- Study on tanker navigation safety standards. Requires the USCG to report on the adequacy of existing laws and regulations to ensure safe navigation of vessels transporting oil. The study is divided into 12 parts.

- Tank vessel manning. Mandates maximum working hours on board tankers in 24 and 72 hour periods.

- Autopilot, unattended engine room, and second licensed officer on the bridge. Establishes tanker navigation regulations which govern the use of autopilots and establishes minimum bridge manning levels.

- Establishment of double hull requirements. Requires phased in program of double hulled tank vessels based on age and size.

- Research in tanker grounding. Non-mandated USCG study being conducted at MIT to explore the behavior of tanker structures during grounding.

- Escorts for certain tankers. Designates certain U.S. waters (Prince William Sound [PWS], Rosario Strait, and Puget Sound) where at least two towing vessels must escort single hull tankers greater than 5000 GT.

- Revision of National Contingency Plan.

- Clean Water Act of 1977 (FWPCA) penalties. Increases penalties and creates new class of penalties.

- Terminal and tanker oversight and monitoring. Establishes Regional Citizens Advisory Councils (PWS and Cook Inlet).

As you can see, there are numerous preventive measures resulting from OPA 90. Now I would like to briefly talk about recent initiatives the oil industry here in Alaska has taken with the hope of preventing another major oil spill.

TAPS Vessel Owners/Operators Initiatives

- Providing an "ice scout vessel" for laden tankers in PWS when ice has been reported in the ship lanes.
• Laden TAPS tankers departing PWS will be escorted by Ship Escort and Response Vessels System (SERVS) vessels until they are clear of Seal Rocks.

• Laden TAPS tankers will not depart PWS if the prevailing weather conditions would prevent the SERVS escort vessels from rendering assistance near Seal Rocks.

• Feasible, cost effective recommendations from the Disabled Tanker Towing Study initiated in 1992 will be implemented.

• Once clear of Seal Rocks, laden tankers bound for the lower 48 will remain at least 100 miles offshore of the coastline of Southeast Alaska.

Nonpersistent Tank Barge Owners/Operators Initiatives

• Only twin screw tugs will tow member barges.

• Emergency tow lines present on all barges.

• Retrieval hooks on all coastwise tugs.

• Stricter tow wire maintenance and replacement standards.

As you can see, industry has instituted numerous voluntary initiatives that should assist in the prevention of a major oil spill, or in some instances mitigate its effects.

That covers my presentation today. I hope I have given some of you additional insight as to what has happened since the grounding of the Exxon Valdez relative to prevention. Have we come a long way? I think the answer is yes. Have we come far enough? That depends upon who you ask. I do know changes have been made, additional requirements are in the wings, and it is no longer business as usual. I think most people would agree that that is a good thing.
The Significance of Human Factors in the Prevention of Oil Spills

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Abstract

The development of automated systems arises in part from widely held concern about high operating costs. Driven by new technology, owners have partially automated marine systems. There has not been a clearly defined allocation of functions. Operators, owners, and regulators have been slow to reengineer the marine industry. Expectations of new technology have yielded new solutions, but with new problems, e.g., a user-centered approach. There is little doubt that advancing technology can assist people in the performance of tasks, but the human-computer interaction is still uncertain.

This paper discusses human factors and organizational behavior as it relates to the marine and oil industries. The paper’s theme is stress. Stress comes from job displacement, reengineering, work place design, and more. Stress can move a person in a positive or negative direction. This paper points out needed modifications in the quality of life at sea.

Introduction

Not recognizing the applicability of human factors has tremendous consequences. The Exxon Valdez oil spill is only one example of such a consequence. The Vincennes and Three Mile Island are examples that “became the center of that uniquely American mega-event: a media blitz. Screaming headlines blared the worst oil spill in U.S. maritime history.” Besides the environmental damage and destruction of catastrophic proportions, we cannot afford repeat performances (Peak 1990). With a company’s image, reputation, and profits at stake, management in the oil industry cannot afford to ignore the importance and relationship of human factors in the prevention of oil spills.

Mastery and control of future events are more likely by applying human factors principles. Some principles are allocation of functions, human reliability analysis (HRA), job design or reengineering, perfor-
mance aids, workload or manning, proficiency, selection, training, and task analysis. For example, a person’s situation awareness is needed for job performance. The marine industry has yet to consider situation awareness. Each of these principles, if gone unchecked, will yield a stressful environment.

Getting the oil to market as cheaply as possible is not the bottom line. Getting the oil to market with minimum risk of an accident or a potentially catastrophic event, is the bottom line. This implies consideration of all the human factors caveats. Critical decisions are biased by any impediment. Psychological stress is “a particular relationship between the person and the environment that is appraised by the person as taxing or exceeding his or her resources and endangering his or her well-being” (Lazarus 1989). This state of well-being has important consequences on the performance and productivity of an organization’s members. Sutherland and Cooper explain that to an organization in the oil industry, “the costs are enormous...in terms of reduced physical and/or psychological well-being and increased accident potential” (Lazarus 1989). When an employee’s well-being is at stake, an organization’s ability to effectively conduct its mission is impaired. Excessive stress may cause erroneous interpretation of radar data, jeopardize the safety of the vessel, or go undetected. Industries can prevent excessive stress by applying human factors principles.

Discussion

Management has recognized the value of teamwork or shipboard resource management (SRM). SRM is founded on a premise of value added and support where individuals work to a common goal. SRM is an allocation of functions. The allocation of functions designates who or what performs a task. Another example of function allocation is determining human-computer equivalency (HCE) aboard vessels with sophisticated automation. The human that operates and controls this technology cannot be ignored and must be in the hierarchy of control. Humans are preferred and needed, for human control cannot operate effectively without adequate communication or information of functions and performance. Humans are to remain in the loop. SRM and HCE will create a synergism that will yield both user acceptance and cost savings. The operation of today’s and tomorrow’s ships is different from yesterday’s. Vessel safety has been a paramount concern. The anxiety about safety and risk will be alleviated when the marine environment realizes and implements the new paradigm, i.e., SRM and HCE.

Conditions are exacerbated by the perception of risk. The sea is perceived to be inherently risky and hazardous. Work with chemicals such as oil dispersants and related errors, such as oil spills, are hazardous and
call for caution. Sutherland and Cooper (1989) show that “awareness of
the dangers and the consequences of making a mistake were significant
predictors of depression.” The solutions are in educating or training
personnel in situation awareness (Wilson 1994). Sutherland and Cooper’s
studies show “accidents, media attention and the need for special training
to deal with emergency routines heighten the level of risk awareness...”
Situation awareness is training to cope with emergencies and will alleviate
anxiety and stress. When organizations incorporate situation awareness
and invest in reengineering, safety and risk perceptions will be reflected.

The at-sea or offshore environment requires working hours atypical
to most other industries. These hours include long working shifts and night
shift work that lead to fatigue, more specifically sleep deprivation. When
the crew is tired, the skill to make decisions is impaired. Risk and safety
issues are aroused and induce stress. The work, rest, sleep times (WRST)
need to be determined. Workload analysis needs to be determined. More
than a 70-hour work week is too much. Thompson elaborates that automa-
tion, “has allowed ship operators to reduce the size of the crew. But
according to the Coast Guard’s Report in October 1989, ‘The effects [of
automation] seem to be crew fatigue and neglected vessel maintenance
due to reduced manning...’” (Thompson 1990). Currently, manning is set by
laws pertaining to watch standing, enacted over 50 years ago. It seems
proper that workload vs. human error be the catalyst as justification for
determining the manning requirements.

