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Factors Affecting Marine Structural Inspection Performance

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Abstract

Owners, operators, and regulators must ensure that ships and marine structures operate efficiently and safely, without undue risk to cargo, personnel, or the environment. Because load histories are uncertain, and because there is incomplete knowledge of the capability of operational structures, periodic inspections are carried out to assess structural condition. Inspection is a critical means of maintaining structural safety and functionality, yet the circumstances under which they are carried out are far from ideal.

The work described here is part of an investigation of the likelihood that flaws will be detected during a particular inspection. This paper presents a model of the factors that affect performance in the inspection of tankers, including characteristics of the vessel, of the inspector, and of the environment in which the inspection is carried out. A study of historical tanker inspection data highlights the importance of prior knowledge on the outcome of an inspection.

1. Introduction

The owners, operators, and regulators of ships and marine structures must ensure that these facilities operate efficiently and safely, without undue risk to cargo, personnel, or the environment. Because the loads on structures are uncertain, and because we have incomplete knowledge of the capability of operational (i.e., as-built/as-maintained, as opposed to as-designed) structures, periodic inspections are used to help ensure that these goals are met.

Inspections are in many ways the "last resort" in ensuring the safety of marine structures. However, from a human factors perspective, the circumstances surrounding marine inspections are far from ideal. Consider, for example, the conditions facing the inspector of an oil tanker, described in Williams and Sharpe (1):

> "...picture ... a large gymnasium. The compartments...are on that scale. The inspector usually enters this compartment via a ladder from the main deck...wearing coveralls and armed with a flashlight, hopefully an atmosphere monitor, a hammer, pen and inspection book. Often the only available light source is the natural light coming from a few 350mm diameter tank washing openings in the deck. Usually the tank has not been staged for repairs. Now, given those conditions, consider that the inspector is tasked with being able to find a 25mm crack on the framing as far away as the back corner of the gymnasium."

Marine structural inspections generally involve an initial overall visual inspection: a trained inspector "looks over" the structure, focusing on known problem areas and on anomalies. Depending on the type of structure, this overall visual inspection may be followed by close-up visual inspections and the investigation of selected areas using an instrumented method of non-destructive evaluation. Inspections are labor intensive and physically demanding. There has been a significant interest in making inspections safer, faster, and more effective. New technologies for marine inspection are described in, among other sources, Holzman (2), Goodwin and McClave (3), and Allen et al. (4).

This paper presents a model of the factors that influence inspection performance — that is, the factors that influence the likelihood that, if a defect exists, it will be found during an inspection. The model should be of use in guiding research into new inspection technologies and as a starting point for quantifying inspection performance in terms of probability of detection (POD). Although it is developed to describe factors affecting the inspection of crude oil tankers, the model should be applicable to other marine structures as well. The model was devloped based on a review of the literature and interviews with those involved in marine inspections. Work by Ayyub and White (5) addressed many of the same issues as the work described here and is referenced throughout this paper.

2. Factors Affecting Performance

Each inspection represents a unique combination of vessel, personnel, and environment. Holzman (2) noted that inspection performance depends on the inspector, the tank being inspected, and the method of inspection used. Ayyub and White (5) provide a more detailed breakdown of factors influencing inspection:

- vessel factors related to the design and construction of the ship, such as the type of structural detail, the material used, the structural access provided,
- defect factors that depend on the type of defect, i.e., cracks, corrosion, or buckling,
- service factors, including coatings, cleanliness of the tank, and type of corrosion system,
- environmental factors, including weather, the time allowed for inspection, the number of inspections planned for a day, and the location of the vessel, and
- personnel factors, including experience and training.

In considering inspection performance, and the steps that might be taken to improve perforamnce, it is helpful to group factors according to the extent to which they can be modified at each stage of a vessel's life. Taking this approach led to the model of inspection performance shown in Figure 1. Inspection performance is influenced by the vessel, the inspector, and the environment. Vessel factors are divided into design factors that represent decisions made when the vessel was designed (or redesigned as part of the repair process) and condition/maintenance factors that represent the use of the vessel. Inspector factors are those related primarily to the inspector and the inspector's workload. Environmental factors are further divided into external factors that are to some extent beyond the control of the parties involved in a particular inspection, and procedural factors that are primarily within the control of these parties.

The factors shown in Figure 1 can reasonably be expected to influence the probability of detecting flaws. It important to keep in mind the difference between factors that influence the initiation and existence of defects and factors that influence the probability that existing defects will be detected during an inspection. The initiation and existence of defects may be due to the inadequate load carrying capability of the as-designed structure, to misalignments introduced during fabrication, and/or to the route the vessel has traveled. However, these aspects of the vessel's history have only an indirect influence on the ability to detect the defects during inspection. The direct influence on probability of detection is through characteristics of the defect (type, size, and location), the inspector's prior knowledge of the vessel and sister ships, and the other vessel, environmental, and personnel factors shown in Figure 1. Understanding the way in which design, fabrication, operation, maintenance, and repair influence the initiation and existence of defects is important and could improve inspection performance. However, the focus of this paper is on the factors that determine the likelihood that a defect, once it exists, will be detected.

Ideally, a comprehensive set of factors that are mutually independent in their influence on inspection performance could be defined. Each factor's influence could then be combined directly with a "baseline" performance to yield the probability of detection in a particular situation. In reality, the extent to which one factor, such as time available, influences performance is likely to be highly dependent on other factors, such as the inspector's experience. As as result, incorporating the affect of multiple factors will be more complicated. The following sections discuss each of the factors in greater detail.

2.1 Vessel

Characteristics of the vessel affect the likelihood that defects will be detected. Vessel characteristics can be divided into two categories: design factors and condition factors. Design factors, (structural layout, size, and coatings) are fixed during initial design or through the redesign that may accompany repair. Condition factors reflect the changes in a vessel as it ages. These include the cargo history of the vessel, and characteristics of individual defects such as the type of defect, its size, and its location.

2.1.1 Design

Design factors influence POD in several ways. The structural layout and size of the vessel help how easy or difficult it will be for an inspector to gain access to all portions of the structure, and how effective efforts to clean the tank will be. The existence, type, and condition of coatings can also affect the likelihood that a defect will be detected, as can the configuration of structural details.

The choice of structural material has been mentioned as a design factor influencing inspection performance (5). At present, choice of material for tankers is limited to mild and high strength steel; several grades of each are used. The choice of material and the way in which the material is used to carry loads within the structure can have a major impact on whether or not defects will occur over the lifetime of the structure. However, the different types and grade of steel do not appear to have a major influence on the probability that a particular defect, once it exists, will be detected. There may be an indirect influence (such as differences in the location of fatigue fractures), but this would be captured by the "defect" factors described in Section 2.2.2.2. Therefore, "material" is not included as a factor in the model presented in Figure 1.

2.1.1.1 Structural Layout

The major impact of structural layout on POD is though its influence on access. The existence of ladders, catwalks, and bulkhead openings large enough to allow easy passage by an inspector can improve access to various regions of the tank, allowing a close-up view of the structure and increasing the likelihood that defects will be found. A summary of design modifications that can improve access is provided in (2). Structural layout and details also influence the extent to which residue accumulates in the areas where defects are likely to form, and the ease with which these and other areas can be cleaned.

The structural layout of double hull tankers is quite different from that of single hull vessels. At present it not known how POD for a double hull tanker will compare with POD for a single hull vessel.

2.1.1.2 Size

The size of a vessel can impact the likelihood that a defect is found, although this effect is highly coupled with the time available for an inpsection. An estimate by U.S. Coast Guard field personnel of the percent of internal structures actually inspected ranged from roughly 75% for 20-40 KWDT vessels down to roughly 20% for vessels greater than 200 KWDT, Bell et al. (6). It is reasonable to expect that, as the percent of a vessel inspected decreases, POD also decreases.

