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SSC-389

INSPECTION OF MARINE STRUCTURES

SHIP STRUCTURE COMMITTEE

1996

SSC-389 INSPECTION OF MARINE STRUCTURES **Ship Structure Committee 1996**

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An Interagency Advisory Committee

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INSPECTION OF MARINE STRUCTURES

This report presents a review of the factors, which impact the likelihood that a person checking the structure of a ship for failures will find the existing failures. This study was necessitated by several factors:

- Even a small hull failure on a tanker can create a significant oil spill with damages in the millions of dollars.
- The cost of laydays for inspections and narrow profit margins for the shipping industry.
- The time it takes to conduct a full inspection of a large ship's structure.
- The continued emphasis on reducing the size of all government workforces.

Each of these factors require better understanding of the human factors in the hull inspection process. Through this improved understanding, inspections can be better focused to receive the greatest return on the effort invested. A follow-on project is aimed at analyzing the results of actual inspections to quantify the impact of each of the factors indentified in this project.

This report supports the Coast Guard's new program for "Prevention Through People," which addresses the human error causes of marine casualties.

JC Card
J. C. CARD
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee

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16. Abstract

This report addresses the development of a better understanding of probability of detection in tanker inspections. 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 is developed. A review of the treatment of probability of detection in aviation, nuclear power, manufacturing, and offshore structures provides examples of the various methods that have been used to assess probability of detection: controlled experiments on small scale samples, controlled experiments on large scale samples in simulated field conditions, use of historical data, and use of an out-of-service structure. Four approaches to analyzing inspection performance are identified and evaluated for application to the tanker inspection problem: solicitation of expert opinion, laboratory experiments, *in situ* experiments, and benchmarked inspection data. The results suggest that *in situ* experiments, benchmarked inspection data, and a hybrid (*in situ* test on an out-of-service vessel) are potentially useful tools for further work on probability of detection. A case study demonstrating the use of benchmarked inspection data is provided. The case study demonstrates the feasibility of the approach, but also its difficulties. The results highlight the important influence that prior knowledge of likely defect locations has on probability of detection. Based on the research presented in this report, it is recommended that further efforts to understand probability of detection in the tanker inspection environment be carried out through *in situ* tests of either an in-service or an out-of-service vessel, and through analysis of benchmarked inspection data.

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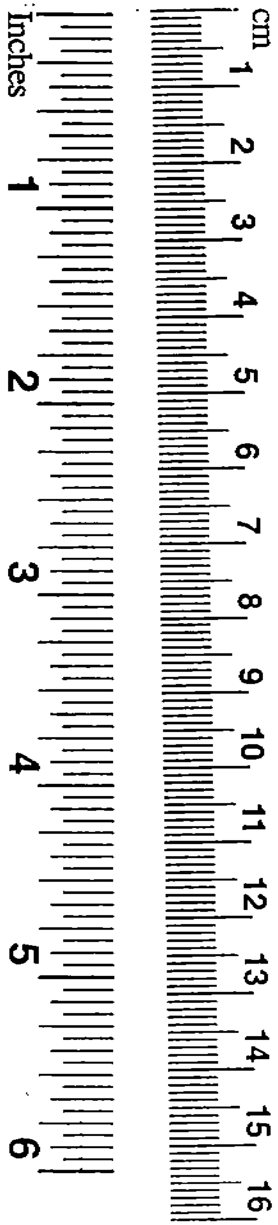
METRIC CONVERSION CARD

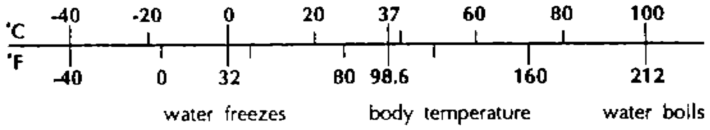
Approximate Conversions to Metric Measures

Symbol	*When You Know*	*Multiply by*	*To Find*	*Symbol*
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	metric ton	t
		VOLUME		
tsp	teaspoons	5	milliliters	mL
Tbsp	tablespoons	15	milliliters	mL
in^3	cubic inches	16	milliliters	mL
fl oz	fluid ounces	30	milliliters	mL
c	cups	0.24	liters	L
pt	pints	0.47	liters	L
qt	quarts	0.95	liters	L
gal	gallons	3.8	liters	L
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	degrees Fahrenheit	subtract 32, multiply by 5/9	degrees Celsius	°C