Automation or technology is the primary reason human factors is
more important than ever before in industries and can be most beneficial
in the offshore and at-sea environment. The task analysis is the justifica-
tion for what work an individual is to perform. The intelligent vehicle
highway system (IVHS) is an excellent model for how to use human
factors and is the most dramatic example of HCE. For example, what are
the hand-eye motions to maneuver a car of the future? IVHS America is
looking at a car that is still to be manufactured. The user perception of
future technology has not been implemented by the Coast Guard nor the
shipping industry. The Coast Guard has used equivalency before and will
probably use it again. Industry must make the case. For example, since
many vessels already have periodic unattended engine rooms, it makes
sense to have main control in the wheelhouse, yet regulations still require
main control to be located below the main deck. With the introduction of
more sophisticated automation, personnel will be displaced for the watch-
standing task, but not for maintenance or reliability. In order to have the
benefits of technology, sophisticated automation needs to be user-centered.
Management cannot downplay the risks of human error when automation
is solely technology driven.
Another significant factor is profit pressure from management. In the effort to meet deadlines and profit goals, shortcuts are made or at least considered. This is where reengineering fits into job design. With crews operating at manpower minimums, many incentive programs support the quick fix or shortcut. Thompson states that, "the owners and managers of some ships have certainly stretched the envelope of safety—and common sense—to the breaking point. Some cost-cutting measures appear to cut too many corners. Among them: schedules that don't leave enough time for travel; maintenance or safety; hiring cheaper foreign crews that may have inadequate training or experience; registration of ships with "flags of convenience" from countries that offer relaxed enforcement of safety and crew certification standards" (1990). It is not just organizations related to the merchant marine. It is management in general that has perpetuated this business practice. Managing a 9:00 am to 7:00 pm operation five days a week is different from managing a 24-hour-a-day, seven-day-a-week operation for 90 to 120 days at a time. Marine transportation management cannot operate with a financial management mentality without incurring increases in risk. Reengineering the shipping business has yet to occur.

Workspace affects personnel. The physical work environment on board vessels is traditional and needs to be redesigned. This is partly because of the developing regulations that administer the merchant fleet. The unions and the private sector have met "the physical demands of the living arrangements...still on many ships berthing is in close proximity to the working areas. The sharing of confined spaces, lack of societal norms, or inadequate recreation—leisure facilities" can be counterproductive during long voyages. The confines of the ship dictate the relationships on board. Feeling "lonely in the company of other people" is often exacerbated by the conditions where social networks are confined too (Sutherland and Cooper 1989). Working relationships can be affected. Peers and management are forced to get along with each other. For many, these conditions are worsened by lengthy voyages, stays away from the support of friends and family. The feeling of isolation or sensory deprivation (Sutherland and Cooper 1989) is another significant factor and it is usually a dissatisfier. As the crew size decreases, the sensory deprivation increases. Workplace design is a job satisfier and can counter sensory deprivation. Physical well-being contributes to mental well-being.

Facilities such as a workshop, fitness center including a swimming pool, and satellite television reception brings societal norms to the at-sea environment. Mental well-being is also important to an employee’s state of mind. The information age will help to alleviate the mental stress. In any 24-hour society, the constant peer-to-peer and manager-to-labor relationships may not be smooth. Leadership, motivation, and productivity...
are achievable, but the challenge is greater. Workspace design is more important than ever before. Redesigning the ship's workplace will have positive affects on behavior and performance (Sutherland and Cooper 1989). For improved productivity, the wheelhouse needs substantial redesign. All wheelhouses should be standardized like the cockpit of an aircraft. Aircraft standardization is by design not by chance.

Measurements of Effectiveness

The relationship between the effects of human factors on organization behavior and the linkage to potentially harmful accidents has been examined. The costs of ignoring human factors are high. With such high stakes, management must be concerned with implementing human factors. The maritime environment has characteristics particular to itself (Wilson 1992). Therefore, a means of measurement can only be effective if it is marinized.

Physiological Measurements

Alcohol and drugs are a factor in the sequence of events that lead to an accident. Both are considered to be a strong indicator of stress experienced by people everywhere. Naturally, "excessive stress can lead to several health problems in the form of . . . abuse" (Schermerhorn 1994). Although a drink per day is recommended by the American Medical Association, incidents of excessive alcohol consumption interfere with performance, and are easily recognizable by coworkers or authorities. Sobriety tests are indeed a measure of fitness and readiness for duty.

Another measure of effectiveness is the medical examination. The Federal Aviation Administration requires all commercial pilots to be physically examined every six months. Healthy employees are more productive. Biological measures such as "blood pressure, heart rate, galvanic skin response, and respiration rate are some physiological indexes used to measure stress" (Lazarus 1989) and performance. It is in management's interest to not only monitor these indicators, but also to provide the resources for activities such as exercise and physical fitness. Access to a fitness center should be provided to employees.

Stress can improve or weaken performance. Therefore, the measurement of performance can be used as an indicator of the presence of stress. Performance tests "measure the after-effects of exposure to a stressor. If subjects show lowered ability to do certain tasks after having been exposed to such stressors as loud noise . . . then it may be assumed that the impaired performance was due to the stress . . . performance tests should not be used alone as an indicator of stress, but should be supplemented by other devices" (Lazarus 1989).
Another method used to measure performance is feedback reporting. As trips or tasks are completed, members can be solicited for feedback on their own performance and the performance of other team members. Review of these reports can alert management to potential problems. Data from these reports should be maintained for building profiles of human reliability. Changes in personnel or workload must be monitored over periods of time as the profiles give a historical perspective for analysis.

Psychological Measurements

Except for drug and alcohol tests, there have been no quantifiable methods to test mental reasoning. Although these are widely accepted in the detection of stimulants and depressants that impair reaction time, the ability to test performance as a function of workload has only recently been explored. New computer software packages have been created to measure performance (McGinley 1992).

Predicting Performance

A performance testing software package called Factor 1000, developed by Performance Factors, Inc., tests mental alertness and coordination of Domino’s Pizza truck drivers, warehouse workers, and dough makers. The test is a simple video game that measures hand-to-eye coordination by having the user try to keep a swinging pointer centered on a computer screen. A Domino’s employee who fails the test is simply assigned paperwork or other tasks that do not involve much stress or danger (McGinley 1992).

Delta, a more enhanced performance testing package from Essex Software, is being piloted by a Japanese nuclear power utility, a foreign navy, and a major U.S. oil company. This package combines the technology from Factor 1000 with 20 tests that measure perception, reasoning skill, and judgment. Jeffrey Lapides, vice president of commercial products for Essex, claims that the software is not expensive (about $1,000 per copy) in comparison with the liability and employee disability law suits stemming from preventable accidents. Since testing began, many private companies have reported a decrease of on-the-job accidents by 67% (McGinley 1992).

Oil Spill Prevention and Recommendations

Since March 1989, life in the maritime industry has changed forever. If a single solution is chosen for oil spill prevention it must be human factors. Inasmuch as statutory reform is late or absent, training and education is the first step and is one aspect of human factors. Besides past
and current training, human factors principles must be taught. This will reduce or contain the by-products of stress, such as human error. As a marine inspector, I have inspected many ships and evaluated many mariners. Knowledge, skills, and abilities (KSA) ensure performance.

"Training was almost always lacking, not so much on the part of the officers but with the rest of the crew . . . Spills by oil tankers provide an object lesson in the costly failure of a technical-training system to keep itself updated . . . because an inadequate technical-training curriculum creates the illusion of competence, it virtually ensures the accident it is intended to prevent" (Thompson 1990). Management and industry must address this education issue or the regulator will. KSA will be the determinator for tomorrow's education and training. The feeling of personal mastery and control of a situation is desirable. Human errors are reduced by KSA. Risks are minimized by KSA. Job satisfaction increases with KSA. Users must control technology. It is time for a new paradigm (Wilson 1992).

Training can be accomplished in many ways. Oil spills provide empirical data that must be used. These historical reviews can be used for scenario analysis. An individual's response and decision-making skills can be sharpened through walk-throughs or mental modeling. Technology exists today, i.e., simulation and expert systems that will capture the expertise for different training scenarios in a knowledge base. Today's ship should not sail without simulation games for training and recreation.