2.1.1.3 Coatings

Ayyub and White note that the existence and type of coating may have a major impact on inspection performance:

> "There will be a lot of difference in the inspector's ability to detect failures in a coated fresh water tank than in an uncoated crude oil tank...Coal-tar epoxy coatings are usually quite thick and provide an irregular surface. This makes visual detection of cracks very difficult. On the other hand, some co-polymer coatings are very light in color, and cracks show up as lines of running rust, making them very easy to spot." (5)

Williams and Sharpe also find coatings to have a mixed impact on inspection performance:

"Coatings for tanks vary widely and can either assist an inspector or can hide problems. In the best situation the coatings are light and allow the cargo to runoff well when the tank is washed. Often a crack can stand out quite well with this type of coating as heat causes the oil to slowly seep out of the cracks in the coating well after cleaning. In other cases the coatings may not harden, leaving a coating which flows or stretches over cracks and prevents them from being seen." (1)

The impact of coating on inspection performance was also noted by many of inspectors interviewed for this study. Inspectors felt that coatings could mask fractures in the structure, that the scaling and corrosion that accompany coating breakdown could hide crack damage, and that epoxy coatings in ballast tanks can make underway inspections more difficult due to slipperiness. On the whole, coatings appear to have a mixed impact on probability of detection.

2.1.1.4 Structural Details

The design of structural details influences the probability that a defect will be detected. Detail design helps determine the likely locations at which a defect will occur, and how visible these locations will be to an inspector. Visibility is influenced directly by the detail design, and indirectly by the extent to which a design promotes cleanliness. A structural detail in which the likely defect locations are easily visible will lead to a higher probabilty of detection than one in which a defect is likley to occur behind a flange or in an otherwise obstructed location. With respect to cleanliness, probability of detection will be lower for a detail whose configuration allows silt (in a ballast tank) or crude residue (in a cargo tank) to collect over likley failure areas.

2.1.2 Condition/Maintenance

Condition/Maintenance factors reflect the changes in a vessel as it ages, and include the age and cargo history of the vessel and characteristics of defects such as the type of defect (crack, corrosion, buckling), and its size, age, and location. Ayyub and White also include corrosion protection among service factors, their category closest to condition/maintenance. However, aside from coatings, the effect of which is described above, corrosion prevention systems do not appear to have a significant impact on the probability that a defect, once it exists, will be detected during inspection.

2.1.2.1 Age

Prior knowledge of defect areas on a particular vessel or class can influence the probability of detection. On an older ship, "trouble areas" will be known from previous inspections or from sister ships. An inspector will focus attention on these areas, and therefore be more likely to find any defects that exist. On the other hand, in an older ship that inspectors feel they know well, a defect in an unanticipated location may be overlooked. Furthermore, as a ship ages and undergoes more loading cycles, fatigue cracks will become more common. With more defects in a wider variety of locations, the chances that an individual defect will be detected may decrease.

2.1.2.2 Cargo

The ease with which defects are detected will depend in part on the cargo that a tank has carried. Ayyub and White state that -

"Fresh water tanks are often the easiest to inspect because of the cleanliness of the water and tank...Ballast tanks...are easier to inspect because of their relative cleanliness. Crude oil tanks are often difficult to inspect because, even with thorough washing, residue builds up in exactly the locations which need inspection." (5)

The affect of cargo on POD is closely related to the quality of cleaning. Again, it is important to call attention to the difference between the incidence of a defect and the likelihood of detecting that defect. With equivalent protection systems, a ballast tank may be more prone to corrosion than a cargo tank. However, because the ballast tank is likely to be cleaner, the probability of detecting a particular defect may be higher in the ballast tank.

2.1.2.3 Defects

Characteristics of defects have a major impact on probability of detection. In fact, POD is typically expressed as a function of a defect characteristic, most often crack length. Relevant defect characteristics include the type of defect, its size, its age, its location, and the number of existing defects.

Defects are generally classified in three categories: cracks, corrosion, and buckling. Different inspection practices may be better at detecting different types of defects (5). Because cracks and buckling result from the loading of a structure, a priori knowledge of the critical areas may make the POD somewhat higher for these defects as compared with corrosion. However, no documentation of this effect has been found.

The size of a defect clearly has an impact on POD; the larger the defect (by almost any measure), the more likely it is to be detected. Based on the interviews carried out as part of this study, inspectors feel that the lower length limit for reliable detection of fractures is 50 mm to 75 mm (two to three inches) under general conditions when reasonable access is provided and when no special instructions have been given. Fractures much smaller than this (under 10 mm) can be detected when special attention is paid to a particular location.

The length of time a defect has existed will also affect the probability of detection. In interviews, inspectors noted that one of the reasons longer cracks are easier to detect is that there has been sufficient time for the crack to open up and rust to develop.

The location of a defect undoubtedly has a major impact on the likelihood that it will be detected, and for two reasons. First, there are some locations in the tank that are difficult to inspect. The underdeck area is an example. Other things being equal, defects in these areas will be harder to detect, and therefore detected less often, than defects in other areas. Second, there is the "critical area" effect. Experienced inspectors know which parts of a structure have a history of problems, and are likely to focus their attention on these areas. This tendency is supported by the existence of requirements such as the Critical Area Inspection Plan (CAIP) for TAPS tankers. It certainly makes sense to focus attention on known problem areas. However, this may mean that defects in "non-critical" or "newly-critical" areas are less likely to be found.

The number of defects may also affect the probability that a particular defect will be found. A vessel in which an unexpectedly high number of defects are found will probably receive an extended inspection, increasing the likelihood that any single defect will be found. Furthermore, if several defects exist in the same area, the chance that each will be detected may be improved. An inspector carrying out a visual overview of the tank need only notice one of the defects, and approach the area for a closer look. Upon doing so, the chances of the other defects being noticed may be greatly increased.

2.2 Inspector

The inspector can greatly influence its outcome. In other industries, such as aviation, personnel factors have been found to be the most significant source of variation in inspection performance, Spencer et al. (7). Performance varies not only from inspector to inspector, but also from inspection to inspection with the same inspector based on mental and physical condition. Factors associated with the inspector include overall experience, experience with a particular vessel, training, fatigue, and motivation.

2.2.1 Overall Experience

Experience is repeatedly mentioned as a critical factor. Ayyub and White state that it is the most important of their personnel factors (5). One inspector interviewed as part of this study felt that it takes two years of experience to become qualified to do inspections. Ayyub and White sound a note of caution, however:

"[experience] can be a two-edged sword. Often a new, relatively inexperienced inspector will perform a more detailed and careful inspection precisely because he or she has no preconceived notions about where the most likely damage will be located.... An experienced inspector may go into an inspection with the knowledge gained from previous inspections of similar circumstances and be able to head directly to one source of structural damage...[but] may completely miss a type or source of damage which is different from previous cases." (5)

The impact of experience is increased by the wide variation in background of inspectors. Williams and Sharpe note that "the requirements... vary widely depending on who they work for and who is requiring the inspection" (1).

2.2.2 Experience with Vessel

Several of the inspectors interviewed for this study mentioned that not only is inspection experience important, but that experience with the same vessel or same class of vessel can greatly influence the likelihood of finding a defect. This was attributed both to knowing how to get around the structure with ease and to knowing where the trouble spots are located. One inspector commented that knowing the history of the vessel and patterns of deterioration in details was extremely important, and felt that the probability detection for an inspector who was "just wandering around" would be near zero.

