection

Tubular elements in the splash zone (jacket members or risers) present a particularly challenging environment for passive fire protection. For this demonstration, the protection system was required to limit the temperature of a jacket tubular member to 400°C in the event of a two-hour jet fire engulfment. In addition the system had to have a proven anti-corrosion protection performance.

The test specimen selected for the jet fire demonstration was a steel tubular, 9 m long and 1.1 m outside diameter, with a wall thickness of 35 mm. A 50 mm thick FRP coating was filament-wound onto part of the tubular. The same thickness of FRP with hand-applied woven rovings was applied manually at a field joint and the remainder of the specimen was protected with an epoxy intumescent coating that was to be used above the splash zone. Figure 5 shows the specimen before testing.

In the two-hour test the maximum temperature recorded on the steel under the factory-applied coating was 223°C and under the field joint 197°C.

FRP tubular protection of the type tested has been installed offshore on some oil and gas risers, for which 70 mm thick FRP was needed to limit the temperature of the riser to 200°C during a two-hour fire engulfment scenario.

Figure not available at press time

FIG. 5 - The FRP protected tubular test specimen

Summary

Recent work has demonstrated that FRP composite materials can be used to passively protect vulnerable equipment against jet fires. Full-scale, two-hour jet fire tests have been conducted successfully on two FRP systems, one to protect emergency shutdown valves and the other to protect tubulars. FRP valve enclosures and riser protection systems have now been installed, where necessary, on offshore facilities in the North Sea.

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[2] L.C. Shirvill, "Performance of Passive Fire Protection in Jet Fires", Paper presented at 'Major Hazards Onshore and Offshore', UMIST, Manchester, 20th-22nd October 1992 and published in I.Chem.E. Symposium Series No.130.

[3] Statutory Instrument 1029, The Offshore Installation (Emergency Pipeline Valve) Regulations, 1989.

Acknowledgement

The author wishes to acknowledge the contribution of his colleagues in Shell Research and Shell Expro to this work, and in particular John Bennett, Dick Wade and Ross Connell.

A Course of Action for Introducing Composites into Offshore Operations

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As the petroleum industry has moved into deeper and deeper water for the recovery of oil and gas, weight-sensitive floating platforms have replaced stationary, bottom-founded structures. The cost penalty for weight or vertical tension supported by floaters such as tension leg platforms (TLPs) is in the range of $5-10/lb. Hence, there is considerable incentive to reduce the weight of equipment or structural members on these platforms and downward forces exerted on these platforms by production and export risers, and mooring lines. Thus, there are numerous opportunities for utilizing light-weight, high-strength composites.

The high strength-to-weight ratio, low corrosivity, and other excellent performance characteristics of composites have long been recognized by offshore petroleum operators but high initial costs have prevented widespread utilization of composites. Recent factors such as reduced market pressures from the defense industry have resulted in reduced costs for composites to the extent that a re-examination of composites for offshore utilization is warranted.

The following figures present a general course of action for introducing composites into offshore operations. It must be emphasized strongly that any such plan must clearly demonstrate both technical feasibility and cost-effectiveness of any specific application. Remarks pertinent to particular applications, e.g., composite production risers, are also provided.

The basic objective of this course of action and critical steps of the approach being proposed are given in Figure 1. It is important and encouraging to note that different potential applications have differing levels of "maturity." Topsides' applications such as low-pressure piping, storage vessels, grating, etc. are commercially available and utilization will depend primarily upon educating potential users of such products of their existence, merits and cost-effectiveness. Other potential products such as continuous, spoolable tethers (or tendons) for vertically mooring TLPs are attractive albeit unproven concepts.

Following the identification of a specific application, it is recommended that each step of the proposed approach be addressed, more or less in the order presented. Once a given step has been accomplished satisfactorily, the next step can be taken. If a satisfactory resolution cannot be reached, it is probably appropriate to focus on a different application. As an example, the offshore industry has felt very comfortable with the technical feasibility of composite production risers due to the efforts of IFP and Aerospatiale, but progress has halted due to doubts regarding the cost-effectiveness of this product.

Ultimately, product development will probably have to rely upon the collaborative effort of multiple end-users and composite manufacturers in order to share development costs. An alternative might be the development of a product for a specific project due to perceived cost savings or technically enabling performance.

Figure 2 addresses relatively mature composite products for topsides' applications. These include low-pressure piping, fire-water systems, storage tanks, grating and blast walls. It has been observed that North Sea operators have been much more progressive in seeking applications for composites than have Gulf of Mexico operators. Their current practices would thus be a good place to begin the identification of possible topsides' applications. Discussions with existing composites' manufacturers, e.g., Morrison Molded Fiber Glass, would also be worthwhile.

Composite production risers are the topic of Figures 3, 4 and 5. These are critical elements of a floating production platform such as a TLP. As mentioned previously, it is believed that their technical feasibility has been amply demonstrated by IFP and Aerospatiale through the auspices of multiple joint industry programs. It is further believed that cost minimization and riser "qualification" through a statistically meaningful test program are yet to be accomplished. Brunswick Composites has shown considerable interest in the development of a cost-effective, reliable product and has proposed a joint-industry program to accomplish this development.

Figure 4 summarizes the status of composite production riser development while Figure 5 addresses breakeven costs for a composite riser. A number of assumptions were made in developing the cost curves of Figure 5. First of all, it was assumed that only 90-percent of the steel riser would be replaced with composites. In particular, the ends of the riser where significant bending might occur would be avoided — this simplifies the performance requirements for the composite riser. Furthermore, the riser "cost" used here is the cost of a nominal 9⅝-inch riser tubular <u>exclusive</u> of mechanical threaded connectors but <u>including</u> the materials and labor for attaching the composite tubular to the metal end pieces. The riser tubulars were assumed to be 75 feet in length. The curves basically reflect the tradeoff of increased riser costs with reduced payload (riser-tension) costs. With regard to the latter, a multi-tube riser having an outer composite riser tubular has about one-half the submerged weight as an all-steel riser. The abscissa for these cost curves is the product of the Riser Tension Factor and the Payload Penalty. The top tension of the riser (supported by the platform deck) is the product of the Riser Tension Factor and the submerged weight of the riser. The Riser Tension Factor is typically around 1.2 - 1.4.

Payload Penalty is the cost per pound ($/lb) of <u>incremental</u> deck payload; payload could be the weight of physical equipment or, in this case, the force required to support a production riser. Payload Penalty is a function of floater type and to some extent, of the offshore operator/designer. For TLPs, current Payload Penalties are believed to be in the $5-10/lb range.

For a Riser Tension Factor of 1.2 and a Payload Penalty of $5/lb, the composite-riser break-even cost is estimated to be $250/ft as indicated by the lower solid curve. If, in fact, the riser could be produced for $150/ft, a savings of $270,000 per riser could be realized under the above assumptions. If 20 risers were required, the total system savings would amount to $5.4MM. The other dotted and dashed curves correspond to additional savings associated with the riser tensioner and the threaded metal connectors used to couple the finite-length (75-ft) riser tubulars. Possible individual tensioner savings of $100M and $200M have been assumed. Also, savings of $1M per riser-connector pair (pin and box) have been assumed. The "allowable" or break-even cost increases or, more importantly, potential system savings result. It should be possible to simplify the tensioner since the load (tension) that it must support will be halved. Furthermore, the composite tubular can be designed to be more axially compliant than the steel riser it replaces and, hence, may not even need a tensioner. The inner steel tubulars, including the production tubing, typically have higher tensile strengths than the riser tubular and, hence, can tolerate higher strains. The tensioner can thus be simplified in view of reduced performance requirements, e.g., stroke. Similarly, since the mean and dynamic tensions in the composite-riser connectors will be much smaller than those experienced in a steel riser, the connectors can be simplified and their price reduced.

For the case of 20 production risers, a composite-riser cost of $150/ft, tensioner savings of $200M/tensioner and connector savings of $1M/pair, system savings of $10.8MM are indicated for a Tension-Factor/Payload-Penalty product of $6/lb. This is viewed as being a realistic scenario.

Production risers terminate at the seafloor at fixed (built-in) wellheads. For all practical purposes, the wellheads do not translate or rotate. Hence, large bending moments can develop. Tapered riser sections called stress joints are commonly introduced above the wellhead to facilitate the bending moment and curvature transition of the riser. Typical performance requirements for stress joints are that the moment exerted by the riser on the wellhead not exceed some design value and that the curvature within the stress joint not exceed some other design value. Since composites are "engineered" materials, it seems logical that they could be utilized for this purpose. Once again, cost effectiveness becomes a very important issue. Competition with steel is a real challenge but some applications require costly titanium when steel will not work. In this situation, demonstrating cost effectiveness should be less of a challenge. Figure 6 focuses on composite production-riser stress joints. An analogous opportunity exists for drilling-riser stress joints.

Figure 7 identifies TLP tendons (or tethers) as a logical application for composites. These are the vertical members, typically steel tubulars, that moor the floating TLP hull. They provide horizontal station-keeping by virtue of their top tensions and, more importantly, serve to virtually eliminate wave-induced heave of the floater. Heave suppression is important for the integrity of the production risers. TLP tendons must be designed to withstand large storm-induced tensions, and wave-induced cyclic-fatigue damage occurring over a period of around 30 years. Evacuated tubular tendons must also be designed to withstand hydrostatic collapse pressures.

It is widely recognized that carbon-fiber composites have tensile strengths (per unit area) which are much higher than steel and have excellent fatigue characteristics. Furthermore, they are light and can probably be used as solid cross-sections thus obviating collapse problems. Recent discussions with Hydril/MMFG, and Bell Helicopter/Neptco indicate that it may be possible to produce continuous, spoolable tendons by the pultrusion process. This would eliminate the need for costly intermediate mechanical connectors used to assemble tendons longer than about 1800 feet (the limit for neutrally buoyant tubulars) and otherwise expedite time-consuming tendon installation.

Past experience indicates that composite tendons having the same axial stiffness as the steel tendons they are designed to replace have about 10-times the required tensile strength. A design compromise suggests itself. Tendon stiffness influences the heave, roll and pitch periods of a TLP and, thus, will impact dynamic loading and fatigue damage of the tendons. TLP designers do not have natural-period design requirements per se; system reliability is the issue. Hence, by reducing composite-tendon stiffness, material costs are reduced at the expense of increasing vertical response periods. As long as sufficient tensile strength and fatigue life exist, this cost reduction approach may be acceptable. At some point, motion considerations may become a limiting factor. In any event, this potential application merits additional investigation.

In the above discussion, composites have been synonymous with fiber-reinforced plastics. Figure 8 focuses on a different type of composite, namely steel-clad concrete. TLP hulls are presently being constructed using all steel, or concrete internally reinforced with steel rods. Others have suggested that cost savings could result from steel-concrete-steel sandwich construction. This seems totally within the spirit of composites design. Others have even suggested that fiber-reinforced plastics could even be considered for this enormous-volume application. It is only offered here to stimulate thinking.

A partial list of currently or recently active composite developers and manufacturers is given in Figure 9. For each such organization, composite products being developed or considered are also indicated. Most of these composite products have considerable potential for application in offshore operations.

Finally, as shown in Figure 10, it should be emphasized that in the view of the author, most, if not all, of the above-mentioned composite products are not absolutely needed for operations in current waterdepths of interest, i.e., 2000-4000 ft. As such, they are not truly "technically enabling" at the present time. They do, however, offers some cost-savings' potential and thus may be viewed as being "economically enabling."