The maritime schools are our educational centers of excellence. The simplest and most effective solution to oil spill prevention lies in the education of the maritime work force. The linkage to performance is clear: providing education and training results in a work crew that is able; esteem and morale improve; job satisfaction improves; stress is reduced; and productivity will increase. In a time where TQM (total quality management) means business, human factors means safe, reliable, and effective performance. Human factors is a part of business that a company cannot afford to do without.

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Development of a Computer-based Model to Estimate the Staffing Needs of Commercial Ships

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Abstract

Technological developments and economic pressures have led to a 50% reduction in crew requirements on commercial ships. The promise of a “one-man bridge” and other technological changes may make additional reductions possible. However, the effect of these reductions on overall ship safety is unknown. In the past, crew requirements have been based on an evolutionary approach that has slowly adapted the crew size to meet the demands of the ship operation. Rapid changes in technology and operating conditions may render this evolutionary approach unworkable. This paper addresses the problem of specifying crew requirements by describing the development of a model that will provide a formal, objective method for determining the crew complement required for merchant vessel operation. This model will combine the time and expertise requirements of individual shipboard functions to estimate the crew resources required for different ship, technology, and route configurations. The viability of a proposed crew complement will depend on whether the calculated work hours for any of the crew exceed predefined work-hour limits. The primary benefits of this model are the ability to provide consistent estimates of crew requirements, facilitate communication between industry and the Coast Guard, and identify how staffing changes influence the overall safety and efficiency of ship operation.

Introduction

The issue of shipboard staffing is a complicated legal, economic, and human factors engineering question. The worldwide trend in shipboard staffing is toward increasingly smaller crew sizes—in the case of some Japanese ships, crews are composed of as few as 11 persons. Crews
of these sizes are made possible by advanced technologies permitting unmanned engine rooms and one-man bridge operation, as well as reductions of deck crew for cargo handling. A fundamental question that arises as a result of such crew reductions is the extent to which smaller crews compromise ship safety and the ability to respond in an emergency. This question has not been addressed satisfactorily, and there is a need for a systematic method of establishing safe crew levels that can be applied on an international basis. A number of authors share this opinion (Seitz 1981, Knudsen and Mathiesen 1987, Froese 1987, Joseph 1987, Gaffney 1987), and several approaches have been developed.

Although a variety of methods can be used to evaluate staffing requirements, the 1990 National Research Council (NRC) report illustrates the limitations of these techniques. For example, adjusting ship staffing and evaluating the rate of subsequent accidents could be catastrophically expensive. Furthermore, the many concurrent changes that might accompany crew reductions make it very difficult to identify a causal link between crew reductions and subsequent changes in accident rates. Computer-based models provide a safe, cost-effective alternative. A computer-based model that can predict the consequences of changes in manning levels on ship safety could enable ship owners and regulators to evaluate a wide range of potential staffing alternatives.

In the context of this paper, "model" refers to a simplified representation of a system that translates input variables, such as changes in manning, into output variables, such as changes in ship safety. In essence, a model provides a simplified, abstract representation of an actual system, to evaluate system effectiveness. Therefore, any model developed will have limitations that include the types of scenarios it accommodates, decision support capabilities, ease of use, and the detail with which it describes shipboard tasks. However, as technological and economic pressures combine to modify staffing structures, even limited models of the human element aboard ships will help evaluate the safety consequences of proposed changes.

The need for a model of ship staffing is driven by the need to understand how reduced or modified staffing influences ship safety. The general issue of ship safety involves several more specific concerns, such as the ability of the crew to operate the ship without exceeding work-hour limits, the effects of increased technology, emergency response effectiveness, and maintenance capabilities. In establishing safe crew levels, government and industry need to consider demands on the crew, each vessel's technology, type of service, crew skills, quality of management, and training programs. Evaluating how these and other issues affect ship safety provides a crucial step toward developing a technical basis for estimating the staffing needs of commercial ships.
One simple criterion of ship safety is work hours completed by the crew. If any crew member exceeds agreed-upon work-hour limits, then the ship requires more crew members to operate safely. Therefore, a basic requirement of a staffing model is the ability to test whether a proposed crew can operate a ship without exceeding work-hour restrictions. The need to match crew qualifications to the task requirements complicates this simple requirement. Therefore, the model must incorporate information concerning both the time and skill requirements of each task. Developing a model that matches the time and expertise requirements of shipboard tasks with the proposed crew can help evaluate the effects of automation, the viability of maintenance plans, and emergency response capabilities.

Introducing advanced technology may automate many functions and offer opportunities to reduce crew size. However, it is not always obvious whether automation justifies crew reductions. Automation promises to reduce the physical and mental workload of ship personnel; however, the capability of automation to reduce workload in a way that promotes ship safety, especially in abnormal situations, is poorly understood. Research in the aviation and process control domains suggests that introducing automation often compromises system safety rather than enhancing it (Woods, Potter, Johansen, and Holloway 1991, Wiener 1985). In many instances designers automate what is most easily automated, leading to a patchwork of systems that inhibit rather than support personnel. In addition, automation often operates smoothly during normal operations, but fails when the personnel need it most, during abnormal operations, leading to workload peaks greater than those experienced without automation (Wiener 1989). A model that matches task requirements to the proposed crew complement will identify workload peaks that might jeopardize ship safety. Therefore, the model will help avoid simplistic assumptions of workload reductions that might justify crew reductions. Thus, the model will help avoid unjustified crew reductions that may jeopardize ship safety.

Besides the problems associated with introducing new technology, emergency response capabilities represent an aspect of ship operations that may be especially sensitive to changes in staffing. Emergency response requires a coordinated effort of the crew, often in unfamiliar and adverse situations. Emergencies may require more people than normal operations, and the demands on these people may exceed those of routine activities. In addition, the ability of personnel to react efficiently to emergencies has immediate implications for the safety of the crew and for the integrity of the ship. Predicting the ability of a proposed crew complement to mitigate emergency situations would provide crucial information concerning how changes in staffing structure affect overall ship safety.
Like emergency response capabilities, the ability of a ship's crew to maintain the ship effectively may be particularly sensitive to changes in the staffing structure. Because ship safety is directly dependent on the quality of the maintenance, conditions which lead to inadequate maintenance require identification. Preventive and shore-based maintenance both act to alleviate unexpected maintenance demands. However, the effectiveness of these techniques, in conjunction with reduced staffing, has not received a detailed examination. A model can examine how different combinations of shore-based maintenance and modified staffing structures combine to affect ship maintenance.

In summary, to estimate the staffing requirements of a commercial ship a model must consider several issues. Most simply, a model that supports staffing decisions must consider whether the proposed crew can operate the ship without exceeding work-hour limits. This criterion can be used to address the impact of increasing complex technology, emergency response capabilities, and maintenance effectiveness. To evaluate the feasibility of producing such a model we examined past modeling efforts in the maritime and non-maritime domains. Past efforts show that no model currently exists that provides answers to these questions; however, previous efforts show that developing a model is feasible.

**Approach**

**Identification of Desired Model Capabilities**

To be most effective, the model developed during this project must include capabilities required by both the Coast Guard and industry. To ensure that the model includes these capabilities the views of labor representatives and ship operators will be solicited throughout the development process. At the beginning of the development process, a list of desired capabilities was generated through discussions with Coast Guard personnel, ship operators, and labor representatives. The interviews with ship operators ranged from oil tankers and container ships to research vessels and tug-barge combinations. Some capabilities were also identified from previous studies, such as Lee and Sanquist (1992), NRC (1990), and Grabowski and Hendrick (1993). Although we have tapped a range of sources, these capabilities represent an initial identification of what the model should be able to achieve. As development of the model progresses, additional capabilities are likely to be identified.

The model capabilities include the ability to examine the impact of automation, the emergency response capabilities, and the feasibility of maintenance programs. Specifically, the model will evaluate the effects of automation by adjusting or eliminating the time requirements of those
tasks affected by the automation. The model will then show how these changes influence the overall staffing requirements of the ship. The model will also evaluate the emergency response capabilities of a crew by examining whether sufficient crew members exist to perform all the tasks associated with a variety of common emergency response scenarios. To evaluate the viability of maintenance proposals the model will enable decision makers to evaluate whether sufficient crew and time are available to perform maintenance tasks when some are allocated to shoreside or riding crews.