2.2.3 Training

Training also has an impact on performance, though perhaps to a lesser degree than experience. Ayyub and White note that both initial training and periodic refresher training can reduce the variation in inspection performance (5).

In other industries, classroom training beyond a minimum level has been shown to have little effect on demonstrated proficiency in the field, Rummel et al. (8). Furthermore, to be effective, training must be ongoing and extend through the entire career of the inspector. For example, one aircraft operator has five percent of the inspector force in formal training at all times, Shepherd and Parker (9).

2.2.4 Fatigue

Inspection of tanker structures is a physically demanding job. Holzman notes that "the physical nature of the inspector's job currently requires it to be a younger person's profession" (2). In an interview, one inspector noted that the physical demands of inspection are such that there are few people with more than 10 years of experience. Williams and Sharpe note that "Fatigue is an omnipresent consideration" (1). It seems reasonable to expect that inspectors who are fatigued will have a lower level of performance, other factors being equal. The degree of fatigue is influenced by the inspector's physical condition, by the number of hours worked prior to an inspection, and by other physical and emotional demands.

2.2.5 Motivation

Motivation affects the performance of nearly every task. Based on common experience, it seems reasonable to assume that motivation is particularly important when working conditions are difficult or when a task becomes monotonous. To some extent, tank inspection encompasses both of these cases; the inspection environment is harsh, and, at least in many vessels, there are few defects found. However, the effect of motivation on inspection performance is difficult to assess, in large part because motivation itself is difficult to assess.

A survey by the Coast Guard of its inspectors emphasized the effect of human factors, including motivation, on inspection performance (6). Based on field comments, inspection personnel were found to be suffering from overload. Many Coast Guard inspectors were working up to seventy hours a week in a hard, tiring job. In part because of the workload, it was difficult to maintain the high motivation needed to stay in the inspection program; many of the young Coast Guard inspectors just wanted to get away from the inspection program (6). Even though these inspectors may have tried to do a good job on each inspection, one cannot help but suspect that their performance was poorer than it could have been under different circumstances.

2.3 Environment

The environment has a major influence on performance. In Figure 1, an attempt has been made to distinguish between environmental factors that cannot be modified by inspection procedures and those that can be (or could be with the right technology). The former are referred to as external factors; the latter as procedural factors. For some factors, the appropriate category is not obvisous. An example is the classification of weather vs. that of temperature. Because the weather at a particular time and place cannot be controlled by those planning the inspection, weather is included as an external factor. Weather can, however, be predicted, and anticipated weather conditions could (and should) be taken into account when scheduling inspections. Nonetheless, weather is included as an external factor. Temperature is to large extent a function of the weather. However, temperature is included as a procedural factor because steps could be taken during the inspection to change the temperature in the tank (for example, by blowing cool air into the tank) or to minimize the impact of in-tank temperature on the inspector (for example, by providing the inspector with appropriately insulated clothing).

2.3.1 External

External factors are the aspects of the inspection environment that are to a large degree outside of the control of those planning the inspection. External factors include weather and the location of the vessel.

2.3.1.1 Weather

Weather can affect inspection performance. Ayyub and White note that

> "Hot, humid weather affects the inspectors by reducing the amount of time... in a tank, or by making them so uncomfortable that they might hurry through the inspection. The humidity can make climbing tank walls dangerous because of moisture accumulation. Exceptionally cold weather is no better. Again it can affect the inspector's desire to spend the time needed to make a very thorough inspection." (5)

A tank ambient temperature of 35 degree Celsius with 95% relative humidity can restrict the effective working time for an inspection to as little as fifteen minutes per hour, Exxon (10).

Heavy seas can degrade inspection performance to a greater or lesser extent depending on the location of the vessel during the inspection. Heavy seas make inspections while underway difficult or impossible. Seas that cause roll of five degrees or more preclude safe inspection by rafting.

2.3.1.2 Location of Vessel

Inspections can be carried out in drydock, at dockside, at anchorage, or while underway. Underway inspections present the most physically challenging environment due to the motion of the ship and slipperiness of the surface (epoxy coatings in ballast tanks; oil in cargo tanks). Poorer levels of cleanliness (silty mud in ballast tanks and crude oil in cargo tanks) and lighting add to the difficulty. Despite these problems, inspectors interviewed felt it was possible while underway to detect 85-90% of the fractures which would be found in a shipyard.

The probability of detection is increased in the shipyard due to better access, to better lighting, and to the tanks being dry. Although one inspector estimated that restricted access, tank size, and the limited staging used for repairs resulted in the detection of as few as 50-60% of existing cracks during a shipyard inspection, others feel that the percent detected is much higher.

2.3.2 Procedural

Procedural factors are those which are to a large extent under the control of those planning the inspection. Procedural factors reflect the condition of the tank during inspection (lighting, cleanliness, temperature, ventilation), the way in which the inspection is conducted (access method, inspection method, inspection strategy, area inspected, crew support, time available), and the overall specifications for the inspection (inspection type and objectives)

2.3.2.1 Lighting

Lighting has a significant impact on visual inspections. The lighting typically available in a tank has been described as

> "a feast or famine situation, with some bright lights in a few locations and shadows over much of the area. In general, the lighting in a tank does little good other than assisting the inspector in finding his way through and over the structure framing; the failures must be found with a flashlight." (1)

Inspectors interviewed as part of this study and for other studies consistently mention lighting as a critical issue in inspections (2), (3). Current work by the U.S. Coast Guard investigates improvements in inspection lighting, (4).

2.3.2.2 Cleanliness

Like lighting, cleanliness of the tank was mentioned by nearly every inspector as critical to the quality of inspection. Tank structures undergoing drydock inspections typically receive the most thorough cleaning. Cleaning is important to enable defects to be seen. Cleaning is also important for reasons of safety: residue can be slippery, and access for extended periods requires thorough removal of residual oils or mud and maintenance of a gas-free environment.

Williams and Sharpe note that

> "[T]he degree of cleanliness is highly variable. Sometimes the cleaning leaves a layer of sludge on the bottom of the tanks that makes finding cracks on the bottom very difficult. In those cases the inspector can either require the tank to be cleaned further, causing delays, or do the best he or she can with the given conditions." (1)

In general, inspection will be easier and defects more readily found in a clean tank. However, one inspector noted that cleaning can remove rust marks that help draw attention to a defect.

2.3.2.3 Temperature and Humidity

Weather conditions and poor ventilation can cause extreme temperatures in the tank. As noted above, an in-tank ambient temperature of 35 degree Celsius with 95% relative humidity can restrict the effective working time for an inspection to as little as fifteen minutes per hour (10).

Even under less harsh conditions, temperatures outside the optimal comfort range can accelerate inspector fatigue.

2.3.2.4 Ventilation

Proper ventilation of the tank is essential for inspector safety. Half-mask filter respirators are required when benzene levels are above an acceptable level (2). The forced air flow necessary to create adequate ventilation can result in noise levels in excess of 85 dB, requiring the use of ear plugs (2). It is reasonable to expect it may have an influence on performance, both directly and indirectly through the resulting requirements for respirators and ear plugs.

2.3.2.5 Access Method

Access is a critical factor in inpsections; it is difficult to detect a flaw of modest size from afar. The most common means of access are walking the bottom, temporary staging, rafting, and climbing. Access can also be accomplished through suspended platforms, permanent staging, mountaineering-like cable arrangements, remotely operated devices, divers, or other means. The primary access method used by U.S. Coast Guard inspectors is bottom walking (90%), with limited use of staging (8%) and rafting (2%) (3). Commercial and class society inspectors make much greater use of staging, rafting, and alternative methods. Each method has benefits and drawbacks; the "best" is the one which allows closest access given constraints on time, cost, and safety. A summary of advantages and disadvantages of various access methods can be found in (2).