Approximate Conversions from Metric Measures

Symbol	*When You Know*	*Multiply by*	*To Find*	*Symbol*
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares ($10,000\ m^2$)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	metric ton (1,000 kg)	1.1	short tons	
		VOLUME		
mL	milliliters	0.03	fluid ounces	fl oz
mL	milliliters	0.06	cubic inches	in^3
L	liters	2.1	pints	pt
L	liters	1.06	quarts	qt
L	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	degrees Celsius	multiply by 9/5, add 32	degrees Fahrenheit	°F



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The work described in this project was carried out in a timely fashion consistent with the original proposal and subsequent quarterly reports. However, the first author was unacceptably late in delivering both the draft final report and this report to the Maritime Administration. The responsibility for this delay lies entirely with the first author, and should in no way reflect upon the other authors. The patience of those involved in administering this project is gratefully appreciated.

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1. INTRODUCTION

1.1 IMPORTANCE OF INSPECTION

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.

Periodic inspections are required by classification societies and by the U.S. Coast Guard. Because an effective inspection and maintenance program can greatly extend the life of a structure, owners and operators also have an economic incentive to carry out periodic inspections. A planned system of inspection and maintenance has been shown in some circumstances to result in life-time costs of about one sixth of the cost of neglecting the damage and replacing the structure when necessary [Weber 1984]. These savings come from preventive maintenance and from improved planning and execution of required repairs, including the ability to plan and carry out alternative repair strategies [Bureau Veritas 1987]. An additional benefit of periodic inspections is the ability to assess and provide feedback on the performance of materials or designs. Figure 1 summarizes the reasons marine structures are periodically inspected.

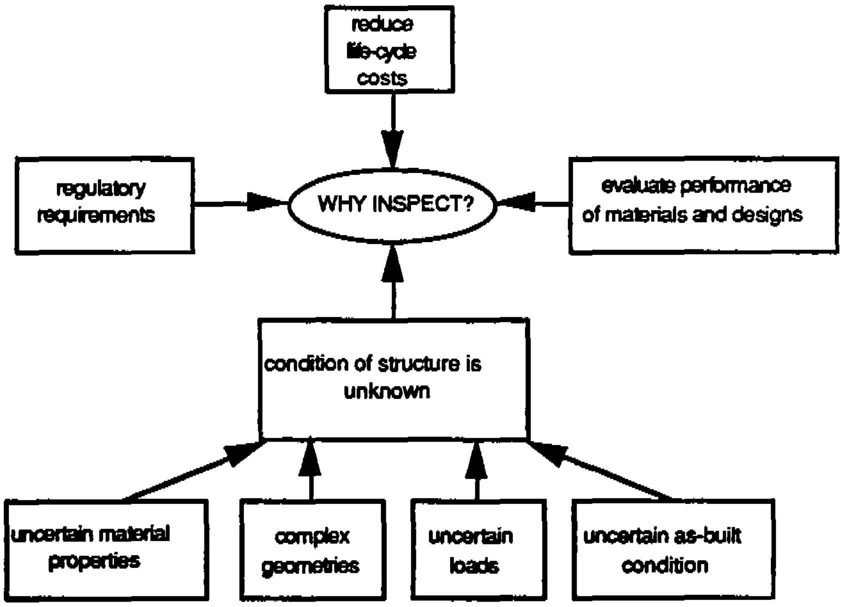

Figure 1. Motivation for Periodic Inspection

Periodic inspections are particularly important in fatigue loading situations, where detecting and repairing cracks before they reach a critical length is crucial. Inspections take on increased importance when structures have been designed using advanced methods that result in a reduction of excess load carrying capacity. Use of a "fail-safe" approach to design, based on the detection and repair of flaws, as opposed to a "safe-life" approach, based on the structure not failing during its lifetime, also increases the importance of inspection [Basar 1985]; in essence, the need for inspection is "built in" during design. As the average age of vessels and structures in operation increases, there will be a greater demand for and reliance on periodic inspections.

1.2 PRESSURES AND CONSTRAINTS ON INSPECTION

Inspections are in many ways the "last resort" in ensuring the safety of marine structures. However, 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 [1995]:

> "...picture ... a large gymnasium. The compartments...are on that scale. The inspector usually enters this compartment via a ladder from the main deck. He is typically 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."