Rapid Prototyping Approach to Model Development

Potentially, the model could include a wide variety of capabilities. However, it is not clear how best these capabilities should be implemented. To ensure that a model meets the needs of the Coast Guard and industry, these capabilities will be developed in a series of prototypes. Comments from the Coast Guard and industry will guide the development of successive prototypes so that the capabilities of the model will meet the requirements of the users.

Based on comments from industry and the Coast Guard, each prototype iteration will generate a model that is more useful than the one before. For each prototype, three elements are considered in making a more useful model. Each element is critical and neglecting any one of the three would result in a model that would fail to meet the needs of the Coast Guard. The three elements include:

- Data manipulation capabilities
- User interface enhancements and documentation
- Model accuracy

Data manipulation capabilities concern the ability to combine task/function data with potential crew configurations in different ways to evaluate proposed changes. For example, adding the ability to evaluate the consequences of a variety of shipboard automation alternatives facilitates analysis of shipboard data in a different way. User interface enhancements and documentation do not change the data manipulation capabilities of the model; however, these changes make the model easier to use. These changes also make the output of the model more comprehensible. For example, enabling users to view the output of the model in different formats (graphs or tables) and save results in a convenient format will help them take advantage of the data manipulation capabilities. Enhanced model accuracy is a requirement if the results are to be trusted and used to set
policies. Model accuracy depends on how well the relationships within the model reflect reality. For instance, the first prototype will assume that the tasks occur independently with a fixed frequency. The accuracy of future models will increase as additional information will be used to define when and how frequently tasks occur. Each prototype will include enhancements to the data manipulation, user interface, and model accuracy.

The goal of this project is to develop a model of ship staffing that will help the Coast Guard and industry to determine minimum staffing requirements. One of the primary objectives in developing the model is to ensure that its capabilities reflect the needs of potential users. To achieve this objective, model development will consist of a series of prototypes. Each prototype will be evaluated by ship operators, Coast Guard personnel, labor representatives, and modeling experts. The modeling experts will guarantee model accuracy and the others will ensure that the model contains the requisite features and capabilities. Based on comments from these groups, the model will be revised and a new prototype will be developed (see Figure 1).

**Framework for Model Development**

To arrive at an accurate estimate of crew size will require sophisticated data processing and modeling mechanisms. These mechanisms must be paired with an extremely flexible user interface that can deliver information in an easily comprehensible form. Furthermore, these requirements must be satisfied in the context of a limited budget and time.

![Figure 1. A diagram illustrating the process used to create a model to estimate the staffing needs of commercial ships.](image-url)
To satisfy these criteria, a customized user interface will be developed as a shell that surrounds a powerful computational engine. The primary benefits of this approach include:

- A user interface, free of computer jargon and simulation syntax, that eliminates the need for specialized modeling expertise.
- Access to the power of task network simulation and a relational database.
- A powerful, customized application that avoids the majority of software development costs.

Figure 2 illustrates some of the main features associated with a custom tailored shell that surrounds task network simulation and relational database engines. The user interface manages the flow of information so that the user never needs to encounter the database or simulation engine. The left side of the figure shows several information flows into the model, and the right side shows several information flows leaving the model. For example, the model will enable users to enter a variety of emergency scenarios, such as engine room fire. The right side of the figure shows a variety of output information. One of the more important types of output are model diagnostics. These include assumptions, such as those that might accompany work-hour estimates and workload reductions associ-

![Figure 2](image)

*Figure 2. An illustration of how the user interface shell will work with the database and simulation engines to support users.*
ated with various types of automation. The diagnostics, combined with screen-based charts and tables, clearly describe the implications of manning configurations on personnel work hours.

Conclusion

The capabilities included in the model will provide an effective way to augment the intuitive heuristics that justify the current staffing levels of commercial ships. The model embeds a powerful task network simulation within a user interface that can be tailored to the specific needs of regulators, ship owners, and labor representatives. In this way, the model avoids burdening decision makers with the need to develop, execute, and analyze simulations. The model will support analysis of three critical aspects of ship operation: the effect of increased automation, the effectiveness of various maintenance programs, and emergency response capabilities. Because the model considers all phases of ship operation, the entire crew, and a variety of voyage scenarios, the model can provide a realistic analysis of these issues. This will help avoid indiscriminate crew reductions that might follow the introduction of automation and jeopardize safety.

Developing a series of prototype models will identify the potential scope, flexibility, and role of a computer-based model in the decision making process associated with ship staffing. The rapid prototyping process outlined in this paper provides practical method for examining these issues. In this process, prototypes are developed and presented to the Coast Guard and industry. Based on comments from these groups, these prototypes can be refined and presented for further evaluation. The end product of this process will be a basic staffing model that provides a first step toward a technical basis for evaluating crew requirements. In addition, this process will identify the need for subsequent data collection and model development.

Disclaimer

The views and conclusions contained in this document are those of the authors and should not necessarily be interpreted as representing the official policies, either expressed or implied, of the United States Coast Guard, Washington, D.C., or the U.S. Government.

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The Grounding Resistance of Alternative Structural Systems for Tankers

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**Abstract**

As a result of OPA 90, all single hull tankers in the coastal trade will be replaced by double hull ships by early in the next century. Comparative grounding analyses and oil outflow studies support this legislation.

Stranding tests were performed on quarter scale hull bottom models of the 32,000 dwt *Paul Buck* and an Advanced Double Hull alternative. These tests showed that in addition to the crushing of the bottom structure which occurred prior to inner shell rupture, plastic deflection lifted the innerbottom out of the rock's way.

Grounding analyses of single and double hull tankers were performed with these plastic deflection considerations. Since the quantity of steel in a hull is dictated by longitudinal strength requirements, the shell of a single hull tanker will be thicker than the outer shell of an equivalent size double hull tanker. Hence, for the statistically most likely shallow penetrations, the damaged length of a single hull tanker will be less than for the equivalent double hull tanker, although the double hull tanker will not have spilled any oil. When deeper penetrations involve the innerbottom, the damage length of the single and double hull ships is about the same.

**Introduction**

The Oil Pollution Act of 1990, as adopted in the Code of Federal Regulations (1992) mandates that all tank vessels for which the building contract was awarded after 30 June 1990, must be of double hull configuration if it is intended to transport oil in the navigable waters of the United States, including the U.S. Exclusive Economic Zone. Major conversions of existing tank vessels are also included in this mandate in that they are treated as new construction.

Existing tank vessels built without double hulls, double bottoms, or double sides will not be permitted to operate in U.S. waters after reaching the specific age and date explicitly stated in the Act. This is illustrated in
Figure 1. Age-date limits for single hull tanker operations.

Figure 1, derived from the age-date limit data in OPA 90. The age limit lines for existing single hull, double bottom, or double side configurations are plotted for vessels above 30,000 gross tons. The age-date line for the 120,000 dwt single hull Arco Anchorage intersects the age limit line at the year 1998, when the ship will be 25 years old. Similarly, the first ships of the 80,000 dwt America Sun class and the 75,000 dwt Exxon San Francisco class will become obsolete in 1996 when the ships become 26 years old. In no case can a single hull ship be operated in U.S. waters after 2010, or after 2015 for an existing ship with double bottom or double sides, regardless of the age of the vessel. From a brief review of the TAPS tanker listing in Table 1 derived from the USCG (1990) reference, it is evident that a major portion of the fleet will become obsolete well before these limiting dates.

During the interim period before an existing tanker reaches the limiting operating date, proposed new rules, as presented in the CFR (1993), will require certain structural and/or operational modifications to “provide as substantial protection to the environment as is economically and technologically feasible.”