The effect of access on probability of detection was summed up by one inspector interviewed for this study as "the closer the better". There is an obvious interaction between the method of access and the location of the defect in their impact on probability of detection.

2.3.2.6 Inspection Method

Visual inspection followed by ultrasonic gauging is the predominant means of tanker inspection. Other approaches, such as the use of video cameras, ROVs, classical NDT methods, infrared thermography, vibration testing, and acoustic emissions have been proposed and in some cases used on an experimental basis (2), (3), (4). In one recent unpublished study carried out by an owner organization, the results of a visual inspection carried out while rafting were compared with the results of a magnetic particle inspection of particular structural details carried out in drydock. Conversations with those involved indicated that the visual inspection while underway found roughly 60% of the defects detected in the drydock inspection and also several defects that were not detected in drydock. Although it is reasonable to expect that other methods will yield PODs different from the POD currently provided by visual inspection, the impact of these experimental methods is not yet known.

2.3.2.7 Inspection Strategy

Inspection strategy refers to the extent to which the inspection is guided by previous information about problem areas. Inspectors report that they are guided by experience with similar vessels and knowledge of previously existing problem areas. Essentially, the strategy used is look where you expect there to be problems. The Critical Area Inspection Plan (CAIP) promotes this inspection strategy.

As noted above, the look where you expect there to be problems strategy can be beneficial, but can also mean that unanticipated defects are less likely to be detected. An alternative would be to apply equal attention to all regions of a tank. With current inspection techniques and resource constraints, this approach does not seem as fruitful. If more were known about critical areas and the growth of defects, and if improved technologies allowed selected areas of a structure to be monitored automatically, a third approach might be possible: monitor critical areas, but inspect all areas.

At present, the inspector's experience and the existence of a CAIP are the only available indicators of inspection strategy. The effect of inspector's experience on POD is discussed in Section xxx. No reliable information exists on the impact of a CAIP on POD.

2.3.2.8 Area to be Inspected

Probability of detection will be different in different portions of a vessel. For example, it is generally accepted that one of the most difficult areas to inspect is the underdeck away from the bulkheads. The "area to be inspected" is closely related to other environmental factors (access method, and inspection type, method, and strategy) and to vessel factors (structural layout and defect location).

2.3.2.9 Crew Support

Support from the crew of the vessel is essential in an inspection. The crew is responsible for overall safety, for maintaining vessel operations compatible with inspection, for cleaning the tank, and for ventilation. The crew may also provide lighting and the means of access. A supportive crew should have a positive impact on POD.

2.3.2.10 Time Available

A recent survey of U.S. Coast Guard inspectors found that the time available for inspection has a major impact on performance:

> "As a general rule, inspectors felt that more time, rather than better equipment, would result in the greatest improvement in inspection effectiveness..." (3)

Ayyub and White note that

> "[the] time planned for the inspection and the number of inspections planed for a specific

> day can dramatically affect the results of the inspection. Current practice is to allow the inspectors to determine the amount of time needed for any given inspection, but often they are forced into limiting the time due to scheduling of the number of inspections in a given time period." (5)

Inspectors interviewed for this study noted that in inspections done by regulatory bodies such as the U.S. Coast Guard, the inspector has the ability to hold a ship if the scheduled time does not allow for an adequate inspection. However, this is rarely done. Overall, inspectors felt that, while the time available would affect performance, current practice provided sufficient time in most cases. When time is limited, the attitude was "do the best you can".

2.3.2.11 Inspection Type and Objectives

Classification societies, regulatory agencies, and owner/operators each carry out inspections. Because the objectives of each organization's inspection are different, the procedures required are different, and the inspectors themselves are different, it is reasonable to expect that different defects may be detected during each type of inspection, and that POD will be different for different types of inspection. For example, prior to scheduled repair in the shipyard, an owner/operator may conduct an underway inspection to determine the approximate scope of repair work so that budget and schedule can be planned. This sort of inspection would be considered successful if areas needing repair were identified. It is not necessary in this type of inspection to detect every defect; the tanks will be reinspected in the shipyard under better conditions.

2.4 Summary

The sections above present a model of the factors affecting inspection performance and what is currently known about the impact of each factor. The available information on POD is qualitative at best. Based on this information and on the authors' experience, the following factors appear to have the greatest impact on performance. Of the vessel factors, structural details, the age of the vessel, and factors related to the defect itself appear to be most important. Of the inspector factors, experience with the vessel appears most important. Of the environmental factors, cleanliness, access, time available, and inspection type/objective appear most important.

Over time data may be gathered that will allow the impact of at least some of these factors to be evaluated more precisely. The focus should be on the factors that have the greatest impact on POD, and that can be controlled (or at least measured). The next section describes one such effort.

3. Case Study

As part of an ongoing study of the inspection in marine structures, several approaches for obtaining performance information have identified, Demsetz et al. (11). The case study presented here uses one of these approaches, benchmarked inspection data, in which the results of inspections performed underway are compared with the results of drydock inspections carried out a short time thereafter. The drydock inspection is assumed to be more thorough and therefore a better approximation to the true state of the vessel, and serves as "benchmark" against which the underway inspection is compared. A more detailed description of the advantages and disadvantages of benchmarked inspection data compared with other means of evaluating POD can be found in (11).

By comparing an underway inspection with a drydock inspection of the same ship that occurs a short time thereafter, the Vessel Factors are held nearly constant. Differences in inspection performance are therefore attributed to Inspector and Environment factors.

3.1 Background

Two sister ships belonging to the same owner form the basis of the case study. This owner typically uses a commercial inspection service to carry out an underway inspection several months before a ship goes in to the yard for repair work to determine the approximate scope of repair work. An additional inspection is carried out while the ship is in yard to define the exact scope of repair work. In the case study presented here, the results of inspections carried out in the yard are used as a benchmark against which the results of previous underway inspections are compared.

The case study is based on six inspections: an underway inspection of Ship A carried out in November, 1986; a shipyard inspection of Ship A carried out in April/May 1987; an underway inspection of Ship B carried out in May 1987; a shipyard inspection of Ship B carried out in October/November 1987; an underway inspection of Ship B carried out in 1990; and a shipyard inspection of ship B carried out in 1990. The inspections were carried out by commercial inspectors, with different companies and inspectors involved in the various inspections.

The configuration of the ships is summarized in Figures 2 and 3. Figure 2 shows the general arrangement and tank locations. Each ship has six center cargo tanks and four wing cargo tanks on port and starboard. Wing tanks 3 and 5 are water ballast tanks. The midship section is shown in Figure 3. The ships are of standard single-hull construction with two tie beams across the wing tanks.

3.2 Data Acquisition

Survey reports from the six inspections listed above were reviewed. Cracks were the only type of defect considered in this study. For tanks with a sufficient number of cracks, individual cracks were recorded by length and location (frame number, longitudinal number, general location — e.g., side shell, longitudinal bulkhead, web frame). Additional information was provided by an owner representative knowledgeable of the history of both ships and of the specific inspections involved. This information provided an essential perspective from which to interpret the data.

3.3 Data Analysis: General

The general analysis presented here is derived primarily from discussions with a representative of the owner. It is supported by the inspection reports and by the detailed analysis presented in the next section.

In the November 1986 underway inspection of Ship A, the owner was interested in the condition of the coatings, but also in sideshell cracks. Based on prior knowledge of the structure and loads, there was concern that side shell cracks might form at L9, L8, and higher. The inspection was carried out in rainy weather and under considerable time pressure; planned inspections of Tanks 5P/S were canceled. Tanks 3P and 3S were inspected down to L9; no side shell cracks were noted. However, notes from the inspection indicate that there was a significant amount of mud at L8 and L9 and also at L14 and L15.