Inspection is frequently a physically demanding task, involving climbing (in the case of ship compartments) or diving (in the case of other marine structures). There is often time pressure associated with an inspection. At a minimum, the need for the inspector to move on to the next inspection places a constraint on time. In addition, for the many inspections that require a facility to be out of service, there is a strong incentive to minimize inspection time and return the facility to active service. Time pressure and the vast size of many marine structures make it impossible to inspect the entire structure. The U.S. Coast Guard has estimated that unless a tank is staged and illuminated, on a vessel larger than 200 KDWT less than 20% of the internal structure can be adequately inspected during a drydock inspection [Bell *et al.* 1989].

Because inspections are difficult and may require facilities to be out of service, it would be ideal to inspect only as often as necessary to ensure safety and efficient planning of repairs. To realize this sort of "just in time" inspection requires knowledge of the types and sizes of flaws that can be detected, of how reliably they can be detected, of how fast they grow, and of the size at which they become critical. Rolfe *et al.* [1993] describe a fracture mechanics approach for oil tankers that addresses crack growth and critical crack length. Their results indicate that changes in the quality of inspection have significant impacts on fatigue life. For example, for the bottom shell cracks they considered, changing from an inspection approach able to detect 3 inch cracks to one able to detect 2 inch cracks can lead to a significant extension in fatigue life. Among their recommendations for further research is a study of current inspection practice to verify probability of detection (POD) curves for various ship details [Rolfe *et al.* 1993].

Inspections are carried out by different parties (e.g. owner, classification society, regualtory agency) and with different objectives. For example, an owner may carry out an inspection shortly before a ship comes into the repair yard in order to determine the scope of repair work. This sort of inspection will be considered successful if the areas needing repair and the approximate magnitude of the repair work are identified; in this case, is not necessary for every crack to be identified and precisely measured.

1.3 INSPECTION TECHNOLOGIES

Marine inspections generally involve an initial visual inspection: a trained inspector "looks over" the structure, focusing on known problem areas and on anomalies. Depending on the type of structure, this visual inspection may be followed by the investigation of selected areas using a method of non-destructive evaluation (*e.g.* magnetic particle inspection). Inspections as currently carried out tend to be labor intensive and physically demanding. There has been a significant interest in new technologies that would make inspections safer, faster, and more effective. For example, for tanker inspection proposed improvements have included better lighting, various means of access, the use of hand-held computers for data acquisition, the use of infrared thermography, the use of remotely-operated vehicles, and the use of remote light source with video cameras. These technologies and others are described in, among other sources, Holzman 1992, Goodwin and McClave 1993, and Allen *et al.* 1993.

In order to determine whether or not a new technology is worthwhile, it is necessary to understand its costs and benefits and compare these against the costs and benefits of current inspection practice. One aspect of the "benefit" part of this comparison is the likelihood that a flaw with particular characteristics will be found using a particular technology.

1.4 PROBABILITY OF DETECTION

A knowledge of how likely it is that a flaw will be found during an inspection 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. Ideally, one would like to know the probability that a flaw with certain characteristics will be detected on a particular inspection. This *probability of detection* (POD) is usually expressed in a POD curve, with the POD plotted on the vertical axis and some characteristic of the flaw (for example, crack length) plotted on the horizontal axis. To reflect uncertainty, the POD curve is bounded by confidence intervals. Figure 2 shows this schematically. A POD curve can be derived from theoretical considerations or can be based on observed performance. In either case, it is important to understand the confidence bounds on the curve presented.