For greater depths, it is highly likely that composites will be technically enabling due to needs for weight reduction for long risers and mooring elements and in order to contend with accelerated fatigue damage.

It appears highly desirable to pursue cost-savings' applications in a relaxed atmosphere where they are not absolutely needed so that they will be available in the future when they may be technically enabling.

COMPOSITES FOR OFFSHORE

Objective

Establish technology and cost bases for recommending composite systems for offshore applications. Platform topsides offer low-risk, modest-savings application. Production risers offer high-risk, large-savings application.

Approach

Identify potential application.

Establish technical feasibility.

Estimate possible cost savings.

Determine acceptability to operations.

Determine qualification procedures.

Encourage formation of JIP for prototype development.

Encourage commercialization.

JF311102

FIGURE 1

TLP TOPSIDES

Objective

Provide information on the performance of composite equipment and components to help facilitate their cost-effective and safe use on offshore platforms.

Areas of Composite Performance

Damage tolerance

Performance in fires

Economic considerations

Work Product

Each of the stated performance areas will be surveyed and a topical report will be prepared to assist in the application of composites on platforms.

JF311107

FIGURE 2

TLP PRODUCTION RISERS

Objective

Estimate cost impact for TLP systems. Assess redesign of IFP-Aerospatiale-Coflexip-Brunswick production riser. Quantify strain limitations (> 0.2% desirable). Develop a qualification test program. Recommend JIP.

Performance Criteria

Maintain large steady axial load.

Withstand large dynamic axial strain without exceeding allowable stress levels.

Withstand internal burst pressure without leaking.

Withstand collapse pressures.

Withstand high-cycle fatigue.

Leads

Collaborative (IFP/A/C/B) redesign.

Brunswick Composites design for Shell.

JF311101

FIGURE 3

COMPOSITE RISER DEVELOPMENT

- Composites being considered because system savings are possible.
- Composites not presently viewed as enabling technology but may become so.
- Composites have excellent track record for demanding structural applications.
- Feasibility of composite risers has been demonstrated (IFP/Aerospatiale).
- Performance results encouraging; cost minimization and "qualification" needed.

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FIGURE 4

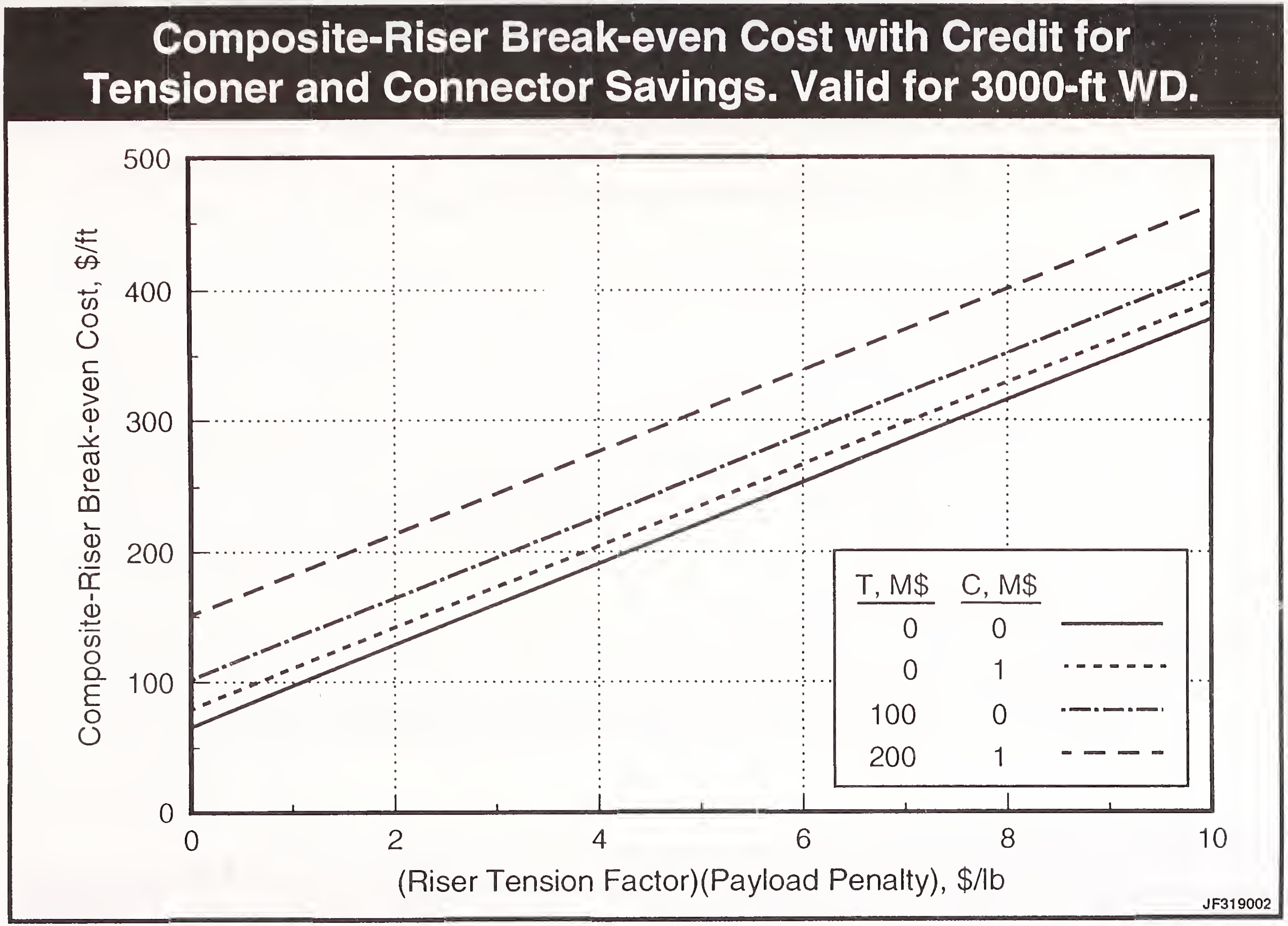
Composite-Riser Break-even Cost with Credit for Tensioner and Connector Savings. Valid for 3000-ft WD.
Composite-Riser Break-even Cost, $/ft
0
100
200
300
400
500
0
2
4
6
8
10
(Riser Tension Factor)(Payload Penalty), $/lb
T, M$
C, M$
0 0
0 1
100 0
200 1
JF319002

FIGURE 5

TLP PRODUCTION RISER STRESS JOINTS

Objective

Develop/refine cost to produce. Identify cost savings associated with moment reduction (wellhead, hull, deck). Assess design of IFP composite stress joint. Examine advantages of hybrid steel-composite stress joint. Develop a qualification test program. Recommend JIP.

Performance Criteria

Maintain large steady axial load.

Withstand large dynamic tensile, shear and bending loads.

Withstand internal burst pressure without leaking.

Withstand collapse pressures.

Withstand high-cycle fatigue.

Leads

IFP production-riser development. IFP proposal for JIP.

AEA Petroleum Services proposal for JIP.

Brunswick Composites expertise.

JF311105

FIGURE 6

TLP TENDONS

Objective

Estimate cost impact for TLP system. Identify the composite construction (including end fittings and intermediate connectors) for TLP tendons that minimizes the installed TLP-system cost. Develop a qualification test program. Recommend JIP.

Performance Criteria

Withstand large axial tension, steady and dynamic.

Withstand high-cycle fatigue.

Withstand collapse pressures (tubes).

Leads

Brunswick Composites study (discrete, filament-wound tubes)

Fluor Daniel (discrete/continuous pultruded tubes)

Robin Webb (continuous pultruded tubes)

Hydril/MMFG (bundled, continuous pultruded rods)

Bell Helicopter/Neptco (bundled, continuous pultruded rods)

JF311106

FIGURE 7

TLP HULL SANDWICH CONSTRUCTION

Objective

Evaluate merits of steel-concrete-steel construction for TLP hulls versus all steel or reinforced concrete. Estimate cost impact for TLP system. Develop a qualification test program. Recommend JIP.

Performance Criteria

Withstand collapse pressures.

Withstand direct wave loading.

Withstand pitch-induced "racking" loads and wave induced "prying" loads.

Leads

British Steel paper at OTC

Ben Gerwick @ UC Berkeley

JF311108

FIGURE 8

COMPOSITE DEVELOPMENTS

- IFP/Aerospatiale
  - Production Riser (JIP)
  - Stress Joint (JIP)
- Brunswick
  - Production Riser (JIP)
  - Export Riser Flex-Joint (Shell)
  - Drill Pipe (Amoco, Pool)
  - Sucker Rod (commercial)
- AEA Petroleum Services (Harwell)
  - Hybrid Stress Joint (JIP)
  - Drill Pipe (JIP)
- Hydril Consortium
  - Coiled Tubing (JIP)
  - Production Riser
  - Hybrid High-Pressure Drilling Riser
  - Hybrid Stress Joint
  - Pultruded Ribbon/Rods (tendon)
- Bell/Neptco
  - Bundled Pultruded Rods (tendon)

JF303601

FIGURE 9

COMPOSITES AS ENABLING TECHNOLOGY

- For current deepwater depths of interest, i.e., 2000-4000 ft, composites have the potential to be economically enabling.
  - May allow marginal fields to be developed.
  - May expedite field development subject to capital constraints.
- For greater depths, composites may be technically enabling as well.
  - May overcome fatigue problems of long steel elements.

JF311103

FIGURE 10

FLAMMABILITY AND FIRE SAFETY OF COMPOSITE MATERIALS

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INTRODUCTION

Studies have shown that demands to reduce weight and improve specific structural characteristics of Naval ships and Submarines can often be met through the use of organic matrix based composite structures. During the past five to ten years, there has been "a resurgence of interest" in the development and application of composites to both primary and secondary load-bearing structures as well as machinery components in Naval ships and submarines. This new interest in composite materials is due to increased need for a corrosion free, light weight, and affordable low cost alternative to metallic components. A significant technical issue which has limited composite use on board Naval ships and submarines is the combustible nature, and hence the fire, smoke and toxicity of organic matrix based composite materials.

The use of composites inside Naval submarines is now covered by MIL-STD-2031 (SH), Fire and Toxicity Test Methods and Qualification Procedure for Composite Material Systems Used in Hull, Machinery, and Structural Applications. This military standard contains test methods and requirements for flammability characteristics such as flame spread index, specific optical density, heat release and ignitability, oxygen-temperature index, combustion gas generation, long term outgassing, etc. Two guiding criteria (1) were established for the use of composite systems aboard Navy vessels. The composite system will not be the fire source, i.e., it will be sufficiently fire resistant not to be a source of spontaneous combustion. Also secondary ignition of the composite system will be delayed until the crew can respond to the primary fire source, i.e., the composite system will not result in rapid spreading of the fire. An abridged version of MIL-STD-2031 is shown in Table 1. The Navy currently has no specific standard for surface ships. The flammability requirements for surface ships are different than submarines. Instead of survivability measured in minutes, as it is in submarine fires, the critical issue in surface ship fires is the residual strength of structures at elevated temperatures for a period of 30-60 minutes.

CDNSWC, Annapolis Detachment (formerly known as DTRC), has been evaluating the fire performance of commercially available composite materials for past several years under the Materials Block Program. This program also included work on thermal/fire barriers to protect the composite structures against fire damage. In 1991, this program was expanded to address the residual load bearing strength or the structural degradation of composite materials during fire.