A drydock inspection of Ship A was carried out in April and May of 1987, and revealed sideshell cracks along the length of the ship at the locations where the tie beams meet the side shell and longitudinal bulkhead: L8, L9, L14, and L15. Cracking was most significant in Tanks 3, 5, and 6, but was seen in Tanks 1, 2, and 4 as well.

The results of the drydock inspection of Ship A were a surprise, given that no fractures in Tanks 3P/S at L8 and L9 had been found in the underway inspection. The owner immediately scheduled an underway inspection of Ship B, with instructions to pay particular attention to possible cracking in the side shell and longitudinal bulkhead at L8, L9, L14, and L15. Progress reports during the underway inspection indicated in Tanks 3 P/S a condition similar to that seen in Ship A's drydock inspection, but with fewer cracks at L14 and L15. In Tanks 5 P/S, similar cracking was found at L8 and L9; at the time of the progress report, L14 and L15 had not been inspected.

Underway and drydock inspections of Ship B in 1990 showed no significant cracking at L8, L9, L14, or L15. This may indicate that repairs made during the 1987 drydocking to solve the cracking problem at L8, L9, L14, and L15 were successful.

The general analysis yields several observations. First, the inspection process worked as it is intended to. That is, cracks in both ships were detected before they were of sufficient length to threaten the structure or to allow oil to seep out of the cargo tanks. Second, experience with a sister ship (Ship A) was used to help guide the subsequent inspection of Ship B. Third, the underway inspection of Ship B was carried out with the purpose of determining whether conditions similar to Ship A existed. Knowing this, an inspector running out of time might not inspect L8, L9, L14, L15 at each web frame, but might instead try to get a general sense of whether or not the cracking problem was present.

3.4 Data Analysis: Specific

To compare the underway and drydock inspections in more detail, bBenchmarked" inspection plots comparing underway and drydock inspections were developed. Selected results are presented in Figures 4-6; a complete set of benchmarked plots can be found in (11). In each figure, cracks are plotted against axes representing position along the length of the ship, as indicated by web frame number (horizontal axis), and height from the tank bottom, as indicated by longitudinal number (vertical axis). Figure 4 compares the underway and drydock results for the 1987 inspections of Ship B; cracks along the port longitudinal bulkhead are shown in Figure 4a, cracks along the port side shell are shown in Figure 4b. Figure 5 shows similar results for the 1990 inspections of Ship B. Figure 6 again shows the 1987 port longitudinal bulkhead. Figure 6a repeats Figure 4a; Figure 6b shows only those cracks with length >= 100mm.

A quick glance at Figure 4 indicates that roughly half the cracks detected in drydock were also reported underway. However, it would be misleading to conclude that the observed detection rate is indicative of probability of detection for tankers in general, or even for this particular class of ship. A primary motivation for the underway inspection was to determine whether the repeated cracking seen in Ship A at L8, L9, L14, and L15 was also present in Ship B. To do this required only that a general sense of condition at the locations in question be obtained. In Tank 3 P, the underway inspection found cracks at L8, L9, L14, and L15 for roughly half the web frames, enough to conclude that a problem similar to that seen in Ship A existed. This conclusion would not have changed even if the cracks at the other half of the web frames had also been detected underway. It is impossible to know to what extent this affected POD.

In the 1987 inspections three types of performance can be observed through the benchmarked plots: good, fair, and poor. Examples of each type of performance are shown in Figure 4.

> Good Performance There are regions, such as the longitudinal bulkheads in Tank 5P, where nearly all the cracks found in drydock were

also detected underway (see Figure 4a). This indicates that at least under certain conditions (in this case, with knowledge of what had recently been found in a sister ship), POD for tanker inspection can be quite good.

Fair Performance In regions such as the side shells in Tanks 3P and 2P, performance is fair (see Figure 4b). Some cracks are detected, but others are missed. For cracks at L8, L9, L14, or L15, it is possible that mixed performance reflects a decision by the inspector(s) to inspect more quickly once cracks had been seen at several web frames.

Poor Performance There are also regions, such as the upper portions (L9 and above) of Tank 4P, where no cracks were found underway (see Figure 4b). It may be that there was no opportunity to raft at this level.

Figure 5 shows that by 1990, the problem observed at L8, L9, L14, and L15 in 1987 has not reoccurred (although a few cracks were reported at L8 and L9). With respect to detection rate, the 1990 inspections show an interesting result. In both port and starboard tanks, very good performance is observed along the longitudinal bulkhead. However, performance along the side shell is poor, with no cracks being detected underway in either the port or starboard tanks. There is no ready explanation for this difference.

A rough indication of the effect of crack length on detection rate can be seen by comparing parts a and b in Figure 6. The detection rate is higher, for cracks with length > 100 mm than it is for all cracks.

3.5 Results

Taken as a whole, the case study highlights the important influence of prior knowledge on inspection performance. The underway inspection of Ship A, carried out without prior knowledge (though with some suspicion) of the problems at L8, L9, L14, and L15, found no cracks at these locations when in fact many existed. Armed with the results of the subsequent drydock inspection of Ship A, the underway inspection of Ship B found significant cracking in similar locations.

For the 1987 and 1990 inspections of Ship B, inspection performance while underway falls into three categories: regions of very good performance, in which most cracks found in drydock were also detected underway; regions of mixed performance, in which many cracks found in drydock were not detected underway; and regions of poor performance, in which cracks were detected in drydock but not underway. Different categories of performance can be observed even within the same tank, suggesting that factors that can vary within a tank, such as access, cleanliness, and lighting, play an important role. In addition, the objectives of the inspection may have caused the inspector's performance to vary within a tank.

The results of the case study show that detection rates were, on average, higher for longer length cracks. In the interviews described earlier in this report, inspectors indicated that a 50 to 75 mm crack could be reliably detected. For the inspections reviewed here, this was not the case; high rates of detection were seen only for cracks greater than 100 mm in length. This may in part be due to the specific conditions of the case study.

4. Summary and Conclusions

Knowledge of how likely it is that a flaw will be found during an inspection, that is, the probability of detection, is important for many reasons: as feedback to design, to provide guidance in setting inspection schedules, and as a common ground upon which to compare different inspection technologies. The first step in determining probability of detection is to understand the underlying factors that have an effect on inspection. Based on a review of the literature and interviews with inspectors and others involved in the tank inspection process, a model of the factors that can influence probability of detection was developed. The model classifies factors based on the extent to which they can be modified throughout a vessel's life.

A case study showed the import influence that prior knowledge of a vessel and sister ships can have on inspection performance. Inspection performance was observed to vary greatly in different locations within the same vessel, indicating the importance of factors such as access, lighting, and cleanliness that can vary throughout a tank or a ship, and the importance of inspection objectives. Furthermore, the limited results presented suggest that the "readily detected" crack size is larger than that estimated by most inspectors, a result consistent with the literature on probability of detection in other industries.