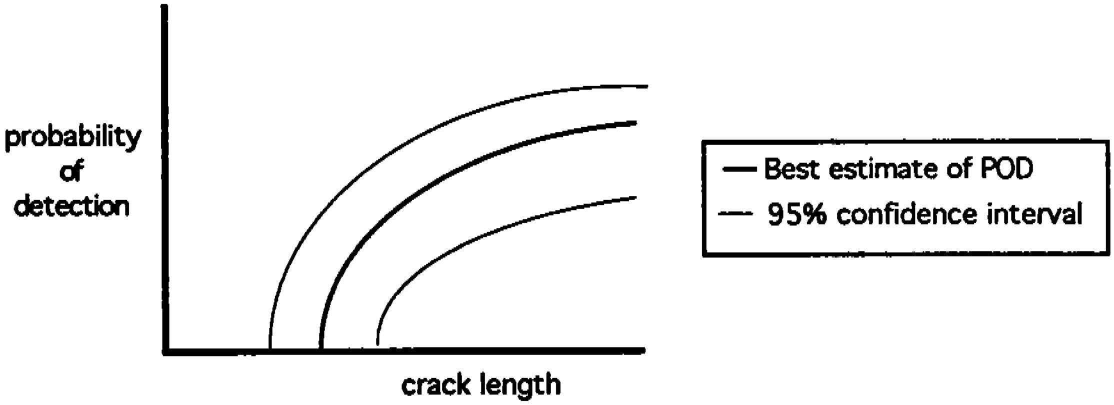

Figure 2. Schematic Probability of Detection Curve
(for illustration only; not derived from actual data)

A typical POD curve shows how the probability of detection varies with changes in a single factor, typically crack length. It is important to understand the probability of finding other defects, such as buckling, coating breakdown, and corrosion, as well, although some of these defects are difficult to quantify. Previous work and the results of interviews carried out as a part of this study show the ability to detect a defect is influenced by a variety of factors related to the environment, the inspector, and the vessel. A single POD curve may not be sufficient to capture these effects. In other words, if the probability of detection is viewed only as a function of, say, crack length, the variation in detection rates (and the corresponding confidence bounds on the POD curve) will be so large as to render the resulting POD curve useless.

If the influence of all factors was known, a family of POD curves could be generated covering the variety of conditions expected to occur in practice. Alternatively, a "baseline" POD curve could be developed, to which "multipliers" would be applied depending on vessel, inspector, and environment factors. A similar approach is used in estimating labor productivity in the construction industry. Baseline productivity values are modified based on the presence, absence, or level of factors known to affect productivity (see, for example, Neil 1982).

Clearly, a great deal of data would be required to learn the precise impact of every factor on overall inspection performance. However, preliminary indicators of the probability of detection for "typical practice" could be developed from a more limited amount of information.

1.5 PURPOSE OF THIS STUDY

The purpose of this study is to investigate means of developing POD curves for marine structures. Work in the aviation, nuclear, and manufacturing industries shows that engineers and operators often use unrealistic inspection performance expectations. In general, in the marine sector we do not understand just how good or how poor a job of inspection we do. The goal of this work is an understanding POD for marine structures, including the factors that influence POD, and the ways in which POD curves could be derived, developed, or borrowed from other industries. Due to the experience and interests of the authors and the Project Technical Committee for this project and to the availability of inspection recrods, the work reported here focuses on oil tankers. The methods presented should be applicable to other marine structures as well, particularly when the primary means of inspection is a visual survey of unobstructed areas.

1.6 RESEARCH APPROACH

A two-step approach was taken for this study. First, information regarding inspection practice and inspection performance in the marine and in other industries was gathered. Then, methods for evaluating inspection performance were identified, developed, and evaluated. In its initial scope, this study was to have produced estimates of POD curves for common inspection procedures and details, estmiates of the accuracy of measurements of fatigue cracks, estimates of the costs of inspection for various inspection types and structures, and quantitative estimates of the probability of detectioning corrosion damange and the accuracy of measurement of such damage. It was anticipated that much of this information would be based on results obtained in other industries. However, the available information was much sparser than anticipated. Therefore, the scope of the study was redefined at the February 18, 1994 meeting with the Project Technical Committee, to focus on the use of historical data as a source of POD information for tanker inspection.

1.6.1 Information Gathering

The first step in this project was to obtain a clear understanding of the factors that may affect inspection performance. The results reported here draw upon two primary sources of information: the literature and interviews with those involved in marine inspections. The review of the literature included publicly available documents describing maritime inspection and inspections in related fields. Where available, in-house documents from relevant organizations were also reviewed. The literature review provided insight into inspection procedures and the handling of inspection performance in other industries. Recent work by Ayyub and White [1992] addressed many of the same issues as the work described here and is referenced throughout this document. Though there are some areas of overlap and some differences in the conclusions drawn, the two studies complement each other.

Additional information was obtained from interviews with individuals currently involved in marine inspections. Interviews were carried out with four inspectors for regulatory agencies, four independent inspectors, and one classification society inspector. In addition, three engineers with vessel operating companies were interviewed. Interviews were conducted by telephone. For the first few interviews, responses were solicited to a specific list of questions. While some participants were willing to take the time to go through the survey, others, particularly those not previously familiar with the project, were frustrated with this approach. Therefore, for the remainder of the interviews, a conversational approach was adopted. This let the participant decide where to lead the interview and produced more detailed results. The interview questions were still used as a guide to keep the conversation going. This seemed to work well, and although all the areas were not covered with each participant, many volunteered additional information and experiences which might have been missed under the more structured format.