Results from this work have been discussed in several papers (2,3,4,5,6). This paper summarizes material flammability work performed under the Materials Block Program. This includes small scale flammability characteristics of conventional and advanced glass or graphite reinforced organic matrix based thermoset and thermoplastic composite materials suitable for surface ship and submarine applications. The composite materials evaluated included vinyl ester, epoxies, cyanate esters, bismaleimides, phenolics, polyimides, polyphenylene sulfide, polyether sulfone, polyaryl sulfone, polyether ether ketone (PEEK), and polyether ketone ketone (PEKK). This work further included the use of integral, hybrid thermal barriers to protect the core of the composite structures. Thermal barrier treatments evaluated in this study included Ceramic coating, Intumescent coating, Silicone foam, Phenolic skin or chopped fiber reinforced sprayable phenolic, APM (Ablative Protective Material), Interam^R endothermic mat E-10A[1], and Interam^R intumescent mat I-10A[1]. This work further include evaluation of residual flexural strength retained (%RSR) after exposure to 25 kW/m^2 for a duration of 20 minutes (ASTM E-662) for selected composite materials. A methodology is also presented for the assessment of residual strength of composite materials during fire exposure by inter-relationship of mechanical property, temperature, thickness, and time.

FIRE-PERFORMANCE OF COMPOSITE LAMINATES:

The fire performance of composite materials are those characteristics which describe the response of polymeric materials when exposed to fire. These include flame spread (fire propagation), smoke evolution (visibility), combustion gas generation (toxicity), fire endurance (residual strength after fire exposure), heat release, ignitability, and ease of extinguishment (oxygen index).

The thermoset materials we have evaluated included fire retardant vinyl ester (VE), epoxies (EP), cyanate esters (CE), bismaleimides (BMI), phenolics (PH), and polyimides (PI). Thermoplastic materials we have evaluated included polyphenylene sulfide (PPS), polyether sulfone (PES), polyaryl sulfone (PAS), polyether ether ketone (PEEK), polyether ketone ketone (PEKK), and thermoplastic nylon J-2. The flammability characteristics evaluated in this study included flame spread index (ASTM E-162), specific optical density of smoke (ASTM E-662), combustion gas generation, residual flexural strength (ASTM D-790), heat release and ignitability as measured by cone calorimeter (ASTM E-1354). Table 2 shows the comparison of selected glass or graphite reinforced composite materials.

As shown in Table 2, with the exception of vinyl ester, all glass or graphite reinforced composite materials met the requirements of flame spread index (maximum 20). Also, with the exception of fire-retardant vinyl ester and thermoplastic J-2, all glass or graphite reinforced composite systems met the requirements of specific optical density at 300 seconds (maximum 100) and maximum smoke density of 200 as per MIL-STD-2031.

Combustion gas generation is defined as the gases evolved from materials during the process of combustion. The most common of gases evolved during combustion are carbon monoxide and carbon dioxide, along with evolution of HCL, HCN and others depending upon the chemistry of matrix resin of a given composite material. The Committee on Fire Toxicology of the National Academy of Science has concluded that as a basis for judging or regulating materials performance in a fire, combustion product toxicity data must be used only within the context of fire hazard assessment. The committee believes that required smoke toxicity is currently best obtained with animal exposure methods for purposes of predicting the fire hazard of different materials.

Heat release may be defined as the heat generated in a fire due to various chemical reactions occurring within a given weight or volume of material, the major contributors being those reactions where CO and CO_2 are generated and oxygen is consumed (7). This characteristic provides a relative fire hazard assessment for materials in that the material with low heat release per unit weight or volume will do less damage to the surroundings than the material with high release rate. The rate of heat release, especially the peak, is the primary characteristic determining the size, growth, and suppression

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[1]: This is a proprietary material (3M Co.). Evaluation or reporting of this material does not constitute an endorsement by U.S.Government.

requirements of a fire environment. MIL-STD 2031 requirements of peak heat release at 75 and 100 kW/m^2 are 100 and 150 kW/m^2 respectively. Glass or graphite reinforced phenolic, polyimides, and many of the thermoplastics composites met this requirement. This is shown in Figure 1.

Table 1: MIL-STD-2031(SH) Fire Performance Acceptance Criteria.

Fire Test/Characteristic	Requirement	Test Method
Oxygen-Temperature Index (%) % oxygen at 25°C % oxygen at 75°C % oxygen at 300°C	<u>Minimum</u> 35 30 21	ASTM D-2863 (Modified)
Flame Spread Index	<u>Maximum</u> 20	ASTM E-162
Ignitability (sec) 100 kW/m^2 irradiance 75 kW/m^2 irradiance 50 kW/m^2 irradiance 25 kW/m^2 irradiance	<u>Minimum</u> 60 90 150 300	ASTM E-1354
Heat Release (Kw/m^2) 100 kW/m^2 irradiance, Peak Average for 300 sec 75 kW/m^2 irradiance, Peak Average for 300 sec 50 kW/m^2 irradiance, Peak Average for 300 sec 25 kW/m^2 irradiance, Peak Average for 300 sec	<u>Maximum</u> 150 120 100 100 65 50 50 50	ASTM E-1354
Smoke Obscuration Ds during 300 secs Dmax	<u>Maximum</u> 100 200	ASTM E-662
Combustion Gas Generation (25 kW/m^2)	CO = 200 ppm CO_2= 4%v HCN= 30 ppm HCL= 100 ppm	ASTM E-1354
N-Gas Model Smoke Toxicity Screening Test	No deaths Pass	Modified NBSTTM
Quarter-Scale Fire Test	No flashover in 10 minutes	NSWC Quarter-scale test
Burn-Through Fire Test	No burn-through in 30 minutes.	Burn-through Fire Test (NSWC)

Ignitability has been defined as the ease of ignition. In general, ignition may also be looked upon as the resistance of the polymeric material to participate in the fire scenario. MIL-STD-2031(SH) requires the ignitability of organic matrix based composites to be 60 and 90 seconds at radiant heat fluxes

Table 2: Comparison of flammability data for various Thermoset and Thermoplastics Composites.

Composite	FSI ASTM E-162	Smoke density ASTM E-662		Gas Generation ppm %v ppm ppm				Ignitability, Secs ASTM E-1354				Peak Heat Release ASTM E-1354 kW/m^2				Average Heat Release, 300s, ASTM E-1354. kW/m^2				Extinction Area, ASTM E-1354, m^2/kg				Total Heat Release, ASTM E-1354, MJ/m^2				Oxygen Index ASTM D-2863		Res. Flex. str.
		Ds(300s)	Dmax	CO	CO_2	HCN	HCL	25	50	75	100	25	50	75	100	25	50	75	100	25	50	75	100	25	50	75	100	25°C	75°C	%
Gl/VE	27	463	576	230	0.3	ND	ND	203	61	34	21	188	199	300	256	118	122	147	139	827	1107	1316	1173	36	40	47	43	31		14
Gl/EP	11	56	165	283	1.5	5	ND	535	105	60	40	39	178	217	232	30	98	93	93	470	580	728	541	10	30	28	24	49	48	5
Gr/EP	11	75	191	115	0.9	15	tr	NI	–	53	28	0	–	197	241	0	–	90	–	601	–	891	997	0	–	30	28	32	27	0
Gl/CE		4	84					199	58	20	10	121	130	196	226	74	71	116	141	794	898	1023	1199	30	49	58	47			
Gl/BMI	17	34	127	300	0.1	7	tr	503	141	60	38	128	176	245	285	105	161	199	219	324	546	604	816	40	60	76	73	67	62	21
Gr/BMI	12	6	171	175	0.8	3	ND	NI	–	66	37	0	–	172	168	0	–	130	130	238	--	933	971	0	–	45	41	55	53	16
Gl/PI1	4	6	57	300	1	1	ND	NI	187	69	28	0	35	59	76	0	12	39	64	0	28	41	144	0	17	27	44	58		
Gr/PI1	8	2	11	300	1.5	1	ND	NI	195	24	35	0	37	55	73	0	30	37	54	0	107	175		0	19	20	35	48	26	53
Kev/PI1	30	2	62	700	1.5	2	ND	NI	163	33	15	0	51	93	104	0	40	54	72	0	156	240	333	0	57	45	95			
Spec/PI1	48	1	241	700	2	2	ND	NI	129	28	10	0	98	141	234	0	83	92	131	0	294	500	580	0	107	104	96			
Gl/PMR-15	2	1	16	200	1.0	tr	2	NI	175	75	55	0	40	78	85	0	27	49	60	0	170	131	113	0	21	22	20			45
Gl/PPS	7	8	87	70	0.5	2	0.5	NI	105	57	30	0	52	71	183	0	25	56	106	0	585	575	749	0	32	24	41	64	59	36
Gr/PPS	3	2	32	100	0.5	1	ND	NI		69	26	0		81	141	0		60	80	0		431	752	0		37	37			41
Gl/J-2	13		328	180	1.0	ND	10	193	53	21	13	67	96	116	135	38	49	48	76	803	911	866	1011							
Gr/PES	10	1	5	110	1	1	1	NI	172	47	21	0	11	41	65	0	6	23	39	0	145	88	189	0	3	22	23			
Gr/PAS	8	2	3	55	0.1	tr	ND	NI	122	40	19	0	24	47	60	0	8	32	44	0	79	211	173	0	1	14	14	64	59	34
Gl/PEKK	3	1	4	200	1	tr	ND	NI	223	92	53	0	21	45	74	0	10	24	46	0	274		891	0	15	20	24			
Gr/PEEK	3	1	1	tr	tr	ND	ND	NI	307	80	42	0	14	54	85	0	8	30	56	0	69	134	252	0	3	35	28	57	55	75

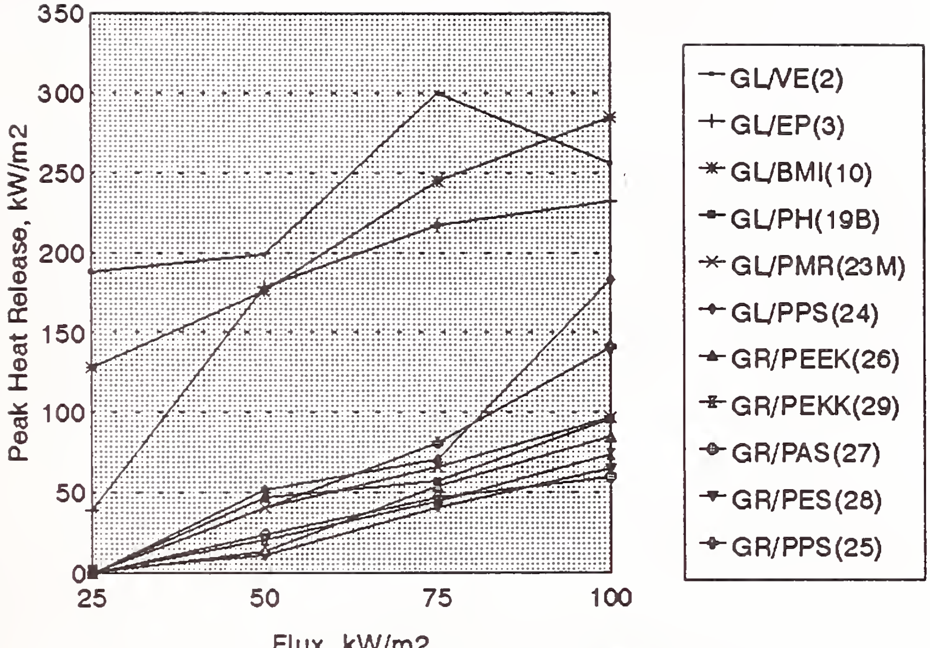

Fig. 1: PHR vs Flux for selected composite materials.