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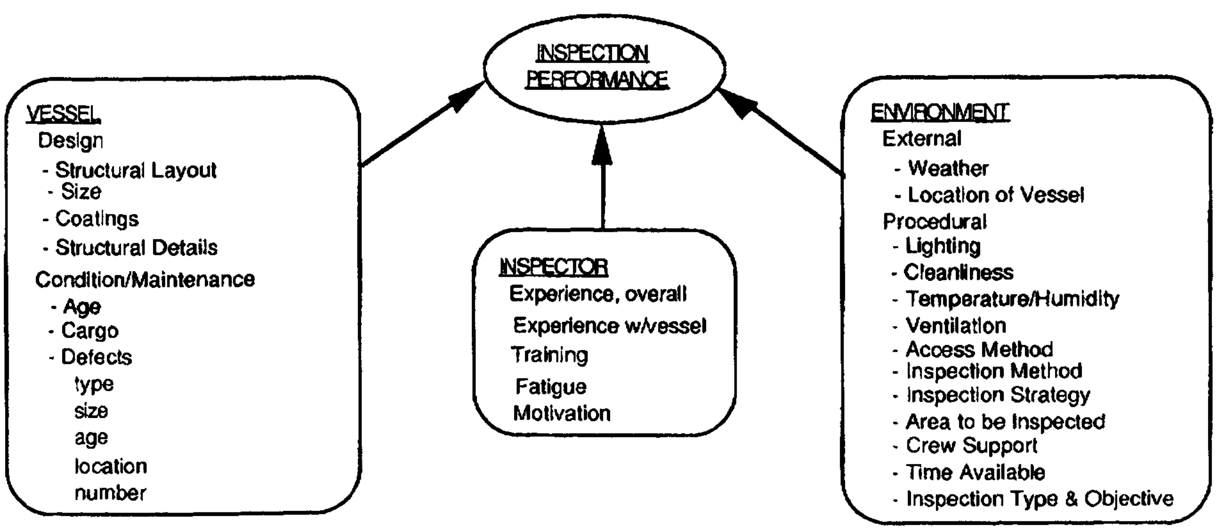