It should be noted here that double hull tank vessels did not originate with OPA 90. Double hulls were introduced many years ago as safety and antipollution measures for the transport of hazardous and toxic
<table>
<thead>
<tr>
<th>Tanker Identification</th>
<th>Gross Tonnage</th>
<th>Builder</th>
<th>Delivery Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>America Sun class</td>
<td>80,755 dwt</td>
<td>37,269</td>
<td>Sun</td>
</tr>
<tr>
<td>Arco Anchorage class</td>
<td>120,300 dwt</td>
<td>57,691</td>
<td>Bethlehem</td>
</tr>
<tr>
<td>Atigun Pass class</td>
<td>173,400 dwt</td>
<td>74,250</td>
<td>Avondale</td>
</tr>
<tr>
<td>Chevron Oregon class*</td>
<td>39,200 dwt</td>
<td>16,941</td>
<td>FMC Corp</td>
</tr>
<tr>
<td>Exxon New Orleans class</td>
<td>67,800 dwt</td>
<td>32,035</td>
<td>Newport News</td>
</tr>
<tr>
<td>Exxon San Francisco class</td>
<td>75,650 dwt</td>
<td>34,266</td>
<td>Avondale</td>
</tr>
<tr>
<td>Exxon Long Beach</td>
<td>211,500 dwt</td>
<td>94,999</td>
<td>NAASCO</td>
</tr>
<tr>
<td>Massachusetts class</td>
<td>262,400 dwt</td>
<td>117,515</td>
<td>Bethlehem</td>
</tr>
<tr>
<td>San Diego class***</td>
<td>188,000 dwt</td>
<td>83,650</td>
<td>NAASCO</td>
</tr>
<tr>
<td>Sansinena class</td>
<td>70,500 dwt</td>
<td>35,633</td>
<td>Bethlehem</td>
</tr>
<tr>
<td>Sun &quot;TAPS&quot; class*</td>
<td>122,000 dwt</td>
<td>60,384</td>
<td>Sun</td>
</tr>
<tr>
<td>Mobil Arctic</td>
<td>125,000 dwt</td>
<td>57,834</td>
<td>Sun</td>
</tr>
<tr>
<td>Arco Texas***</td>
<td>89,950 dwt</td>
<td>5,935</td>
<td>Bethlehem</td>
</tr>
<tr>
<td>Exxon Baytown**</td>
<td>57,720 dwt</td>
<td>32,204</td>
<td>Avondale</td>
</tr>
</tbody>
</table>

* pre-OPA 90 double hull; ** double bottom; *** jumboized by N.N. 11/81
cargoes, including liquefied gasses. In some cases, double hull configurations were adopted to insure purity of high value liquid cargoes and to facilitate cargo tank cleaning.

The discussion in the following paragraphs is concerned with the design and construction of new double hull tankers conforming to the requirements of OPA 90. In particular, the grounding resistance of alternative double hull structural systems is compared with the grounding resistance of an existing single hull tanker, for tanker designs of approximately the same size. Interim results from an ongoing major double hull structural research program are used in the analysis.

**Advanced Double Hull Research at CDNSWC**

Under sponsorship of the Office of Naval Research, the Carderock Division, Naval Surface Warfare Center (CDNSWC, formerly the David Taylor Research Center) has been engaged in a major research and development effort leading to practical application of advanced double hull structural design concepts to naval combatants and auxiliaries and commercial tank vessels. (The advanced double hull concept is a unidirectional structural configuration consisting of longitudinal web members connecting the inner and outer hulls. This cellular arrangement has such inherent strength that conventional transverse web frames are unnecessary.) The Advanced Double Hull (ADH) Technology Project has been designated a Congressional Interest Project and funds were appropriated for FY 92 and FY 93, with the period of performance extending through FY 94. Results of the research completed during the first year have been applied primarily to commercial tanker design.

Conventional single hull tanker structure consists of a complex grillage of longitudinal framing, widely spaced transverse web frames, and oil-tight longitudinal, and transverse bulkheads providing cargo subdivision. Conventionally framed double hull tanker structure includes a similar grillage of longitudinal and transverse framing. The ADH framing system which is the principal subject of the research program is an alternative concept with only longitudinal, unidirectional, framing. Advantages claimed for this concept are simplification of structure, improved resistance to collision and grounding, and reduced construction and maintenance costs. Examples of these structural systems are shown graphically in the following section of the paper.

The ADH program consists of 18 tasks in the general areas of structural integrity, affordability and survivability, as shown in the task summary, Table 2. The program includes major expenditures for structural model tests and correlating analytical studies, including large scale model
Table 2. Advanced Double Hull Technology Project.

<table>
<thead>
<tr>
<th>Structural Integrity</th>
<th>Affordability</th>
<th>Survivability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collapse behavior</td>
<td>Automated fabrication</td>
<td>Resistance to underwater explosion holeing damage</td>
</tr>
<tr>
<td>Fatigue life of cellular structures</td>
<td>Corrosion protection</td>
<td>Resistance to underwater explosion whipping damage</td>
</tr>
<tr>
<td>Stress behavior</td>
<td>Outfitting of distributive systems</td>
<td>Acoustic signature control</td>
</tr>
<tr>
<td>Foundation concepts</td>
<td>Hydrodynamic performance of new design concepts</td>
<td>Damage control</td>
</tr>
<tr>
<td>Grounding response</td>
<td>Ship integration</td>
<td>Equipment shock response</td>
</tr>
<tr>
<td>Internal deck options</td>
<td>Inspection, maintenance, and repair</td>
<td>Resistance to air explosions</td>
</tr>
</tbody>
</table>

tests to investigate stranding and grounding response. Tests completed to date include collapse behavior of nine small-scale and five large-scale column models, loaded in axial compression to determine post-buckled residual strength. Also completed are stranding tests of one-fourth scale tanker double bottom models with conventional framing and advanced unidirectional framing systems. Future tests of particular relevance to this forum will include large-scale grounding tests of double bottom structures. Results of these tests will be published in reports to the ONR sponsor and will be presented before professional societies in future papers.

Comparison of Three Tanker Designs

Two existing U.S. flag product tanker designs were selected for this study, the Overseas Alice and Paul Buck classes. The principal characteristics of the classes, as built, are summarized in Table 3. Product tankers of approximately this size are the most likely for near-term construction for U.S. flag coastal and intercoastal service in the protected Jones Act trades.

General arrangement sketches of the Overseas Alice class product tankers are shown in Figure 2. While the ships of the Overseas Alice class were delivered in 1968 and 1969, at least seven of this class are believed
Table 3. Principal characteristics of representative 32,000-37,000 dwt product tankers.

<table>
<thead>
<tr>
<th>Ship Characteristic</th>
<th>Overseas Alice Class</th>
<th>Paul Buck Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length BP (feet)</td>
<td>630.0</td>
<td>587.5</td>
</tr>
<tr>
<td>Breadth, mid (feet)</td>
<td>90.0</td>
<td>90.0</td>
</tr>
<tr>
<td>Depth, mid (feet)</td>
<td>48.8</td>
<td>653.67</td>
</tr>
<tr>
<td>Draft, mean (feet)</td>
<td>36.6</td>
<td>536.05</td>
</tr>
<tr>
<td>Displacement, total (1 ton)</td>
<td>46,243</td>
<td>41,584</td>
</tr>
<tr>
<td>Deadweight, total (1 ton)</td>
<td>37,814</td>
<td>32,446</td>
</tr>
<tr>
<td>Cargo Tank Arrangement</td>
<td>3 x 5</td>
<td>7 x 2</td>
</tr>
<tr>
<td>Number of Tanks, ex slops</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>Propulsion Machinery</td>
<td>Steam turbine</td>
<td>Low speed direct diesel</td>
</tr>
<tr>
<td>Power, max continuous (hp)</td>
<td>15,000</td>
<td>15,300</td>
</tr>
<tr>
<td>Service Speed (knots)</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Hull Configuration</td>
<td>Single</td>
<td>Double</td>
</tr>
<tr>
<td>Builder</td>
<td>Bethln Stl/Sparrows Pt, Tampa &amp; Avondale</td>
<td></td>
</tr>
<tr>
<td>Year Delivered</td>
<td>1968</td>
<td>1986</td>
</tr>
</tbody>
</table>

Figure 2. Sketch arrangement, 37,000 dwt Overseas Alice.
to be in operation in U.S. flag service. These ships were conservatively built to a high standard and will probably remain in service until the mandated dates of obsolescence.