The interviews provided an understanding of current inspection procedures and problems in tanker inspection, and of the ways in which inspections in the marine environment differ from practices in other industries. Information was obtained on personnel issues such as inspector background, experience, and training, and on operational issues such as access, equipment, inspection times, problems encountered, and performance. The interviews were also helpful in obtaining additional reference materials, particularly in-house documents, and in obtaining comments on possible experimental setups.

There were, however, some limitations to the information obtained in the interviews. The main drawback was that the interviews did not yield much quantitative information on inspection performance. In most cases, participants were unable or unwilling to assess quantitatively either their own performance or the performance of others.

The sources of information reviewed for this project are summarized in Figure 3.

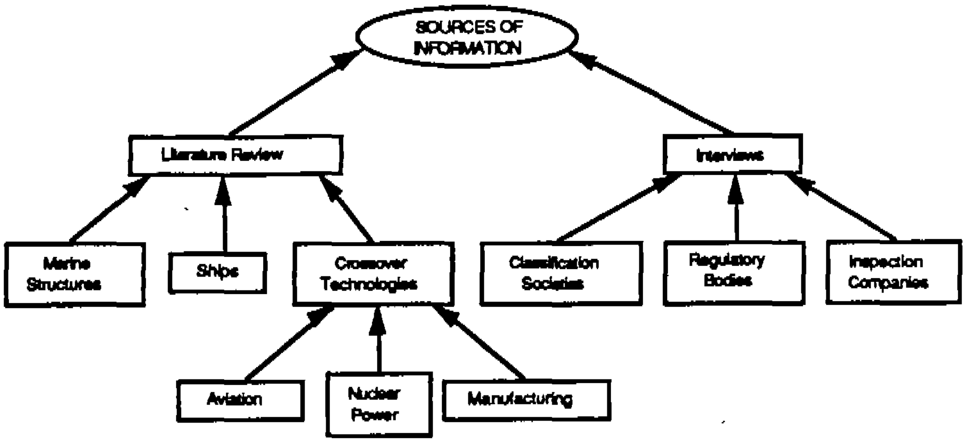

Figure 3. Sources of Information

1.6.2 Methods for Evaluating Inspection Performance

The second step in this study involved the identification and evaluation of methods for developing POD curves for tanker inspection. Four methods were considered: solicitation of experts, laboratory experiments, benchmarked inspection data, and *in-situ* experiments. An example application of benchmarked inspection data was carried out.

1.7 CONTENTS OF REPORT

Section 2 of this report describes the factors that affect inspection performance. Material is drawn from the literature on marine and other industries, and from interviews with inspectors. Section 3 presents related work on evaluation of inspection performance in aviation, nuclear power, manufacturing, pipe welding, and marine applications. Section 4 summarizes the issues involved in evaluating inspection performance. Section 5 presents the various approaches that can be used to quantify inspection performance. Section 6 presents conclusions and recommendations. References are provided in Section 7. Appendix A contains a questionnaire to be used at the time of an inspection to record information on the factors that can affect performance. Appendix B contains the data used in the case study of the benchmarked historical data approach. Appendix C summarizes the drydock inspection of one of the ships examined in the case study.

2. FACTORS AFFECTING INSPECTION PERFORMANCE

2.1 FACTORS AFFECTING PERFORMANCE: OVERVIEW

Each inspection represents a unique combination of vessel, personnel, and environment. Holzman [1992] noted that inspection performance depends on the inspector, the tank being inspected, and the method of inspection used. Ayyub and White [1992] 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, 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 and augmenting previous work with the results of the literature review and interviews carried out during this project leads to the model of inspection performance shown in Figure 4. Inspection performance is shown as being 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 the parties involved in the inspection.

The factors shown in Figure 4 are those that can reasonably be expected to influence the probability of detecting flaws. It important to keep in mind the difference between factors that influence the *existence* of defects and factors that influence the probability that existing defects will be *detected* during an inspection. The 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 do not influence the ability to detect the defects during inspection. Rather, it is the resulting characteristics of the defect (such as type, size, and location), along with other vessel, environmental, and personnel factors, that determine the likelihood that the defect will be detected. Understanding the way in which design, fabrication, and operational decisions can influence the existence of defects is important. However, the focus of this report is on the factors that determine how likely it is that a defect, once it exists, will be detected.