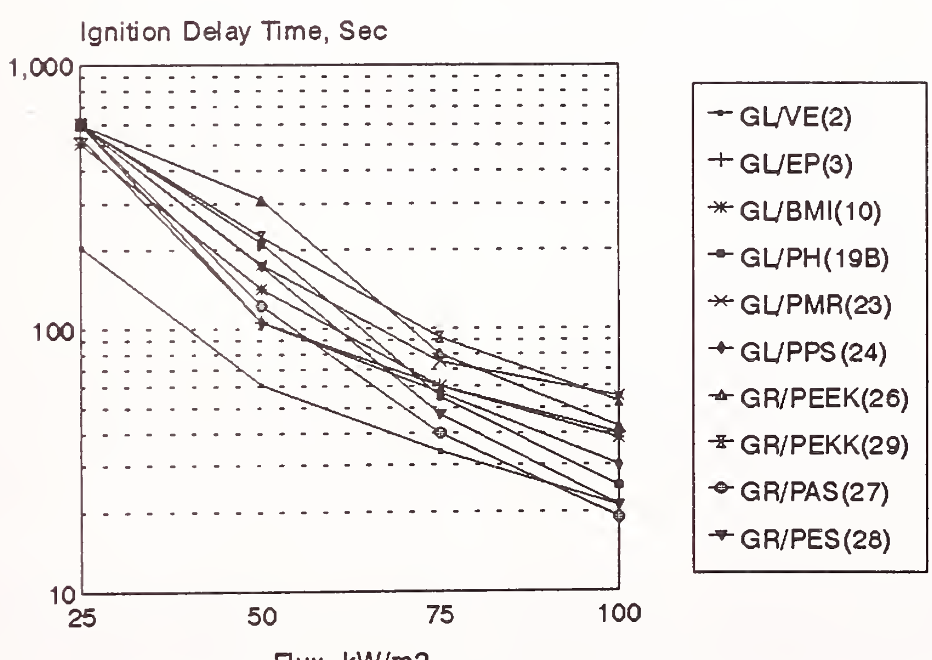

Fig. 2: Ignitability of composite materials.

of 100 and 75 kW/m^2 respectively. All composite materials evaluated in this study failed to meet the ignitability requirements. This is shown in Figure 2. It is in this area of ignitability where fire barrier treatments provide the most benefit by delaying the onset of spontaneous ignition providing greater time interval for the fire fighters to control the fire.

FIRE BARRIERS:

Fire performance characteristics of composite systems can be greatly enhanced by the incorporation of fire barrier treatments. In a recent study by U.S.Navy, several fire barrier treatments were evaluated in conjunction with glass/vinyl ester and glass or graphite/epoxy composites. Fire barrier treatments function either by virtue of their ability to reflect the radiant heat back towards the heat source or delay heat penetration by their insulative, ablative, or endothermic properties. This delays the heat-up rate and reduces the overall temperature on back side. As an example, exposure of intumescent coatings to flame produces a viscous carbonaceous or inorganic mass that expands into a foam by the gas generated. This thermally stable insulating char protects the substrate from the thermal effects of the flame.

Thermal barrier treatments evaluated in this study include ceramic fabric, ceramic coating, intumescent coating, hybrid of ceramic and intumescent coatings, silicone foam, phenolic skin, thermoplastic coatings, APM (ablative protective material, Interam endothermic mat E-10A, and Interam intumescent mat I-10A. The composite systems evaluated in combination with thermal barrier treatments included glass/vinyl ester, and glass or graphite/epoxy.

Data show that without any fire barrier treatment, all composite systems evaluated in this study failed to meet the ignitability and peak heat release requirements of MIL-STD-2031 (SH) at radiant heat fluxes of 75 and 100 kw/m^2 respectively.

Data also show that intumescent coating (4), a hybrid of intumescent and ceramic coatings (5), APM (ablative protective material), Interam endothermic mat E-5A, and Interam intumescent mat I-10A were the most effective fire barrier treatments for composite systems evaluated in this study. Using any of these fire barrier treatments, all composite systems met the ignitability requirements of 90 and 60 seconds at 75 and 100 kw/m^2 respectively. Figure 3 shows the heat release rates for glass/epoxy (1003) panel by itself, glass/epoxy/APM (0.125"thick, 1004), glass/epoxy/I-10A (0.125"thick, 1041), glass/epoxy/I-10A (0.250"thick, 1044), glass/epoxy/E-10A, (0.20"thick, 1042), and glass/epoxy with 30 mils of water based intumescent coating (1047). In all cases, the panels were exposed to a heat flux of 75 kW/m^2 in horizontal orientation.

RESIDUAL STRENGTH OF COMPOSITES:

Recently, the assessment of composite structural performance during and after fire has become a subject of intense discussion within Navy community. Due to the nature of their construction, composite materials do not lend themselves to easy analytical calculation of their behavior when exposed to a high heat flux. Composites exhibit anisotropic heat transfer, they burn, give off smoke and release heat, char, and delaminate.

Composite materials are made of organic matrix resins. These resins undergo viscoelastic transitions during thermal exposure. Composites retain most of their load bearing characteristics below a certain "critical" temperature. Above this critical temperature, composites begin to lose their mechanical properties rapidly and, in some cases, catastrophically. During fire, beyond a critical (glass

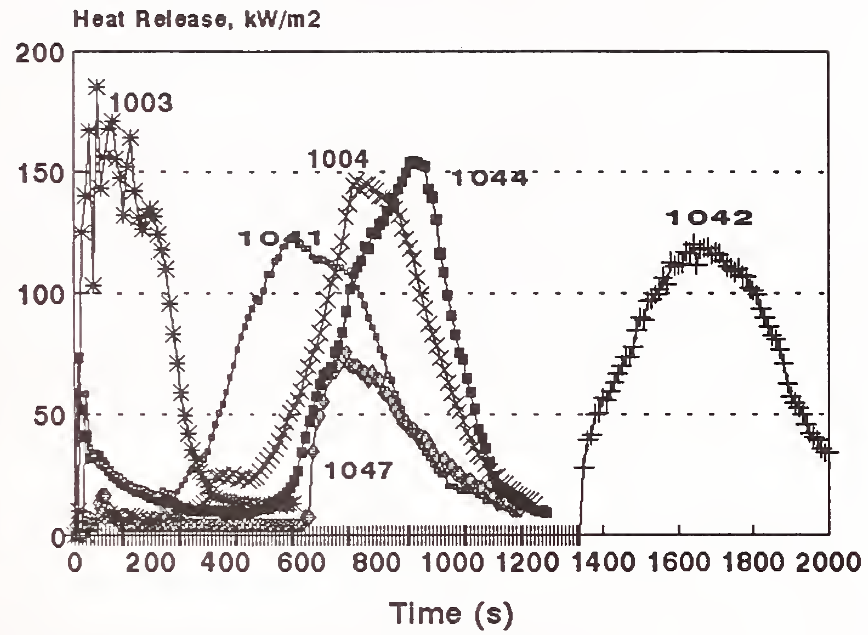

Fig. 3: Heat release rates for Gl/EP with and without fire barriers.

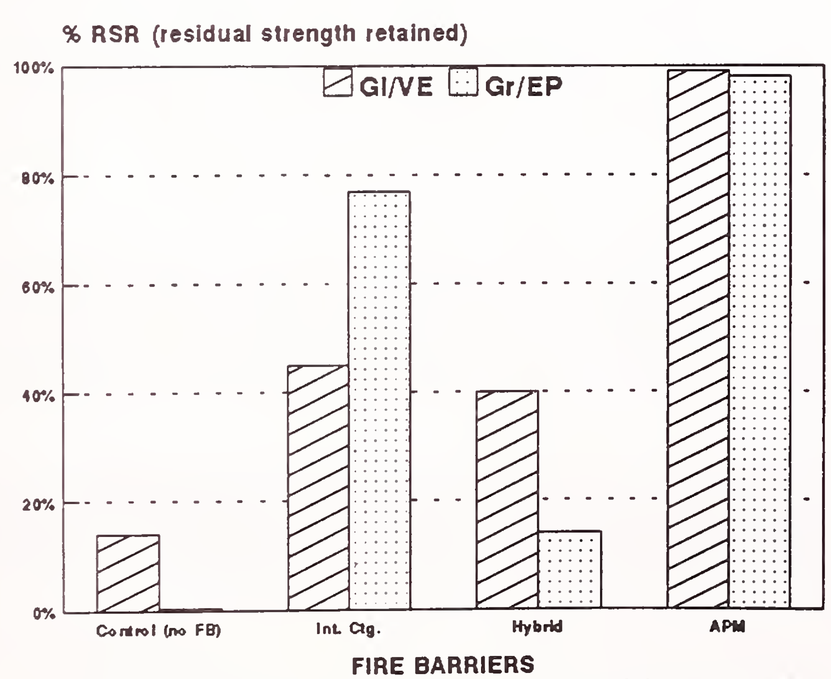

Figure 4: Residual Strength (%RSR) at 25 kW/m2 for 20 minutes.

transition) temperature, these resins can no longer transfer load to the fiber. As such, the residual strength of load bearing structures is much lower during fire than after fire. This critical temperature (during fire) is about 200 ^{0}F for glass/vinyl ester. However, when cooled, (after fire), irreversible damage does not set in until 500^{0}F.

The percent residual flexural strength (modified ASTM D-790) retained (%RSR) after the fire test for selected composites with and without fire barriers treatments is shown in Fig. 4. As part of the testing protocol, all specimens (3x3 in., 0.25 in. thick) were exposed to radiant heat source of 25 kW/m^2 for a duration of 20 minutes during ASTM E-662 (smoke density) in a flaming mode. Specimens were tested for flexural strength before and after the fire test. The percent residual strength retained (%RSR) after the fire test for selected thermoset and thermoplastic composite materials is given in Fig. 3. Graphite/PEEK retained the maximum flexural strength (75%) of all composites evaluated at this level of fire exposure followed by graphite/phenolic (53%). Glass/epoxy delaminated during the fire exposure due to resin charring resulting in loss of interlaminar strength. Also, panels treated with intumescent coating (4) and ablative protective material (11) retain higher residual strength after fire exposure for both glass/vinyl ester and graphite/epoxy composite systems.

CDNSWC has initiated a comprehensive effort focused on the issue of residual structural strength during fire. This is intended to result in mathematical models that can be used by naval architects to design full scale fire-tolerant composite structures. This methodology includes determination of basic composite characteristics at elevated temperatures, determination of isothermal material characteristics for use in the computer model, determination of creep characteristics of materials (creep is an unacceptable structural instability), determination of heat transfer characteristics of composite materials exposed to fire, construction of mathematical models of basic shapes under typical loads using ABAQUS finite element analysis, and verification of these models in small and full scale ASTM E-119 tests.

CONCLUSIONS

With the exception of vinyl ester, all glass or graphite reinforced composite materials met the requirements of flame spread index. Also, with the exception of fire-retardant vinyl ester and thermoplastic J-2, all glass or graphite reinforced composite systems met the requirements of specific optical density at 300 seconds and maximum smoke density as per MIL-STD-2031. Glass or graphite reinforced phenolic, polyimides, and many of the thermoplastics composites met the peak heat release requirement. However, all composites investigated failed the ignitability requirements of the current MIL-STD-2031 of 90 and 60 seconds at 75 and 100 kW/m^2 respectively.