The general arrangements of the more recent Paul Buck class are shown in Figure 3. This class was built to commercial standards, specifically to carry petroleum products on commercial charters to the U.S. government. The tank arrangement is typical of modern double hull product tankers. The cargo tanks are generally shorter in length than the ships of the Overseas Alice class, but are arranged two-abreast rather than the older three-abreast configuration.

Structural midship sections of the two designs are shown in Figures 4 and 5. Both configurations have deep transverse web frames 11'-4" apart supporting longitudinal stiffeners every 34 inches. The bottom plating of the single hull Overseas Alice class is 23 mm thick whereas the highly optimized Paul Buck class has an outer shell plating thickness of 14.7 mm and an innerbottom, or inner shell, thickness of 13.7 mm.

The proposed ADH alternative, unidirectional framing system, for the Paul Buck will be referred to as the ADH T-5 and is shown in Figure 6. The reduced number of structural members and general simplification of the structure is evident in the comparisons with the two midship sections.
in Figures 5 and 6. To minimize differences with the Paul Buck, the same external lines, internal tank geometries, innerbottom depths, etc. were maintained for the ADH T-5 design. Thus, the ADH T-5 was not optimized for either structural weight, producibility, or grounding resistance. The ADH T-5 was designed to the same ABS criteria and minimum scantlings as the Paul Buck. As a result, both variants have the same inner and outer shell thicknesses. The weight of the longitudinal web members of the innerbottom and side shell corresponded to the weight of the longitudinals and transverse frames on the Paul Buck such that the structural weights were within a half percent.

Stranding Tests

Stranding occurs when a ship comes to rest on a rock, sandbar, reef, etc. with no forward speed. The rock counteracts part of the buoyancy thus imparting an upward vertical force on the bottom structure. Models of the
Paul Buck and the ADH T-5 variant were tested to determine the structural failure mechanisms under stranding. The portion of the ship modeled is the double bottom structure extending one tank length between transverse bulkheads, with a width nearly half the beam of the ship, i.e., from the centerline longitudinal bulkhead to the inner side shell. The indentation of the rock was centered in this bottom panel.

Scaling Relationships

For experiments involving high elongation, ultimate strength, tearing, etc., a single set of simple scaling relationships does not accurately predict both the damage patterns and the loads needed to produce them. Jones and Wierzbicki (1983) present a number of experiments showing several scales of a similar structure which exhibit very different final deformed shapes. Tearing damage does not scale by a relationship compatible with the distortion from bending, buckling, and crushing. The discrepancies decrease as one approaches a scale factor of unity. Table 4
Table 4. Scaling relationships.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ratios</th>
<th>Scale Factor</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>$L_p = \lambda L_m$</td>
<td>$\lambda = 4.25$</td>
<td>Length scale factor definition</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>$E_p = E_m$</td>
<td>1 to 1</td>
<td>Ship and model are ordinary steel, OS</td>
</tr>
<tr>
<td>Section Area</td>
<td>$A_p = \lambda^2 A_m$</td>
<td>$\lambda = 18.1$</td>
<td>(Length ratio)$^2$</td>
</tr>
<tr>
<td>Deflection</td>
<td>$\delta_p = \lambda \delta_m$</td>
<td>$\lambda = 4.25$</td>
<td>For similar damage patterns</td>
</tr>
<tr>
<td>Strain</td>
<td>$\varepsilon_p = \varepsilon_m$</td>
<td>1 to 1</td>
<td>For similarity</td>
</tr>
<tr>
<td>Stress</td>
<td>$\sigma = \sigma_m$</td>
<td>1 to 1</td>
<td>Damage occurs at same stress levels</td>
</tr>
<tr>
<td>Force</td>
<td>$F_p = \lambda^2 F_m$</td>
<td>$\lambda = 18.1$</td>
<td>Force = Stress x Area</td>
</tr>
<tr>
<td>Energy</td>
<td>$W_p = \lambda^3 W_m$</td>
<td>$\lambda = 76.8$</td>
<td>Work = Force x Deflection</td>
</tr>
</tbody>
</table>

$p = \text{prototype} \quad m = \text{model}$

Figure 6. Midship section, ADH T-5 with alternative unidirectional framing system.
presents the scaling relationships used. They assume that the model is of the same material as the ship and, therefore, the models reach yield at the same stress.

Model Design

Because of the scaling considerations, it was desired to have as large a scale for the models as possible. The limiting consideration was the 2,540 mm transverse clearance in the test machine. Therefore, the models were limited to a maximum scale factor of 4.25: corresponding to a length of 4,267 mm, a width of 2,540 mm, and an innerbottom depth of 470 mm. Figures 7 and 8 show the model details. All material was ordinary (mild) steel with 4 mm shell plating and 3.2 mm longitudinal webs. Two longitudinal flat bars stiffened each longitudinal web member on each model. The transverse webs on the Paul Buck model were composed of 4 mm plating.

Figure 7. Quarter scale stranding model of Paul Buck.
with vertical flat bar stiffeners. Two of the ten longitudinal webs on the ADH T-5 model were vertically stiffened with square tubes (203 x 203 x 4.8 mm, 406 mm apart) to ensure a more global deformation pattern. Although it was necessary to weld many of the joints from only one side, TC-U4-S welds with backing bars and 100% fill were employed.

**Rock Geometry**

The rock geometry selected for the stranding experiments was the result of the following rationale. Although a blunt rock shape is statistically the most likely to be encountered, the distorted shape of the models was not expected to be very different for the two innerbottom geometries. At the other extreme, it was assumed that a sharp pinnacle shape would cause the same zipper-like tearing of the inner and outer shells regardless of structural configuration, i.e., the rock would penetrate the inner shell without interacting with any of the longitudinal or transverse webs. Furthermore, a sharp pinnacle would likely break off or collect debris so that it would become more blunt after a short time.

Therefore, a shape between the above extremes would be the most useful in a comparative study. A 90 degree cone with a rounded tip was selected as a very severe, yet plausible rock shape. The radius of the model rock tip was 229 mm, resulting in the cone surfaces making contact with the longitudinal and transverse webs before the tip contacted the inner shell; see Figure 9. The base of the cone was 1,829 mm.
The rock tip was constructed from an 458 mm diameter hemisphere (HY80). The rest of the rock consisted of a heavy steel centerpost, 6.4 mm shell plating, and 25 mm thick internal webs. The void spaces were filled with high strength concrete.

**Experimental Setup**

The 12 million pound universal test machine at the National Institute of Standards and Technology (NIST) was chosen as the test facility because it is the largest such machine in the world and has the most clearance in the test area. Rigid boxes were welded to the ends of the models to simulate the support of the transverse bulkheads. The end boxes were grouted and bolted to pedestals such that the models could deform globally (as fixed-fixed beams). Both the end boxes and pedestals were built of 25 mm thick plating. Each model was mounted in an inverted position (outer shell on top) and the rock lowered by the machine head to contact the outer shell; see Figure 10. The rock tip was centered between longitudinal webs, and—in the case of the *Paul Buck*—also centered between the transverse webs, to simulate the expected worst case scenario.

The models were instrumented with strain gages to record the loss of strength of critical members and deflection gages to record global bending. Video cameras recorded the progress of the rock through the innerbottom by viewing both the inner shell and outer shells. In addition, a small “pencil” camera was taken into the interior of the structure when the outer shell opening became large enough for access.

**Experimental Results**

Following is the sequence of events during the stranding test of the *Paul Buck* model measurements are given with scaled prototype values in parentheses. Figure 11 presents the load deflection plot:
Figure 10. NIST experimental setup (Paul Buck model).