Ideally, it would be possible to define a comprehensive set of factors that are mutually independent in their influence on inspection performance. The influence of each factor could then be combined directly with a "baseline" performance level to yield the probability of detection for 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 motivation and experience of the inspector. As as result, the appropriate way to incorporate the affect of multiple factors may be more complicated. The following sections discuss each of the factors in greater detail. Where possible, a preliminary assessment of the impact of each factor on probability of detection is provided.

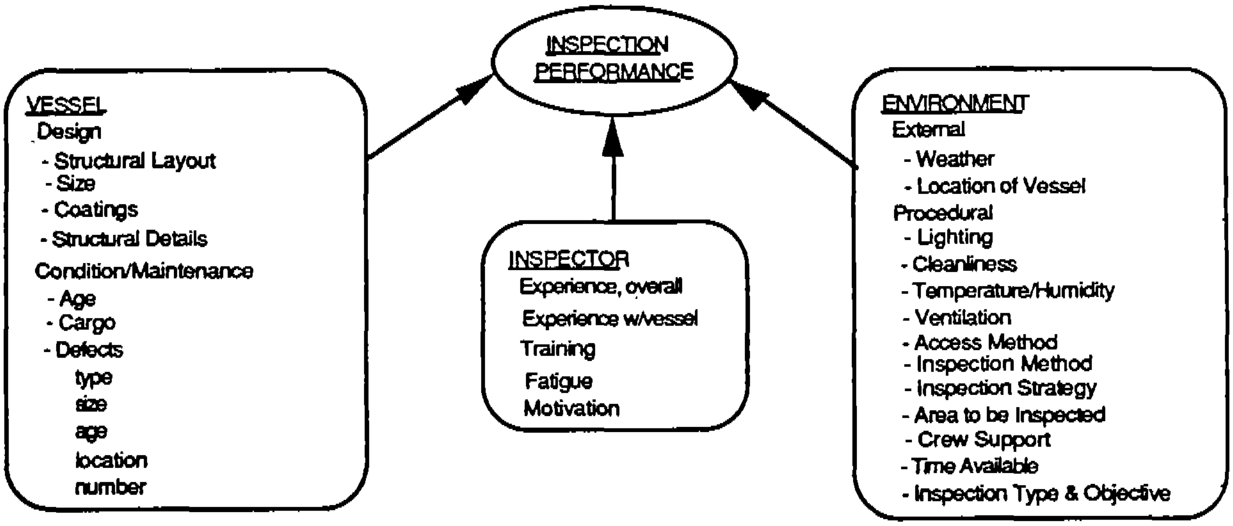

Figure 4. Factors that Affect Inspection Performance

2.2 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, including structural layout, size, and coatings, are fixed at the time of 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.

2.2.1 Design

Design factors influence the probability of detection in several ways. The structural layout and size of the vessel help determine 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 also affect the likelihood that a defect will be detected. The configuration of structural details can have a significant impact on the likelihood that defects will be detected.

The choice of structural material (as opposed to coating material) has been mentioned as a design factor influencing inspection performance [Ayyub and White 1992]. 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, at present, 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 (for example, a different trend 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 4.

2.2.1.1 Structural Layout

The major impact of structural layout on the probability of detection is in 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 an inspector 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 [Holzman 1992].

The 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 prior to an inspection.

The structural layout of double hull tankers is quite different from that of single hull vessel. Access to the between hull region should be physically easier than access in a single hull vessel (or in the cargo portion of the double hull vessel). However, this will be offset to some degree by the greatly increased difficulty of providing adequate ventilation. At present it not possible to say how POD for a double hull tanker will compare with POD for a single hull vessel.

> ***Preliminary Assessment:*** *Other factors being equal, POD will be higher in vessels whose structure facilitates access. Other factors being equal, POD will be higher in vessels whose design allows for easy cleaning of critical details.*

2.2.1.2 Size

Inspections are generally carried out under some sort of time constraint, whether explicit (the inspector must move on to another vessel) or implicit (the cost of keeping the vessel out of service). Therefore, the size of the vessel has an impact on the percent of the vessel that can be subjected to a close-up inspection. An estimate by U.S. Coast Guard field personnel of the percent internal structures inspected on various size vessels is shown in Figure 5. It is reasonable to expect that, as the percent of a vessel inspected decreases, the probability of detection also decreases.