Fire performance of composites can be greatly improved with fire barrier treatments. Data show that intumescent coating, a hybrid of intumescent and ceramic coatings, ablative protective material (APM), Interam endothermic mat E-5A, and Interam intumescent mat I-10A were the most effective fire barrier treatments for composite systems evaluated in this study. Using any of these fire barrier treatments, all composite systems met the ignitability requirements of 90 and 60 seconds at 75 and 100 kw/m^2 respectively.

A methodology has been developed to understand the relationship between fire exposure, temperature distribution, dependence of load bearing characteristics with elevated temperatures, and residual strength. This area is being further explored, on small scale, with high temperature creep experiments and, in future, with large scale testing for verification.

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SAFETY PHILOSOPHY FOR THE USE OF COMPOSITE MATERIALS OFFSHORE

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ABSTRACT

Within the last few years, Amoco Norway has greatly increased use of composite materials offshore. Three major systems have now been or are in the process of being installed at the Valhall field. These are the deluge firewater systems, the produced water treatment system and the open drain systems. Thorough safety evaluations preceeding each of these installations, in part, to confirm acceptability of composite materials.

The safety philosophy used to justify composites offshore is summarized below. The need for system function in an emergency situation defines the detail level for safety evaluation. When no function is required, the evaluation concentrates on assuring that composite component failures during an accident event will not increase personnel risks or contribute to accident escalation. When function during an emergency is required, more thorough evaluations are used in the form of a formal risk analysis study. Such a study sets performance/function requirements of the composite system and then evaluates anticipated behavior during all likely accident events. When necessary, verification explosion and fire tests are performed, with test conditions derived directly from results of the risk analysis.

INTRODUCTION

Amoco has been active in the Norwegian sector of the North Sea since 1965 and currently operates the Valhall and Hod fields. These fields were discovered in 1976 and are located far southwest in the Norwegian sector about 250 km (150 miles) from Stavanger. The Valhall field was developed using a three platform concept consisting of separate quarters, drilling and processing/compression platforms and came on-stream in 1982. The Hod field was developed in 1991 as a remotely operated, normally unmanned satellite platform, with oil and gas production pipeline transported to and processed at Valhall. Oil processing capability at Valhall is about 23 M cu. m/d (150 M bbls/d). Production is pipeline transported from Valhall through the Ekofisk center to shore.

Prior to 1991, use of composite materials at Valhall and Hod had been limited to a few seawater lift risers. However, starting as early as late 1989, interest in composite piping materials rapidly grew. This was due to recurrent availability problems with steel deluge firewater systems caused by internal corrosion and the possible risks of nozzle blockage by corrosion products during use of the systems. Composite materials were rationalized to be a cost effective replacement piping which would be immune to the corrosion problems experienced with steels.

Several previous publications summarize the successful safety justification program performed for composite firewater systems, optimizations of component designs and experiences from the 1991 offshore installation of a prototype system, the first of its kind in the North Sea (refs. 1-3). Since that time, composite piping materials have been used extensively for installation of a new produced water treatment system at Valhall and for replacement of steel open drain systems. The near future of Valhall may involve a new platform addition to the field, for which further uses of composite materials are envisioned.

The following briefly describes the processes used to justify composite materials offshore with respect to safety. The justification process is based upon specific system of interest, necessity for function in an emergency situation and the active use of safety evaluations.

DISCUSSION

Composite Systems Classifications

Piping components are perhaps the largest current uses for composite materials offshore. Storage tanks have seen some limited use and applications for vessels operating at low pressures can be envisioned. Secondary composite structures such as floor gratings, stairways, hand rails and cable trays/ladders have been used offshore. More recent applications include accomodation/office modules and fire/blast walls and panels.

With respect to safety, potential composite systems offshore can be classified into two major groups based upon necessity for function in an accident/emergency situation. Function is not only defined with respect to effective active response, such as for emergency equipment, but should also consider if component integrity must be maintained to prevent significant increases in personnel risks and/or accident escalation. Regardless of function necessity, personnel risk should not be increased by excessive fire induced smoke generation, toxic gas release and/or flame spread from the composite materials themselves. In practice, these latter possibilities are precluded by judicious materials selection and by specifying upper limits for these characteristics based upon appropriate standardized tests.

A further classification for containment systems involves whether or not hydrocarbons or other flammable species are present within the systems. Note that for such systems, integrity during an emergency event must be maintained.

These composite classifications are summarized below (ref. 4):

No Function in Emergency Hydrocarbon Containing Examples: None	Function in Emergency Hydrocarbon Containing Examples: process piping and vessels
No Function in Emergency Not Hydrocarbon Containing Examples: produced water, cooling water, non-critical secondary structures	Function in Emergency Not Hydrocarbon Containing Examples: firewater systems, fire walls, critical secondary structures

The exact definition of hydrocarbon containing systems is not universally accepted, but is often taken to be in the range of several percent. Note that at the present time, the author is aware of no composite applications offshore Norway into the realm of hydrocarbon containing systems. Practically speaking, therefore, current composite uses offshore can be chiefly differentiated with respect to safety based upon the necessity for function in an emergency situation.

Safety Evaluations

Recent changes in Norwegian regulations governing offshore activities have had the impact of effectively promoting greater safety awareness into line organizations. Amoco Norway's response has been to increase the scope of safety, work environment and external environment evaluations in all phases of offshore construction projects, including subsequent operational phases. These are accomplished by active use of:

- process safety studies (Hazop, API 14C)
- reliability/availability studies
- quantitative risk analyses
- emergency preparedness analyses
- separate working environment analyses
- construction/installation safety studies
- evaluation with respect to compliance to environmental standards, strategies and regulations.

Dependent on scope and impact of an upcoming construction project, these evaluations can be simple and concise or quite detailed and lengthy. For composite materials, the lack of required function in an emergency situation will generally result in a relatively simple evaluation, with intent largely to demonstrate no adverse consequences of component failure, i.e., no safety threat to personnel and no contribution to accident escalation. For example, in the case of the Valhall produced water treatment system mentioned above, acceptable composites usage was partly dependent on no need for function (maintaining integrity) during an emergency. It was also dependent on a redundant control and monitoring system to prevent the unknown carry-over of significant amounts of oil from the primary separators into the composite piping of the water treatment system, therefore assuring the system would not be hydrocarbon containing.

For composite systems offshore which must function in an emergency, more detailed safety evaluations are needed, and often evolve into a formal qualitative and quantitiative risk analysis.

The Norwegian Petroleum Directorate (NPD) has actively promoted the use of risk analyses studies as a tool to improve offshore safety for many years (refs. 5-6). Together with emergency preparedness regulation, this practice forms the cornerstone for recently issued revised regulations (7). The approach systematically establishes performance/function criteria, then evaluates performance under a variety of accident events, e.g., explosions and fires. Results of such studies are also useful as engineering tools, as often simple modifications in design can enhance the safety characteristics of systems at minimal or no additional cost. Additionally, the approach forces rationalization into design criteria often followed mainly by common practice.

The main steps involved in risk analyses generally include:

- definition of acceptance/function criteria
- hazard identification
- qualitative review
- consequence analysis
- frequency analysis
- risk calculation and comparison to risk acceptance criteria including evaluation of risk reducing measures.

The reader is referred to previous publications for details on application of risk analyses techniques to safety justification of the composite firewater system at Valhall, for which system function during an emergency situation is required (refs. 1-2).

In summary, two main function criteria were assigned to the firewater system:

- effective operation so as to reduce heat and radiation levels to facilitate personnel escape from an explosion/fire situation

- continued operation for exposure protection of offshore facilities for the approximate duration of a worst case hydrocarbon fire.

Subsequently, composite firewater systems were systematically evaluated with respect to anticipated behavior regarding explosions, fires, long term deterioration and mechanical damage. Overall, it was concluded that an appropriately engineered composite system should meet the firewater system function requirements under all of the accident scenarios studied (ref. 8). Key to this evaluation was results of the deluge systems reliability study, which concluded that automatic deluge (which would fill composite piping with water within 30 seconds) would fail to occur in a fire event at a frequency of once every 100,000 to 1,000,000 years. Based on these results and with application of a safety factor (partly to allow time for manual intervention in the unlikely event of deluge failure), a design criterion for fire insulation of the composite firewater system piping was established.

Explosion and Fire Testing Philosophy

An additional benefit of risk analyses for offshore composite systems is that should any verification/qualification testing of composite materials be required for a given application, realistic test conditions can be readily specified. This is because the risk analyses defines the applicable worst case accident events for the offshore platform facilities. These can then readily be applied to test parameters, e.g., intensity and duration of fire tests.

As described in detail elsewhere, an extensive explosion/fire testing program was performed to verify acceptable behavior during accident scenarios of composite piping for the Valhall firewater system (ref. 1). Three essentially different test types were used, including simulated explosion testing, hydrocarbon pool fire (furnace) testing and gas jet fire testing. Test characteristics and their relationships to the Valhall risk assessment are summarized below:

Test Type	Risk Analysis Findings	Test Parameters
Simulated Explosion*	1. Design overpressure 0.3 bar (4.5 psi)	1. Pipe strained in bending to a deflection corresponding to the design overpressure versus optimized piping support spacing.
Pool Fire**	1. From spilled oil/natural gas liquids 2. Deluge water flows within minutes 3. Worst case fire duration 80 minutes	1. Hydrocarbon Curve heating characteristics used (initial phase) 2. Deluge compensated heating used (remainder of test) 3. Test duration 80 minutes (some tests run 4-6 hours without composite failures)
Jet Fire**	1. From high pressure gas release 2. Personnel escape duration 20 minutes	1. SINTEF jet fire test used (ref. 9) 2. Minimum test duration 20 minutes (30 minutes actual)

* subsequently fire tested to assure acceptability

** deluge piping tested dry for initial 5 minutes, then filled with flowing water at nominal working pressure for the remaining duration of tests

Because accident scenario findings from the risk analysis were based on the maximum intensity of events having a frequency of 1 in 10,000 years and greater, the test parameters used are considered sufficiently conservative for qualifying composite materials for Valhall.

Future Applications

In the short term, composites will likely become dominant offshore for low pressure water handling systems such as drains, ballast water, cooling water, produced water, injection water and seawater lift risers. No regulatory restriction problems are anticipated provided adequate system safety evaluations are performed and include considerations for the use of composite materials. This is also thought to be the case for non-critical secondary structural applications.

Significant future developments are possible for composite materials which must maintain function during accident events such as firewater systems, fire walls and critical secondary structures. A variety of designs and fire insulation systems are possible for obtaining adequate fire resistance, and these will no doubt require verification testing. In this regard, Amoco Norway has continued to be active in sponsoring optimization studies of insulation systems and application methods for firewater piping, with goals of reducing costs without sacrifice to explosion and fire safety.

Possibilities beyond the cast intumescent epoxy half shell systems previously used at Valhall include:

- thin, intumescent paint coatings
- full pipe-length, industrial application methods for intumescent epoxy coatings
- composite piping with enhanced fire resistance (e.g., phenolic base, resins with fire retardant fillers)
- piping onto which an insulation coating is applied as an inherent part (latter stages) of the maufacturing process.

Fortunately, the composite materials verification testing programs previously established for Valhall based on the risk analyses approach have been well accepted internally and by the authorities, so that testing can proceed on any new materials and designs in an expeditious fashion. This, of course, is not universally the case and clearly the lack of agreement on tests and evaluation methods represents an obvious hindrance to more widespread applications of composites offshore.