Figure 11. Load/penetration plot of Paul Buck in stranding.
• Outer shell rupture occurred at a load of 185,000 lbs (1,495 1 tons) when the rock penetrated 6.2 inches (26 inches). Rupture occurred at the perimeter of the rock contact area and not at the rock center.

• The tear in the outer shell propagated longitudinally beyond the transverse webs at a load of 200,000 lbs (1,616 1 tons) and a penetration of 15 inches (64 inches).

• As the rock surface neared the intersections of longitudinal and transverse webs, the slope of the load deflection plot increased. Rock contact with the intersections lifted the inner shell up and away from the rock tip, i.e. the model deflected in global bending as a beam.

• At a load of 400,000 lbs (3,232 1 tons) and a penetration of 19.3 inches (82 inches) a bulge appeared on the inner shell where the rock made contact. Shell stiffeners were tripped and folded flat against the inner shell by the rock.

• The load penetration plot showed a gradual loss of stiffness above 600,000 lbs (4,850 1 tons) indicating a crushing of the web intersections. Severe plate buckling occurred transversely in the outer shell indicating slipped material was being pushed laterally away from the rock surface.

• The inner shell rupture began as a longitudinal crack at the edge of the rock contact area, followed shortly by an abrupt change to the transverse direction. Figure 12 shows the final damage at the rupture site corresponding to a load of 750,000 lbs (6,060 1 tons) and a penetration of 30 inches (127 inches).

• The energy dissipated was calculated from the load-penetration plot to be 776,000 ft-lbs (26,600 ft-l 1 tons).

Following is the sequence of events during the stranding test of the Advanced Double Hull (ADH T-5) model. Measurements are given with scaled prototype values in parentheses. Figure 13 presents the load penetration plot:

• Outer shell rupture occurred at a load of 170,000 lbs (1,374 1 tons) and a penetration of 6.2 inches (26 inches) with a longitudinal crack at the edge of the rock contact area.
Figure 12. Paul Buck model at inner shell rupture.

Figure 13. Load/penetration plot of ADH T-5 in stranding.
Contact was made with the tube stiffened longitudinal webs at a load of 190,000 lbs (1,535 l tons) and a penetration of 13 inches (55 inches).

The portion of the load-penetration plot between 200,000 and 700,000 lbs (1,600 to 5,600 l tons) shows the stiffness associated with the inner shell lifting out of the rock’s way. The undulations in the slope correspond to the web components making contact with the rock and then crushing causing a loss of local stiffness.

As the load approached 720,000 lbs (5,820 l tons), a vertical crack in the longitudinal web propagated to the inner shell. This initiated a longitudinal crack at the inner shell weld line. A maximum rock penetration of 31 inches (132 inches) was achieved. Figure 14 shows the final appearance of the damaged model.

The energy dissipated was calculated from the load-penetration plot to be 807,000 ft-lbs (27,670 ft-l tons), 4% more than the Paul Buck.
Grounding Damage

In a grounding incident, the kinetic energy of the moving ship is primarily dissipated through the crushing and tearing of the hull structure, i.e.:

\[
\text{Kinetic Energy} = \text{Absorbed Energy}
\]

where the kinetic energy is a function of the displacement of the ship and velocity at impact and the absorbed energy \(W_s\) is a function of the cross-sectional material and the length of damage.

Method

This analysis is based on the work done by Vaughan (1977) which is itself an extension of Minorsky's work. Vaughan's collision energy equation takes into account the energy due to tearing during a grounding, in addition to Minorsky's crushing energy.

\[
W_s = 352V_s + 126A_s
\]

where \(V_s\) and \(A_s\) are the total volume and area of displaced and torn material respectively. Vaughan derived the coefficients from Akita and Kitamura (1972).

The volume of crushed steel was calculated by multiplying the "effective thickness" by the stiffener spacing and damage length. The effective stiffness includes structure which supports the hull plating by "smearing" their areas into the hull thickness. Crushed bulkhead and web frame volumes are also included in the hull thickness, as functions of penetration depths. The following expansion of Vaughan's equation (DAV 1990) is for the total energy absorbed during a steady state grounding event.

\[
W_s = L_d[352(B_{d1}t_{pe1} + B_{d2}t_{pe2}) + 126(t_{pa1} + t_{pa2})]
\]

where
- \(L_d\) = longitudinal length of damage
- \(B_{d1}\) = breadth of damage on outer shell
- \(B_{d2}\) = breadth of damage on inner shell
- \(t_{pe1}\) = equivalent thickness of outer shell
- \(t_{pe2}\) = equivalent thickness of inner shell
- \(t_{pa1}\) = actual thickness of outer shell
- \(t_{pa2}\) = actual thickness of inner shell
The units of energy are 1 ton-knot\(^2\); lengths and breadths are in meters and thicknesses are in millimeters. The crushing volume and tearing area are obtained by superimposing the rock shape over the ship cross-section to determine the damaged structure.

As a result of the stranding tests in the last section, it is seen that the bottom structure is deflected out of the rock's path. Therefore, the above grounding damage method was modified in two ways. First, the volume of penetration was reduced by the global deformation of the innerbottom. The maximum penetration of the rock was reduced by one half until the following limits were realized:

<table>
<thead>
<tr>
<th>Ship Type</th>
<th>Deformation Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Single Hull</td>
<td>Elastic Deformation Limit</td>
</tr>
<tr>
<td>Conventional Double Hull</td>
<td>1.6 x Innerbottom Depth</td>
</tr>
<tr>
<td>Advanced Double Hull</td>
<td>1.7 x Innerbottom Depth</td>
</tr>
</tbody>
</table>

Thereafter, global deformation has no additional effect. Second, the kinetic energy dissipated \(E_k\) is equal to Vaughan's equation \(W_s\) plus the work done in deforming the innerbottom up to the elastic deformation limit \(W_{ed}\):

\[ E_k = W_s + W_{ed} \]

At the yield stress \(\sigma_y\), the force \(F_y\) is given by

\[ F_y = 8\sigma_y Z/L_t \]

and the maximum elastic deflection \(\delta\) is given by

\[ \delta = F_y L_t^2 / (192 EI) \]

where \(Z\) is the section modulus of the innerbottom, \(L_t\) is the length of a tank, \(E\) is the modulus of elasticity, and \(I\) is the moment of inertia of the innerbottom. For the \(Z\) and \(I\) calculations, \(B_{dl}\) is assumed for the breadth of the sections. Converting the above expressions to consistent units with equation (1), the work in elastically deforming "N" cargo tank innerbottoms becomes:

\[ W_{ed} = 204N\sigma_y Z\delta / L_t \]

where the units for \(W_{ed}\) are 1 ton-knot\(^2\); \(\sigma_y\) is psi, \(Z\) is meter\(^3\), and both \(\delta\) and \(L_t\) are in meters. \(N\) is assumed that the energy which deforms the innerbottom to the maximum (plastic region) amount entails a crushing
[vertical] of structure which is already included to some extent in
Vaughan's equation [longitudinal crushing].

For very large rocks, e.g., penetrations of several times the
innerbottom depth, neither of the above modifications is significant.
However, for shallow rocks, the effects of innerbottom deflection can be
significant in predicting inner shell rupture, with the elastic deformation
energy modification less so.

**Rock Geometries**

Two rock geometries were selected for grounding scenarios with
several penetration depths studied as parameters, the idealized rocks are
shown in Figure 15. The conical rock was claimed to be an IMO/
MARPOL assumption in the DnV 1990 reference, but some authorities
have questioned the slope value. In any event, the conical rock is quite
similar to the rock used in the stranding tests and was used as one extreme
in this study. The blunt shape in Figure 15 is an assumed idealization
strictly for comparison purposes.
Analytical Results

The following results are based on the assumption that the midships scantlings extend the entire length of the damaged ship length. A comparison of the damages for the conical and blunt rocks as a function of rock depth is given in Figure 16. All of the results are at a constant momentum of 324,000 ton-knots (10 knots for the Paul Buck and ADH T-5 and 9.2 knots for the Overseas Alice).