> ***Preliminary Assessment:*** *Other factors being equal, POD for a larger vessel will be lower than POD for a smaller vessel of similar design.*

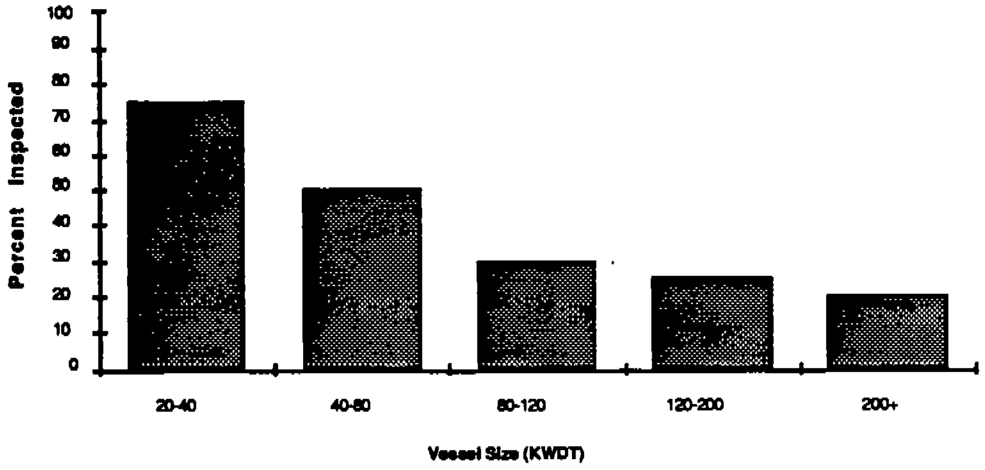

Figure 5. Percentage Inspected of a Vessel Based on Size (after [Bell 1989])

2.2.1.3 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." [Ayyub and White 1992].

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." [Williams and Sharpe 1995].

The impact of coating on inspection performance was also noted by many of inspectors interviewed for this report. 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.

> ***Preliminary Assessment:*** *Other factors being equal, POD for a vessel with a light colored coating that is well applied will be higher than POD for a vessel with dark colored coating or with poorly applied coating. It is*

> *not clear whether POD for an uncoated vessel will be would higher or lower than POD for vessel with a light colored coating.*

2.2.1.4 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 defect that is easily visible to an inspector scanning the area with a flashlight is more likely to be detected than one that can only be seen by looking behind a part of the structure. 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 the case of a ballast tank) or crude residue (in the case of a cargo tank) to collect over likley failure areas.

> ***Preliminary Assessment:*** *Other factors being equal, POD will be greater for structural details in which the likely defect locations do not accumulate silt or residue and are readily visible to an inpsector.*

2.2.2 Condition/Maintenance

Condition or Maintenance factors reflect the changes in the vessel as it ages. The age of the vessel itself affects the likelihood that a defect will be detected; on an older vessel, problem areas are better known. Additional condition and maintenance factors include the 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.

2.2.2.1 Age

Prior knowledge of defect areas on a particular vessel or class can influence the probability of detection. On an older ship, "trouble ares" may well be known from previous inspections or from inspections of 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.

> ***Preliminary Assessment:*** *The impact of the age of a ship on POD is not clear. Increased knowledge of problem areas, which would lead to a*

> *higher POD for an older ship, may be offset by an increase in the number and different location of defects.*

2.2.2.2 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." [Ayyub and White 1992].

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 for the ballast tank as well.

> ***Preliminary Assessment:*** *Other factors being equal, POD for a ballast tank will be higher than POD for a cargo tank.*

2.2.2.3 Defects

Characteristics of defects themselves 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. It seems reasonable to expect that the probability of detecting each type of defect will be different. Different inspection practices may be better at detecting different types of defects [Ayyub and White 1992]. 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 was 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 two to three inches.

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 will be 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.