It is thought that some of the fire protection methods listed above could find application to hydrocarbon containing systems when such service becomes acceptable to offshore operators and the authorities. However, general opinion in Norway on the use of composite materials for hydrocarbon service is that acceptability may be dependent firstly on further developments in the area of non-destructive evaluation of composite materials. Recent developments in this area appear promising. This, combined with a risk analyses approach to set function requirements and verification testing approaches, should result in an eventual acceptance for composite materials in this role.

CONCLUSIONS

1. Current uses of composite materials offshore can be safety classified with respect to necessity for function during an accident/emergency situation.

2. When no function during an emergency is required, a relatively simple safety evaluation of possible composite materials uses offshore may be sufficient. Lack of necessary function is confirmed by assuring component failures would not increase personnel risks or result in escalation of an accident event.

3. When function during an emergency event is required, more extensive safety evaluation of offshore composite systems is needed. This evaluation may include a formal risk analysis and verification explosion and fire testing.

4. Wider application of composite materials offshore is hampered by lack of generally accepted explosion/fire testing techniques and evaluation methods.

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6. Working Groups and Discussion Summary Reports

6.1 Summary and Recommendations of Working Group #1 on Fabrication, Construction, Maintenance, and Repair

6.1.1 Working Group #1 Members

Chairman:

Gerry G. Greaves, Technical Center, Owens Corning Fiberglass Corporation, Granville, Ohio

Cochairman:

Christopher J. Houghton, Phillips Petroleum Co. UK, Ltd., Woking, Surrey, United Kingdom

Members:

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Chris Lundberg, Spyro Tech, Lincoln, Nebraska

Richard S. Parnas, Polymers Division, National Institute of Standards and Technology, Gaithersburg, Maryland

Michael A. Smoot, DuPont Company, Newark, Delaware

Doug Wilson, Fibers and Materials, BP Chemicals (Hitco), Inc., Santa Ana, California

6.1.2 Summary of Discussion

The working group was well attended by representatives of material suppliers, fabricators, oil companies, and government agencies. It began with presentations from each of the panelists (copies of the presentations or papers, as available, are included). Group members then identified, defined, and grouped applications. They thought the needs for each group of applications could be different. For some applications, the technology exists and can be transferred from other applications. For others, there are significant technological hurdles. For each group of applications, the products, typical dimensions, key requirements, fabrication methods, time horizon, technology hurdles, research needs, and implementation recommendations were discussed. Summaries for each of the following applications are given in the Tables 1 through 4.

- High pressure > 49 bar, topside, risers, subsea, flow, and downhole tubing
- Tanks — vented and vessels — high pressure ≤5,000 psi
- Low-pressure pipe ≤40 bar
- Secondary structures — panels, grating housing, handrails
- Primary structure — subsea manifold and well-head protection "beams"

The attached general recommendations can be grouped into the following areas:

- Nondestructive evaluation
- Design and construction manual
- Education
- Joints, fittings, and penetrations
- Joint industry programs

Oil companies are aggressively pursuing means to reduce offshore construction and, thus, operating costs to maintain profits at reduced oil prices. After discussing many potential composite applications for offshore operations, it was clear that existing composite technology can fill needs in many areas; successful performance has been demonstrated in some applications.

Table 1. Potential Offshore Composite Applications: Tanks and Vessels

Product(s)

Tanks:	vented
Vessels:	high pressure ≤5,000 psi

Typical Dimensions

Tanks:	14 m diameter × 14 m
Vessels:	1–3 m diameter × 10–12 m

Key Requirements

Chemical resistance (to hydrocarbons, H_2S, CO_2)
120°C
Leak before burst capability
Impact resistance
Fire resistance
NDE
Repair techniques
Nozzle design
Thermal cycling
Long-term performance (30–70 years)

Fabrication Methods

Filament winding
Pultrusion

Time Horizon

Vented tanks:	Short term
HP vessels:	Medium term

Technology Hurdles

Side penetrations
Design concepts
Materials

Research Needs

Table 2. Potential Offshore Composite Applications: Low-Pressure Pipe

Product(s)

Low-Pressure Pipe (≤40 bar)

Typical Dimensions

1–30-in diameter

Key Requirements

More cost effective fire resistance
NDE on joints

Fabrication Methods

Filament winding with fire-protective coating
Pultrusion

Time Horizon

Short term: <3 years

Technology Hurdles

Low-cost, integral fire-resistant system
NDE defect assessment

Research Needs

Define low-cost fire-resistant material
Identify critical-flaw acceptance criteria

Table 3. Potential Offshore Composite Applications: Secondary Structures

Product(s)

Secondary structures: panels, grating, housing, handrails

Typical Dimensions

Various dimensions (panel: 8 m × 3 m)

Key Requirements

Impact resistance
Fire resistance

Fabrication Methods

Pultrusion
Contact molding
Resin-transfer molding (RTM)

Time Horizon

Short term

Technology Hurdles

Education
Construction experience?
Improved fire resistance

Research Needs

Life-cycle cost and weight savings analysis
Document case histories

Table 4. Potential Offshore Composite Applications: Primary Structures

Product(s)

Primary structures
Subsea manifolds and well-head protection "beams"

Typical Dimensions

Well-head protection: 30 m × 30 m

Key Requirements

Interface with other materials
Long-term performance
Life-cycle cost
Repairs
NDE
Impact resistance

Fabrication Methods

To be determined
Pultrusion

Time Horizon

Long term

Technology Hurdles

To be determined

Research Needs

Fabrication of large, thick structures

6.2 Summary and Recommendations of Working Group #2
on
Material Performance, Damage Tolerance, Durability, and Environmental Degradation

6.2.1 Working Group #2 Members

Chairman:

John P. Dismukes, Exxon Research and Engineering Company, Annandale, New Jersey

Cochairman:

Allan S. Chiu, Imperial Oil Resources, Ltd., Calgary, Alberta, Canada

Recording Secretary:

Leif A. Carlsson, Florida Atlantic University, Boca Raton, Florida

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Sandy Sternstein, Rennselaer Polytechnic Institute, Troy, New York

Francis S. Uralil, Westhollow Research Center, Shell Development Company, Houston, Texas

6.2.2 Summary of Discussion

6.2.2.1 Background and Scope of Assessment

About 35 panelists and members of Working Group #2 participated in the definition of scope and assessment of specific issues underlying material performance, damage tolerance, durability, and environmental degradation of composite materials now being used or under consideration for use in offshore petroleum production operations.

Although recognizing that metal-matrix and ceramic-matrix composites could be suitable, the group focused on fiber-reinforced, polymer-matrix composites because the oil industry has had experience with low-cost polymer composites in secondary structural applications and because they have potential in primary-load structural applications. The discussions centered on two areas of materials performance: mechanical performance and environmental response.

Following the presentations by panelists on October 26, all participants reviewed and evaluated information and assessed the issues that had been raised in submitted questionnaires and by individuals at the meeting. The range of topics reviewed as a basis for recommendations on the use of polymer composites in offshore operation included

- Performance requirements of polymer composite materials and structures
- State of the practice in their use in offshore drilling and production
- State of the art for potential use in offshore drilling and production
- Economics of their safe and effective use in offshore operations
- Technology hurdles in achieving prototype and commercial use
- Research needs and priorities for overcoming technology hurdles

The group structured its deliberations from the viewpoint of identifiable applications, specifically:

- Piping, fittings, and valves (water or process fluids)
- Tanks and vessels (internally or externally loaded)
- Secondary structures (gratings, handrails, cable trays, panels)
- Mechanical components (drive shafts, turbines)
- Downhill tubular structures (drill pipe, tubing, coil tubing, umbilical tubing)
- Drilling/production risers (all composite and composite/metal)
- Primary structures (tendons, mooring ropes, beams, and plate)

Then it identified the following general incentives, based on reductions in operating expense (OPEX) and capital expenditures (CAPEX), for utilization of polymer composite materials and structures in existing and new applications:

- Corrosion resistance/life-cycle cost reduction
- Fatigue resistance/longer life
- Ease of fabrication/construction
- Low-temperature joining/installation
- Parts consolidation/tailored properties
- Enabling properties/system enhancement

6.2.2.2 Polymer Composites in Offshore Operations: State of Practice

For more than 25 years, polymer composite materials have been used in secondary structures onshore. Diffusion of commercial practice to offshore operations has progressed slowly but steadily, as cost effectiveness and the requirements for safe and effective use (e.g., under fire exposure) have been demonstrated. Current offshore uses can be grouped into three categories:

- Low-pressure piping (<300 psi; <65°C)
  – fresh and waste water
  – nonflammable liquid chemicals (hypochlorite, glycol, drilling fluids)
  – fire water
- Tanks and vessels (<150 psi; <65°C)
  – applications not critical during fire
- Secondary structures
  (if not primary escape route or potential location for hydrocarbon jet or pool fire)
  – gratings
  – handrails
  – fire and blast walls with flame-resistant coatings

6.2.2.3 Polymer Composites in Offshore Operations: State of the Art

The state of the art of polymer composites applicable to offshore operations is based on existing onshore commercial use by the oil industry, ongoing Joint Industry Program (JIP) development by the oil industry in collaboration with the composite industry, developments taken from the aerospace industry, and governmental demonstrations and commercialization (e.g., U.S. Navy). The general incentives above justify both short- and long-term interest in the following performance capabilities and applications:

- High-pressure piping (300 psi < pressure < 4000 psi; temperature <120°C)
  – water
  – hydrocarbons
  – flexible pipe
  – high-performance liners
- Tanks and vessels
  – accumulators (1–2 ft diameter, <4000 psi)
  – fuel tanks (no leaks in 15 in/fire exposed)
  – LPG tanks (weep before break)
- Secondary structures
  – improved fire resistance (phenolic resins/thinner protective coatings)
- Downhill tubular structures
  – drill pipes (small radius and extended reach)
  – coiled tubing (ongoing JIP)
- Primary structures
  – risers (prototypes tested/development ongoing)
  – TLP tethers and mooring ropes (ongoing JIP)
  – pultruded structural components/I-beams (ongoing JIP)
- Mechanical components
  – drive shafts and valves (U.S. Navy)

6.2.2.4 Gaps between State of the Art and State of Practice

The group determined that there are four gaps that represent hurdles to be overcome in realizing the state of practice, discussed above, in commercial offshore operations.

- From an operational standpoint, the first is cost. The importance of evaluating cost at the system level cannot be overemphasized, since many of the benefits of polymer composites are achieved after a redesign of the system structure rather than a piece-by-piece substitution at the component level (e.g., for steel).
- Demonstration and proof of designs and of manufacturing technology are required before turning the concept into a product.
- The cost effectiveness and manufacturability by the supplier of polymer composite materials and structures for reliable long-life service in offshore operations must be accepted by the operator.
- Regulations on fire resistance, structural performance and reliability, and environmental durability under offshore conditions must be met.

The group concluded that these four gaps are interrelated, so that cooperative efforts by composite manufacturers, offshore fabricators, operators, and regulatory agencies are required to prove design concepts by product testing and to us this as a basis for operator and regulatory acceptance. One example is the performance and cost advantages of composite risers has to be demonstrated for depths of 3000 ft and more. Another example is demonstration of a cost-effective design for polymer composite piping that will overcome the current 6 to 10 ksi "weeping stress" threshold and the operating temperature limit of about 65°C.