Figure 1
Factors that Affect Inpsection Performance

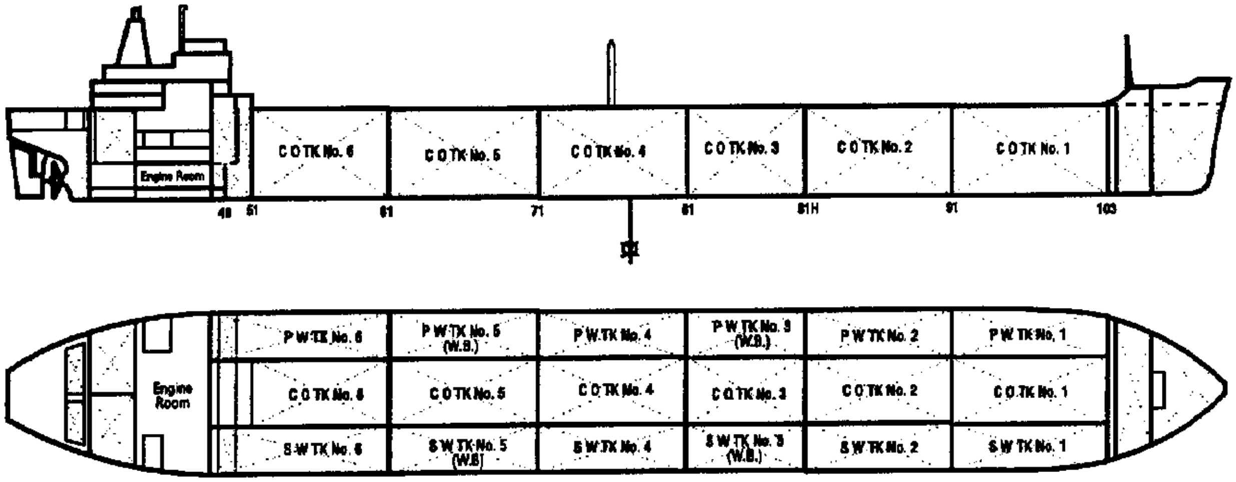

Figure 2
General Arrangement of Ship

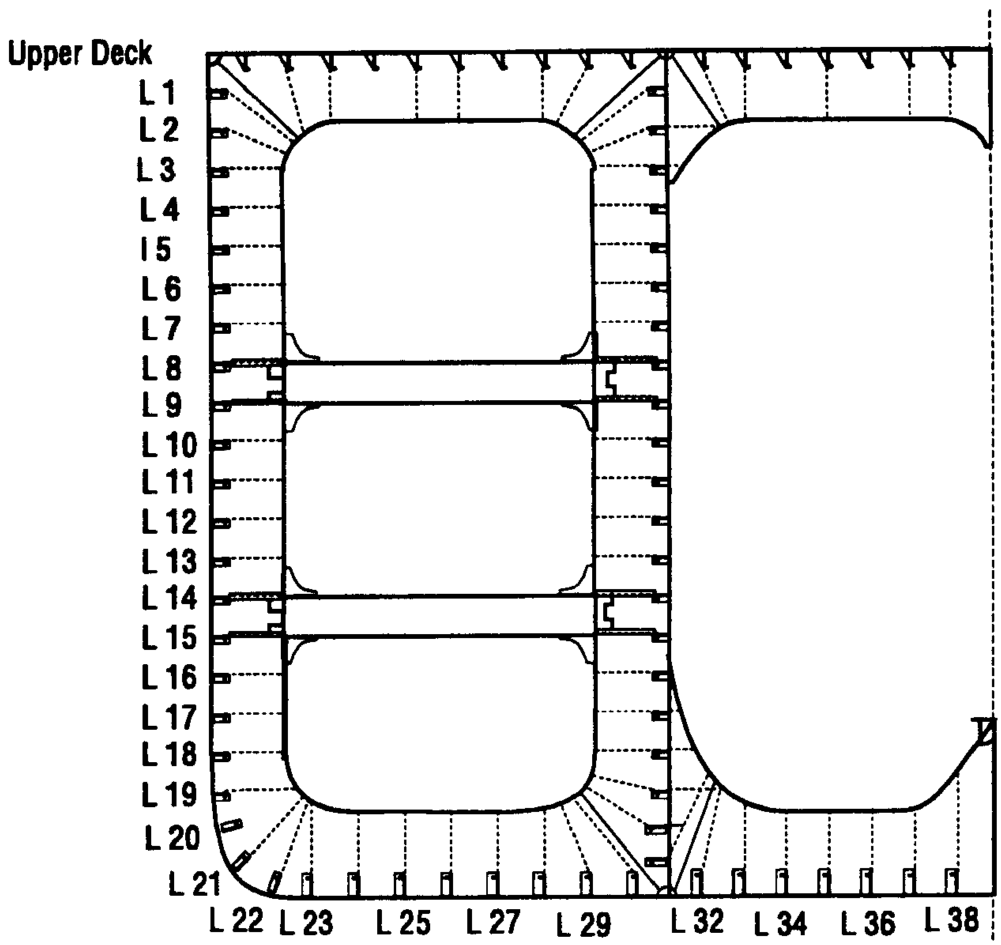

Figure 3
Midship Section

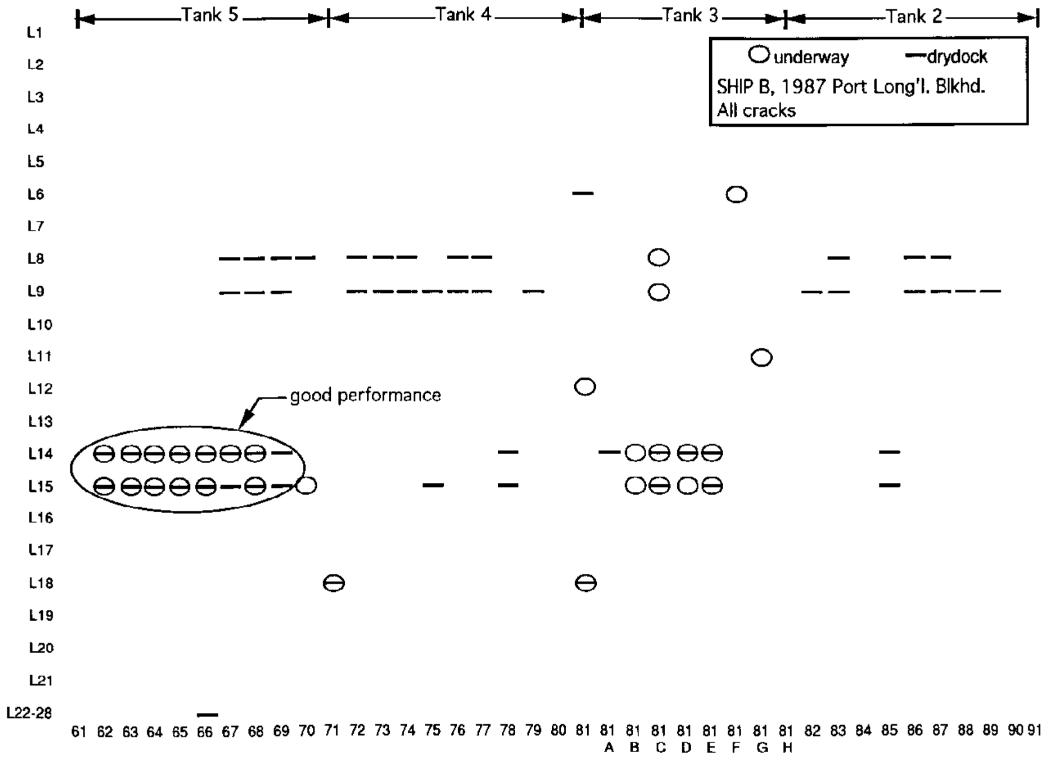

Figure 4a
Ship B 1987 Inspections, Port Longitudinal Bulkhead Cracks

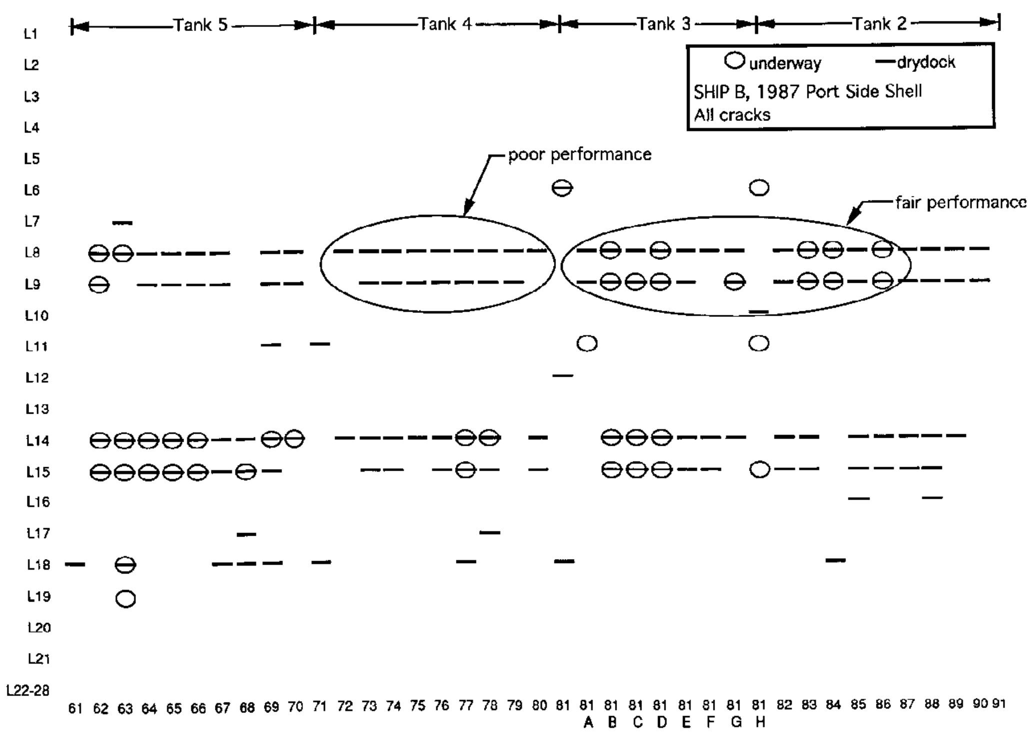

Figure 4b
Ship B 1987 Inspections, Port Side Shell Cracks

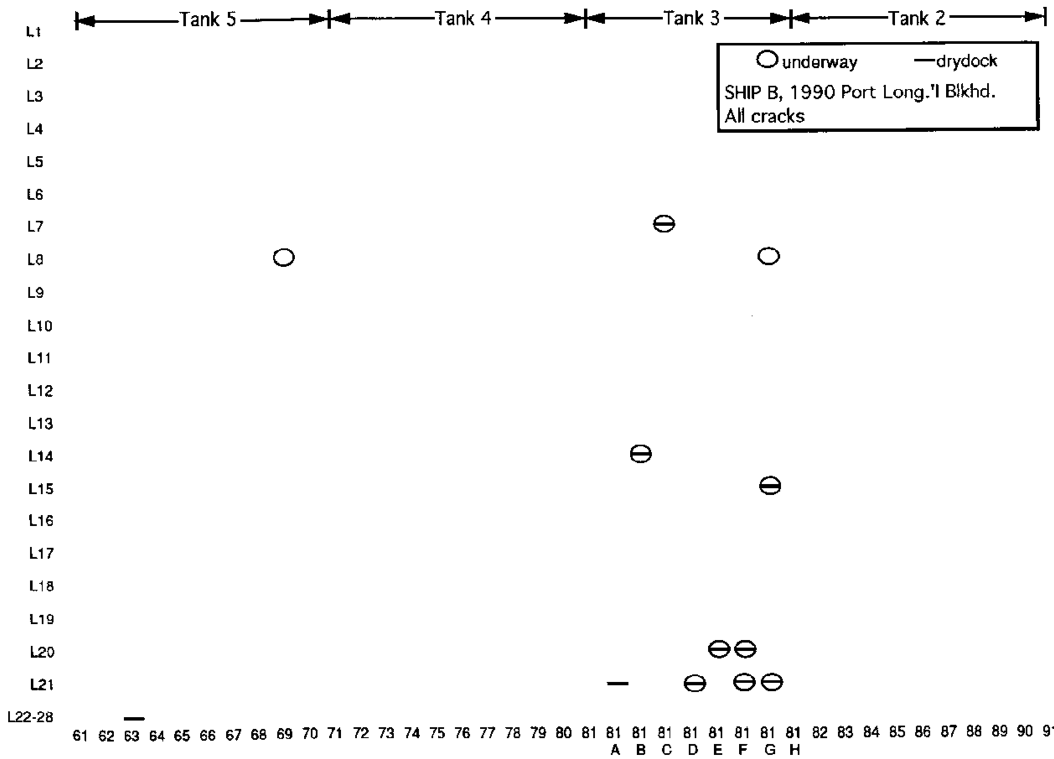

Figure 5a
Ship B 1990 Inspections, Port Longitudinal Bulkhead Cracks

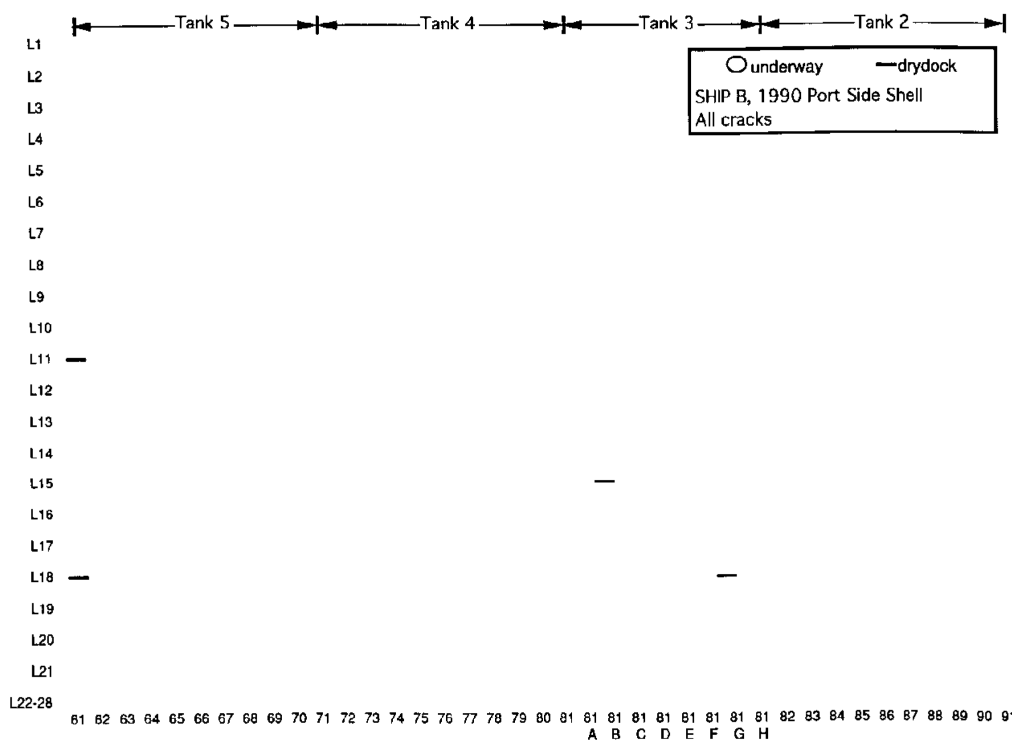

Figure 5b
Ship B 1990 Inspections, Port Side Shell Cracks

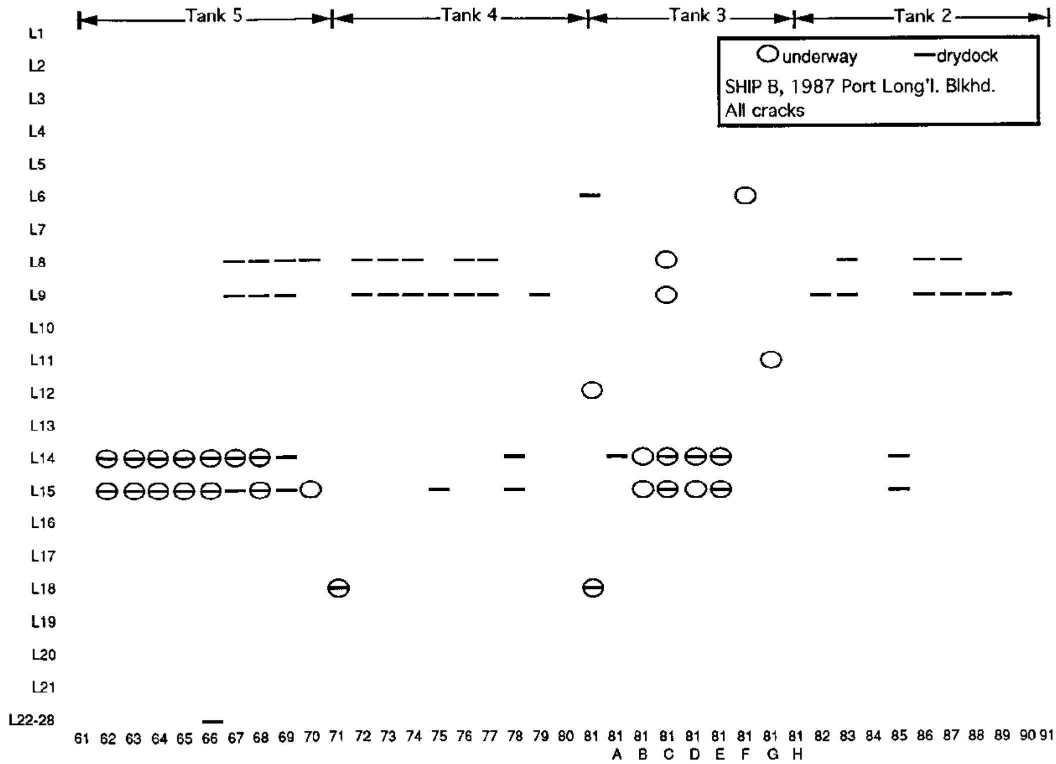

Figure 6a
Ship B 1987 Inpsections, Port Longitudinal Bulkhead Cracks