The quantity and distribution of steel in the hull of a tanker is dictated by longitudinal hull girder strength and local strength.
Figure 17. Predicted damage lengths in grounding.
requirements. Accordingly, for large ships the hull of a single hull tanker will be thicker than the outer shell of the equivalent double hull tanker for the same strength requirements. This occurs because the required hull girder steel is distributed between the inner bottom and outer shell of the double hull tanker. With this in mind, several observations are noteworthy:

- The conical rock acts more like a can opener and tears a much longer length of the ship than the blunt rock.

- The *Overseas Alice* has a shorter damage length than either of the double hull ships. When the rock depth is small (under 3 meters), the single hull ship has a shorter damage length because the rock has not penetrated the inner hull of the double hull ships (no oil has spilled) and does not have as much material to crush. When the rock depth is large, there is no significant difference in the damage length for the three ships.

- The advanced double hull, ADH T-5, has slightly more cross-sectional area than the conventional double hull, *Paul Buck*, and therefore has a slightly shorter damage length.

The lengths of the predicted grounding damage from the blunt rock are presented in Figure 17 for the *Overseas Alice*, the *Paul Buck*, and the advanced double hull version of the *Paul Buck* (ADH T-5). Momentum (1 ton-knots) was chosen as the common ordinate to compare these slightly different sized ships. The rock depths were varied at 2, 3, 4, and 5 meters above the baseline of each ship. Following are some observations from Figure 17:

- The larger rocks caused a shorter damage length than the smaller ones. This is because they have a wider base and therefore crush more of the structure per unit of travel. In the extremes, a can opener will tear open the entire length of a ship without dissipating much energy, whereas a tall, immovable object will cause a ship to stop immediately.

- There is a gap in the curves for the two double hull ships between the 2 and 3 meter rock depths. At the lower value, only the outer shell is crushed while at the larger values both the inner and outer shells absorb energy, thus reducing the longitudinal extent of damage.

From the above analytical predictions, there is little difference in the behavior of the two double hull variants. Future grounding tests are
planned during the ongoing advanced double hull research program. These tests of fifth scale models of the innerbottoms of the Paul Buek and ADH T-5 should shed more light on the grounding phenomenon.

Oil Outflow from Grounding

At some time during the ADH research program, oil outflow calculations for alternative tanker structural arrangements will be conducted for representative scenarios. At this stage in the program such calculations are premature pending outcome of the planned large scale grounding tests. However, it is appropriate to draw some general conclusions regarding oil outflow as related to double hull tanker geometry.

During the intense debates in international maritime forums, which accompanied the enactment of OPA 90, the U.S. decision to unilaterally require double hull tanker geometry was attacked by proponents of alternative systems and concepts. The primary structural alternative proposed was the Mitsubishi mid-deck concept, Figure 18, which relies on external hydrostatic pressure to prevent oil leakage in the event of a grounding. The most strongly proposed operational measures all involved hydrostatic balanced loading, which limits the oil level in cargo tanks to ensure that outflow resulting from grounding is prevented by external hydrostatic pressure. The United States maintained its position with the enactment of OPA 90. Shortly thereafter, the International Maritime Organization (IMO) incorporated the double hull requirement as well as the “equivalent” mid-deck configuration (IMO Regulation 13F).
During the period of investigation and deliberation at the time of OPA 90 adoption, significant model test programs were conducted at the Tsukuba Institute in Japan and at the David Taylor Model Basin in the United States, to compare oil outflow characteristics of mid-deck and double hull tankers subject to grounding damage. The results were reported by Karafiath (1991). The oil outflow characteristics of each concept depend on a variety of environmental factors, including the nature and magnitude of the grounding damage and the existence of external currents.

In one respect, the performance of the double hull tanker model in high energy grounding was better than expected. When the innerbottom was ruptured, cargo oil tended to flow into the empty double hull spaces rather than out into the sea through the bottom shell opening. This is an important observation and should be the subject of further research. It is clear that the structural design of the inner hull void spaces should be such as to minimize obstructions to cargo oil flow into these spaces.

The authors recognize that any proposed design or operational concepts can be supported by its proponents with a hypothetical casualty scenario that demonstrate the merits of the concept. In this connection it should be emphasized that the nature of tanker casualties in U.S. waters...
reflects the relatively shallow water depths at approaches to U.S. ports. Results of a recent casualty survey indicate that groundings total 45% of all casualties, collisions and runnings 25%, fire and explosions 14%, and structural/operational failures 16% of the total. The majority of the groundings involve relatively low energy incidents where the innerbottom would not be breached. The merits of the double hull configuration in the prevention of oil spills are clearly supported by these statistics.

Further support for the double hull requirement is given by Michel and Tagg (1991) in their important probabilistic analysis of tanker oil outflow. Their studies show that to maximize the probability of zero outflow resulting from bottom damage, the double hull geometry is superior to all other alternatives, including the mid-deck tanker. Figure 19 (taken from their paper) shows the probability of zero outflow for casualties involving only grounding damage to the bottom. The probabilities in Figure 19 were developed by Michel and Tagg with the assumption that a rock depth equal to the innerbottom depth would cause rupture and oil outflow. In view of the stranding results presented in this paper, that is a conservative assumption. In fact, the probabilities of zero oil outflow presented for the 3.2 meter innerbottom would be appropriate for a 2 meter depth (1.6 plastic deformation x 2 meters) and the probabilities for a 3.2 meter innerbottom would be higher still.

Conclusions

As a result of OPA 90, all single hull tankers in the coastal trade will be replaced by double hull ships by early in the next century. Comparative grounding analyses and oil outflow studies support this legislation.

Stranding tests were performed on quarter scale hull bottom models of the Paul B. Stinchfield and the ADH T-5 at NIST. These tests showed that in addition to the crushing of the bottom structure that occurred, plastic deflection lifted the innerbottom out of the rock's way (60-70% of the innerbottom depth before inner shell rupture). Thus, the probabilities of zero oil outflow for double hull tankers shown in Figure 19 (from Michel and Tagg) are probably conservative.

Grounding analyses of single and double hull tankers were performed with considerations for the plastic deflection of the innerbottoms away from the rock. Since the quantity of steel in a hull is dictated by longitudinal strength requirements, the shell of a single hull tanker will be thicker than the outer shell of an equivalent size double hull tanker. Hence, for shallow penetrations (less than 1.6 times the innerbottom depth) the damaged length of a single hull tanker will be less than for the equivalent double hull tanker. Keeping in mind that the double hull tanker will not
have spilled any oil. When deeper penetrations involve the innerbottom, the damage length of the single and double hull ships is about the same, all other considerations being equal.

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References


The Prevention of Accidents and Oil Spills on the Outer Continental Shelf

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Abstract

Prevention of accidents and oil spills is a key ingredient in assuring the continuation of safe operations on the outer continental shelf (OCS). The Minerals Management Service (MMS) regulatory program identifies special requirements for industry for the prevention of accidents which could threaten life, property, or the environment. The MMS prevention requirements will be discussed. The emphasis for the discussion will be on the exploration phase of offshore oil and gas activities on the Alaska OCS. A brief summary of the historical activities conducted on the Alaska OCS and a characterization of the challenges of the Alaskan offshore environment will serve as background information to the subject of prevention. Finally, the authors will briefly mention how prevention enters into the development phase of offshore operations.

Introduction

The primary responsibilities of the Minerals Management Service (MMS) are to manage the mineral resources located on the nation's outer continental shelf (OCS), collect revenues from the federal OCS, and distribute those revenues. The Offshore Minerals Management Program administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our nation's offshore natural gas, oil, and other mineral resources. Meeting the challenges of operating on Alaska's vast OCS through technology and the prevention of accidents and oil spills is the main theme of this presentation. Although the primary focus for this discussion is on exploratory operations, a summary of production safety systems is included to emphasize the comprehensive MMS pollution prevention effort.

Offshore drilling and production in United States OCS waters have not been a significant source of pollution. We believe there are good