6.2.2.5 Technology Gaps between State of the Art and New Opportunities: Primary Structures

The group concluded that the generic incentives described above for polymer composite materials and structures could have the greatest impact in the area of primary structures, provided that economics at the system level can be shown to be competitive with existing primary structures, which are typically based on steel. In special applications, metal-matrix or ceramic-matrix composites may be appropriate. To meet these challenges, a number of technological issues need to be addressed; they are

- The stiffness in the design may be critical.
- Residual strength is required after exposure to fire.
- Multiaxial loading, in tension and compression, must be considered.
- Environmental degradation of fiber, matrix, and interface must be understood and prevented. Particularly important here are the combined effects of stress and the environment (e.g., heat, radiation, water CO_2, H_2S, and hydrocarbons).
- Galvanic corrosion is an issue for metal/composite joints and for potential leaching out of the matrix from the composite.
- Static electrical discharge may be a problem.
- Fatigue under tension and tension/compression loads must be understood and prevented.

6.2.2.6 Key Research and Development Initiatives

The group discussions indicated that a number of research and development initiatives can have a strong impact in overcoming the technical and infrastructural gaps and hurdles identified and outlined above. Participation by the oil industry, the composites industry, the oil-field equipment-fabrication industry, and government regulatory agencies in a focused effort is required to provide the most rapid and cost-effective route to commercial acceptance of polymer composites in new applications for offshore operations. Important initiatives are

- Establish requirements for fire resistance in composites.
  – fire-resistant resins (less burning, less-toxic fumes)
  – cost reduction of fire-resistant coatings
- Review/explore reinforcement lay-up, volume fraction, and discontinuous fiber systems.
- Establish methodologies for life prediction in offshore environments based on mechanistic understanding of failure processes.
- Define standardized material systems for testing and database development (material systems are application specific).
- Develop cost-effective processes for manufacture of offshore components.
- Investigate joining of components.
- Establish requirements for damage tolerance that are linked to sequential evolution of fracture and final failure.
- Develop inspection methodologies that are linked to sequential evolution of fracture and final failure.

6.2.2.7 Overall Conclusions and Recommendations

The most promising applications that can benefit from utilization of polymer composite materials and structures in offshore operations were identified for the short and long term. The Working Group #2 assessment established that the state of practice in secondary structural applications is growing rapidly and confirmed the vision that there are strong incentives for extending the offshore use of polymer composites into primary structural applications.

To reap this potential, cooperation and collaboration among the oil industry, materials suppliers, fabricators, and independent and government regulatory agencies is critically needed. Once facet of this effort should include a forum for continued international dialogue and interaction, which is essential for exchange of research and prototype development results, decisions on regulatory requirements, and diffusion of commercial technology.

To provide guidance for more widespread application of existing design and application practices and to prepare for new opportunities in primary structures, current knowledge of polymer composites applicable to upstream operations should be captured and documented in a data base for the education of designers, users, and regulators.

To bridge the technology and infrastructural gaps between the state of the art and new opportunities, interdisciplinary and interorganizational research initiatives should be structured to provide fundamental understanding in enabling technologies and to implement development and demonstration programs as a basis for manufacturing capability, operator acceptance, and regulatory endorsement.

6.3 Summary and Recommendations of Working Group #3 on Structural Design, Optimization, Testing, and Reliability

6.3.1 Working Group #3 Members

Chairman:

S. W. Tsai, Stanford University, Stanford, California

Cochairman:

T. Lundh, AMAT, Sandefjord, Norway

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6.3.2 Summary of Discussion

Observations

- Component design with advanced composites is based on material data.
- FRP pipe and fitting design is based on component test results.
- Composite material knowledge must be incorporated into design.

Key Elements

- Joint industry development and commitment to design and performance specifications (users, manufacturers, suppliers, regulatory agencies)
- Uniform acceptance criteria and standards

Desirable Capabilities from Manufacturers
(in cooperation with users and suppliers)

- Analytical design capability for product improvement and critical applications (design guidance)
- Ability to account for environmental effects on component performance
- Qualification testing to verify products and fabrication processes
- Manufacturing procedures, such as ISO 9000, to ensure reliability
- User-friendly system design capability (for application engineers)
- Reliability — risk assessment
- Optimization procedures
- Training

Available General Analytical Capability

- 2-D models capable of analyzing progressive failures and contacts
- Simulation of manufacturing defects, operational damage, and repair
- Rational acceptance, rejection, and repair criteria
- 3-D models and optimization capability currently under development

FRP Line Pipes and Fittings

- Low-pressure applications
- High-pressure applications
  - composite mechanics
  - controlling failure mechanisms
  - fabrication parameters
  - composite-to-metal connections
  - long-term performance (R&D, engineering)
    - o biaxial loading/failure criteria
    - o design limits
    - o relevant time-dependent rupture data
    - o available design tools (?)
  - temperature, pressure, and environmental interaction
  - uniform testing methods
  - optimization procedures

Composite Coiled Tubing

- Design tailoring to enhance helical buckling resistance
- Design strain limits
- Cross-section ovalization on spooling

Design for Impact Resistance

- Impact specification/performance requirement
- Differences in shell and plate behavior
- Thin-walled vs. thick walled construction

6.4 Summary and Recommendations of Working Group #4 on Nondestructive Evaluation, Condition Monitoring, and Inspection

6.4.1 Working Group #4 Members

Chairman:
Dale W. Fitting, National Institute of Standards and Technology, Boulder, CO

Co-Chairman and Recorder:
Allan Boye Hansen, AMAT, Sandefjord, Norway

Members:
Edward C. Grenawald, Geo-Centers, NRL, Ft. Washington, MD
William D. Cook, University of Houston, Houston, TX
Robert Finch, University of Houston, Houston, TX
Russ Fairles, McDonnell Douglas, ST. Louis, MO

6.4.2 Summary of Discussion

6.4.2.1 The State of Practice in Composites NDE

The state-of-practice for nondestructive evaluation (NDE) of composite materials was judged by the working group to be immature. There is very little in-service NDE performed. Uses of composite materials thus far have largely been in low-criticality applications, where NDE was deemed unnecessary. Some post-fabrication inspection is now done as a check on materials fabrication or construction installation. There seems to be little driving force for NDE at present. The general feeling is "If regulations do not require it, why do it? It costs money."

The working group suggests the following answers to the question "Why do it?". For the materials supplier and fabricators, assurance of product quality is economically advantageous since users of composites will buy quality materials and structures and avoid inferior products. A supplier of inconsistent products will lose market share. For users of composite materials, assurance of safety is of primary importance. The costs of a catastrophic failure are huge. There is the possibility of loss of human life. Failure of a structure carrying petroleum products can lead to a devastating environmental impact. Additionally, lost production from a structural or key system failure can run into the millions of dollars.

Nondestructive testing of offshore composite structures has been limited to visual inspection, pressure or leak testing, acoustic emission, several forms of ultrasonic testing, and more recently, thermography. NDE is most often used **after** the first failure. An awareness of the need for NDE exists; however, there is a severe lack of commitment to development and implementation of nondestructive test procedures. The consequence of different flaw types in composites is also poorly understood.

Because of human factors, NDE will be necessary, even is the material is perfect. Damage may occur during transport to the offshore site and in handling the material. Improper assembly of composite systems can occur. There can be incidental damage during use of the composite structure from impact damage or over pressures. Even though composites are used for their resistance to corrosion, environmental degradation from ultraviolet radiation and harsh weather can occur.

6.4.2.2 State of the Art in Composites NDE

Composites NDE is highly advanced for "in-lab" inspections. NDE research has been highly funded for the last 20 years and a large number of techniques (relevant to composites) have been developed. Most methods; however, have not been developed to the level where a technician can use them in the field. A high skill level is presently required to perform many nondestructive tests and the interpretation of test results often requires a person of considerable skill. A wide variety of test methods are applicable to composites (Table 1). Some useful references which have surveyed or evaluated these methods are given at the end of this paper.

6.4.2.3 Global Condition Monitoring

It is imperative that global condition-monitoring methods be developed. These systems would indicate whether there have been any significant changes in a material or a structure. If no changes have occurred, the structure is likely to be in satisfactory condition. Should changes be observed, the structure may be examined in a detailed fashion. Global monitoring methods help develop confidence in new composite materials and structures. Such methods may also satisfy regulatory requirements for assessing the "health" of a structure.

Table 1.
Methods applicable to NDE of offshore composites.

• Acoustic emission	• Nuclear magnetic resonance
• Electrostatic (capacitive)	• Penetrant
• Hardness	• Radiography
• Holography	• Shearography
• Leak testing	• Thermography
• Microwave Leak testing	• Ultrasonics
• Modal analysis	• Visual

Figure 1 shows a typical plot of the probability of failure of a material or structure as a function of time. During a structure's infancy, failures occur with a higher incidence as the bad parts are weeded out. During the service lifetime of a part, failure is unlikely. As the time of use approaches the end of its lifetime the incidence of failure increases. Removing a structure from use as failure begin to be more common, prevents a catastrophic failure and uses the part for the maximum time. The service lifetime is not only a function of the material type and manufacture, but varies with the service history. Global monitoring can be used to gain confidence in the lifetime assessment of a structure. It is a means for following a material or structure through its history from "cradle to grave." Global methods, which can be used to inspect large areas inexpensively, should be used to monitor a structure periodically and also to record any events of significance.

An example of a global monitoring method is the use of acoustic emission sensors in piping to detect and localize leaks and impact damage. Optical methods, because they are inexpensive and easy to implement, would be particularly useful for structural monitoring. An adhesive or a structural material which changes color when subjected to abnormal strains or temperatures is a good example of a foolproof optical method. Attached or embedded sensors to monitor strain and temperature have been proposed, but tests have not been performed on marine composites.

6.4.2.4 Recommendations

The desired characteristics of an NDE system for inspection of offshore oil structures are listed in Table 2. System developers should refer to the table for guidance. There is a wide gap between the state-of-the-art (high-technology laboratory systems) in marine composite NDE and the state-of-practice (low tech methods such as visual inspection). Table 3 lists the recommendations of the working group for closing the technology gap.

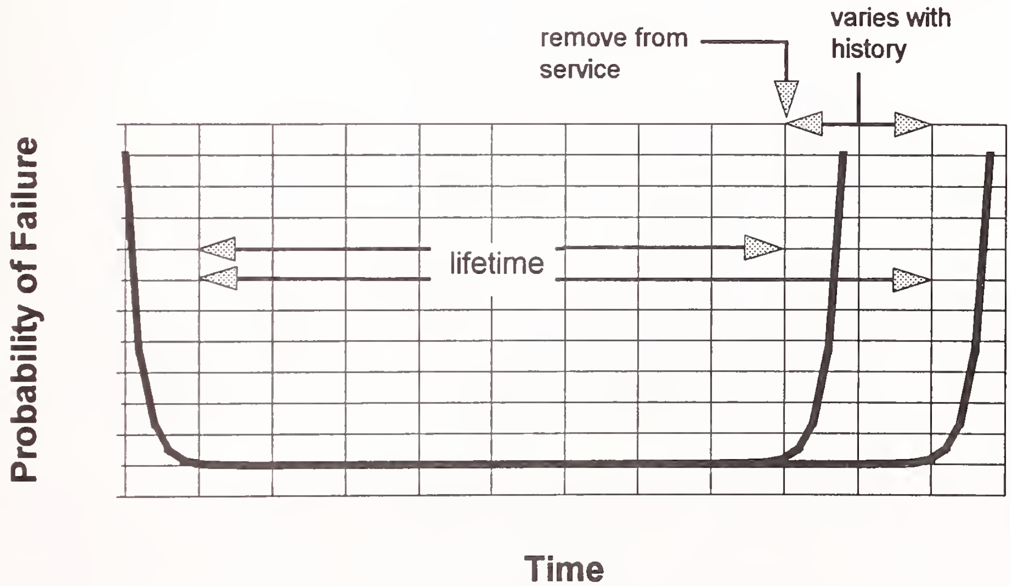

Figure 1. Probability of failure of a structure as a function of time.