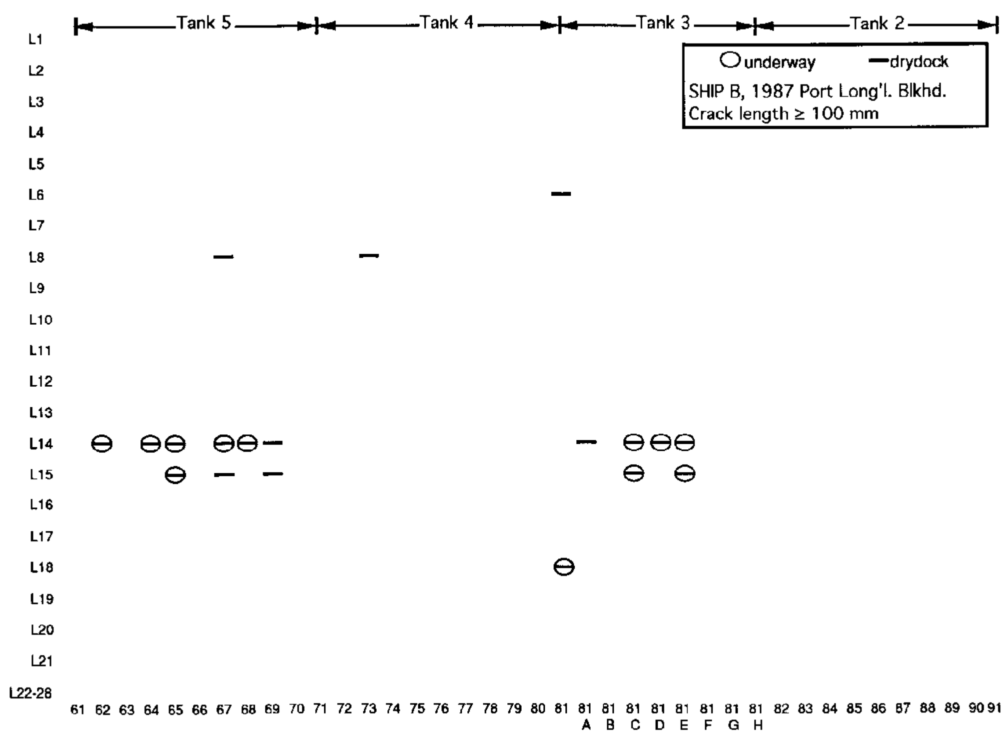

Figure 6b
Ship B 1987 Inspections, Port Longitudinal Bulkhead Cracks ≥ 100 mm

Marine growth is a very simple factor but can cause many problems, as discussed in Chapter 3. The wave force that affects the load on the structure is a function of member diameter, so marine growth will increase member diameter and increase the wave force correspondingly. This factor uses actual measured marine growth (mm)/design marine growth (mm). Table 8.19 illustrates scores for this factor between 0 and 10, where a higher score signifies greater risk. If the measured marine growth exceeds the design value, it increases the environmental load on the platform and therefore increases the li