Table 2
Desirable NDE system characteristics.

• Desired material characteristic is measured **directly** and **quantitatively**	• Procedure is adaptable to a variety of material systems
• Method must be highly developed — The physics should be well understood — System optimization should be possible	• Tests are reproducible — You get the same answer at various times and with various operators
• Global, as well as local, methods are needed	• Skills required for system use are easily taught
• Method is capable of rendering reliable data even under harsh conditions — Cold, heat, humidity, salt, undersea	• High reliability — Few false positives (don't "cry wolf" too often) — Few false negatives (missing a significant flaw can be catastrophic)
• Cost of inspection is low	• Easy to interpret test results
• System is portable	

Table 3.
Recommendations of Working Group #4.

- Fund a global condition monitoring project
- Gather a set of typical composite elements with and without flaws (and substandard material properties) for NDE system developers
- Be willing to design in inspectability
- Transfer technology from the laboratory to offshore (Fund development of robust, portable systems)
- Give NDE a higher priority (Don't make it an afterthought)
- Develop an assessment of flaw criticality (What is the consequence of various types of flaws on long-term performance?)
- Use a multiplicity of sensor types to decrease false positives and false negatives

6.4.3 References

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6.5 Summary and Recommendations of Working Group #5 on Flammability and Fire Retardation

6.5.1 Working Group #5 Members

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6.5.2 Summary of Discussion

Technical issues regarding flammability and fire retardation that must be addressed are listed below. Suggestions for procedures for implementing improvements are shown in the flow diagram of Figure 1.

Fire Modeling

- Fire models linked to structural models
- Model of fire performance applicable to design
  – validate for offshore

Fire and Blast Tests

- Scale — agility
  – small — large
  – large — small
- Effect of fire/structure ratio
- Historical/statistical data base development

- Utilization of failure modes
  – standardized test methods vs. specific application
- Methodology
  – performance based (adopt and develop)
    o UKOOA
    o NIST
  – fire safety of system vs. parts

Performance Requirements

- Specific location on platform (location/application)
- Conflicting requirements
- Regulatory buy-in (participation)
- Breakdown by element (i.e., smoke/toxic)

Economics

- Barrier
- Coatings
  – materials
  – installation
- Life-cycle costs
  – data base

Implementation

- Education on fire performance
- Training — human interface (what to expect)
- Communications
  – designers
  – labs
  – users
  – regulators
  – manufacturers
- Case history data base (good/bad)
- Demonstration project
- US/UKOOA information group
- Support infrastructure
- Professional societies (SPI, SACMA)

Other

- Overall safety
  – installation
  – maintenance

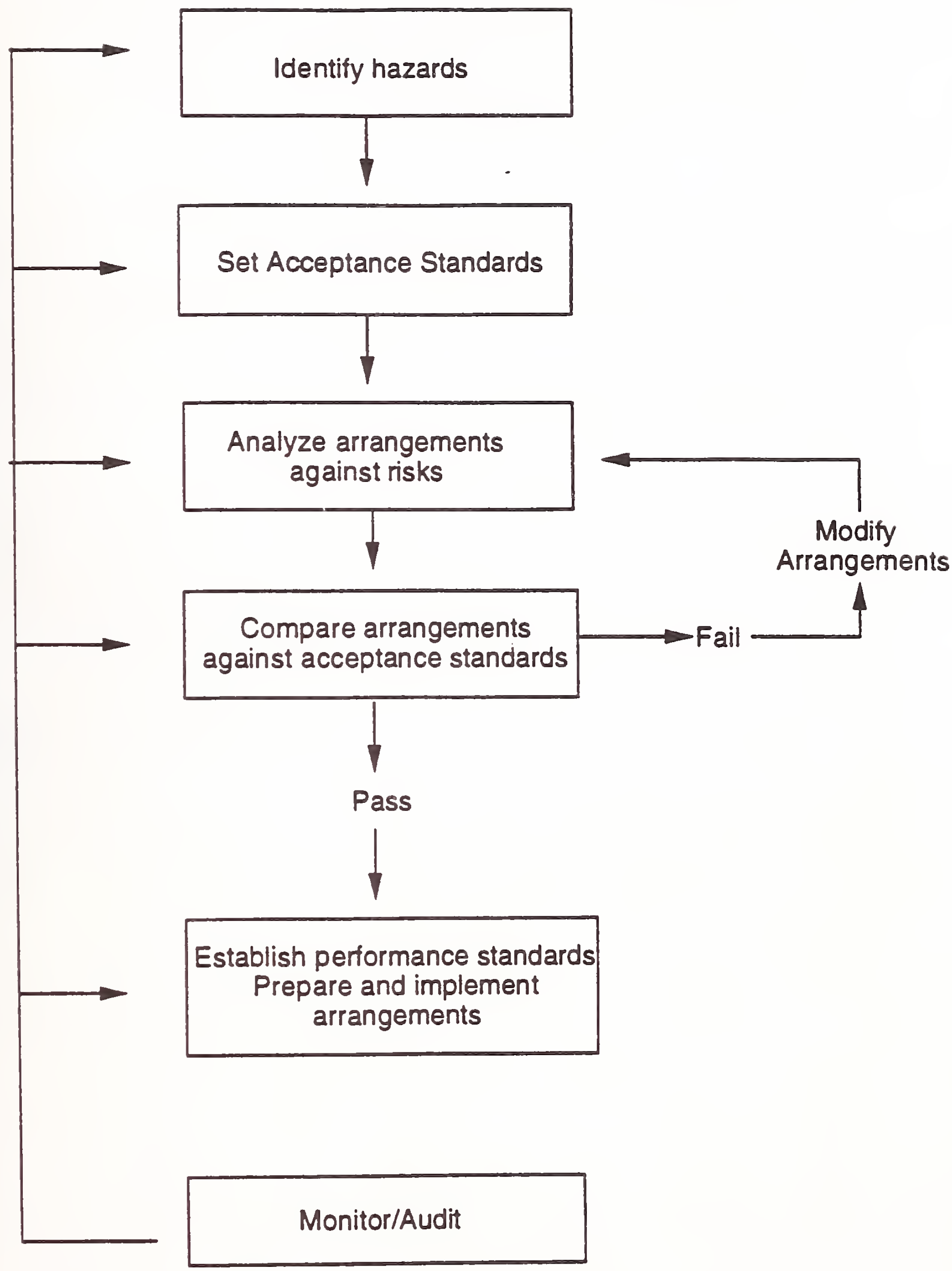

Figure 1. Suggestions for procedures.

6.6 Summary and Recommendations of Working Group #6
on
Facilities and Secondary Structural Applications

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6.6.2 Summary of Discussion

(No report available)

6.7 Summary and Recommendations of Working Group #7 on Advanced Applications

6.7.1 Working Group #7 Members

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6.7.2 Summary of Discussion

Innovations and technological advances are essential to the success of the offshore industry in meeting the challenges of exploiting natural resources in deeper waters. Oil and gas explorations in water depths exceeding 7000 ft (2100 m) and field development at a depth of 2900 ft are currently underway. Although the traditional engineering material for offshore structural applications is steel, other materials (e.g., composites) are now being seriously considered for several critical applications. The primary motives for using composites are to improve efficiency and reliability and to reduce life-cycle cost. The advantage of using these engineered materials can be easily demonstrated for structural systems where high strength, light weight and superior corrosion and fatigue resistance, as well as tailoring to meet other specifications (e.g., for stiffness and thermal expansion), are required. The use of composites also enables greater design flexibility and promotes system-oriented solutions. Efficient exploitation of composite materials dictated by economic or performance requirements is possible if materials, structural, and manufacturing technologies are utilized in an integrated approach.

In an effort to achieve this goal, the University of Houston organized the First International Workshop on Composite Materials for Offshore Operations. One of eight working groups, Working Group #7 focussed on advanced applications: barriers to the application of composites and how to resolve these barriers. Presentations were made by Joseph Fischer of Shell, Bill Anderson of Westinghouse Marine, and Doug Johnson of Brunswich on the use of composites for producing and drilling risers and riser stress joints. Doug Johnson also reviewed Brunswick's development of composite drill pipes. Alex Sas-Jaworsky of Conoco and Joe Roche of Hydril reviewed current efforts to develop high-pressure composite coiled tubing for workover, drilling, and completions. Charles Rogers presented the joint effort of NEPTCO and Bell Helicopter to develop highly aligned, continuous carbon-fiber rods that can be used for the construction of tendons. Winston Webber of Halliburton reviewed the application of composites to tanks and vessels and discussed problems associated with persuading certifying authorities to accept composites. Jemei Chang of Exxon reviewed several oil industry applications for onshore, downhole, and offshore. These applications included tubing and casing, piping, subsea well-head protectors, reinforcement for flexible pipe, and cable tray.

The second part of the working group activities focussed on identifying current barriers to the application of composites and how to overcome them. Detailed discussion on this subject is presented in the paper by Mamdouh Salama. Several needs were identified: the need to demonstrate economic benefits more than performance benefits; the need to evaluate a complete system rather than focus on component substitution; the need to produce building blocks; the need to develop alliances and consortia to leverage the limited available resources; and the need to recognize that the oil industry is structurally different from the aerospace industry. The final message was that members of the offshore industry desire and are ready for the use of composites because they are convinced that they offer the opportunity to improve operations and life-cycle costs.

Highlights of the discussion follow:

Composites — Applications

- Mooring/tendons
- Drilling/production risers
- Tubing
- Taper joints
- Coiled tubing
- Drill pipes
- Vessels
- Pipe
- Torque shaft
- Structural parts
- Seals
- Other

Applications

- Tubular pressure barrier
  – continuous: spoolable pipe (coiled tubing, flow lines)
  – discrete: production/drilling risers; taper joint
- Tendons (assembly of rods

Status of Technology

- Analysis: well developed
- Materials performance: wealth of data
- Fabrication: sufficient technology, low capital investment
- Inspection: adequate technology

Selection and Implementation of Composites

- Feasible only when the payoff value is judged to be greater than the cost at acceptable risk.

Real Barriers

- Composites not considered enabling technology
- Performance requirements not well defined
- Insufficient cost savings for discrete systems
- Major investment required for reliability assessment
- Reactive oil industry — short attention span regarding needs
- Change of culture — outside comfort zone
- Less tolerant to failure
- Lack of available resources (qualified engineers)
- Limited financial resources for development

Technology Needs

- Definition of true function, not design parameters — remove constraints
- Design feasibility to establish total cost ±40%
- Quantification of component and system reliability
- Component demonstration
- Repair

Message

- Demonstrate benefit — economic not performance
- Design system based on function, not on component specifications
- Applications based on complete system, not substitution
- Production of building blocks needed
- Oil industry structurally different from the aerospace industry
- Alliances and consortia needed to pool resources and skills

Impact of New Materials

- Reduced development cost
- Reduced operating cost
- Increased reliability
- Improved safety/environment

Technology Issues for New Materials

- Performance
- Reliability
- System methodology

Composites — Technical Issues

- Performance
- Availability
- Cost
- Reliability
- Repair/inspection

6.8 Summary and Recommendations of Working Group #8 on Certification Issues and Policy Concerns

6.8.1 Working Group #8 Members

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6.8.2 Summary of Discussion

(No report available)

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