> ***Preliminary Assessment:*** *Other factors being equal, POD for larger defects will be greater than POD for smaller defects. Other factors being equal, POD for older defects will be greater than POD for more recent defects. Other factors being equal, POD for defects in difficult-to-access areas will be lower than POD for other defects. Other factors being equal, POD for defects in critical areas will be greater than POD for defects in other areas. Other factors being equal, POD will be greater where a greater number of defects exist.*

2.3 INSPECTOR

The person carrying out an inspection can greatly influence its outcome. In other industries, for example, aviation, personnel factors have been found to be the most significant source of variation in inspection performance [Spencer 1993]. 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.

2.3.1 Overall Experience

Time and time again, experience is mentioned as a critical factor in inspection performance. Ayyub and White state that it is the most important of their personnel factors [Ayyub and White 1992]. 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." [Ayyub and White 1992].

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" [Williams and Sharpe 1995].

> ***Preliminary Assessment:*** *Other factors being equal, POD will be greater with a more experienced inspector than with a less experienced inspector.*

2.3.2 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.

> ***Preliminary Assessment:*** *Other factors being equal, POD will be increased if the inspector has experience on vessels of the same class. POD will be increased further still if the inspector has previous experience with the vessel being inspected.*

2.3.3 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 [Ayyub and White 1992].

In other inspection applications, classroom training beyond a minimum level has been shown to have little effect on demonstrated proficiency in the field [Rummel 1989]. 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 1989].

> ***Preliminary Assessment:*** *Other factors being equal, POD will be greater when an inspector has undergone initial training and periodic refresher training.*

2.3.4 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" [Holzman 1992]. 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" [Williams and Sharpe 1993]. Although no studies have been carried out to show the relationship between an inspector's degree of fatigue and the quality of inspection, it seems reasonable to assume that inspectors who are fatigued will have a lower level of performance, all other factors being equal. The degree of fatigue is influenced by the inspector's physical condition, by the number of hours worked just prior to an inspection, and by other physical and emotional demands.

> ***Preliminary Assessment:*** *Other factors being equal, POD will be lower when an inspector is fatigued.*

2.3.5 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 [Bell 1989]. Based on field comments, inspection personnel were found to be suffering from overload. Many of the Coast Guard inspectors were working up to seventy hours a week in a hard, dirty 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 [Bell 1989]. 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.

> ***Preliminary Assessment:*** *Other factors being equal, POD will be lower when an inspector's motivation is lower. The level of motivation may be difficult or impossible to measure.*

2.4 ENVIRONMENT

The environment in which the inspection is carried out has a major influence on performance. In the model of inspection performance shown in Figure 4, an attempt has been made to distinguish between environmental factors that cannot be modified by inspection procedures and those that can be (or perhaps could be with appropriate technology). The former are referred to as external factors; the latter as procedural factors. While the appropriate category for a particular factor is often obvious, for some factors the distinction is not clear-cut. An extreme example is the classification of weather *vs.* that of temperature. Weather is included as an external factor because the weather at a particular time and place cannot be controlled by those planning the inspection. The weather can, however, be predicted (at least to some extent), 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).

2.4.1 External

External factors are those 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, that is, whether the inspection is performed while underway, while in port, or while in drydock.

2.4.1.1 Weather

Weather conditions can affect inspection performance. Ayyub and White note that

> "Hot, humid weather affects the inspectors by reducing the amount of time they can spend 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." [Ayyub and White 1992]

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 1982].

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. However, the conditions that lead to high seas would not affect an inspection that is carried out in drydock.

> ***Preliminary Assessment:*** *Other factors being equal, POD will be higher when weather conditions are moderate. This effect will be more pronounced for inspections done underway or at port (as opposed to inspections carried out in drydock).*

2.4.1.2 Location of Vessel

Inspections can be carried out in drydock, at dockside, while moored, or while underway. There is nearly universal concurrence that inspections performed in drydock result in the detection of a greater percentage of defects than inspections performed in other locations. Inspections performed underway are generally considered to result in the detection of fewer defects than inspections performed in other locations.

Inspections performed at sea present a more physically challenging environment to the inspector. The motion of the ship and slipperiness of the surface (epoxy coatings in ballast tanks; oil in cargo tanks) are one reason for increased difficulty. 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 inspection.

The probability of detecting damage is increased in a shipyard due to better access, to better lighting, and to the tanks being dry. There is a diversity of opinion as to how many defects would be missed even in a shipyard inspection. One inspector estimated that restricted access, the inherent limitations of tank size, and the limited staging used only for repairs resulted in as few as 50-60% of cracks being detected. Others feel that the percent detected is much higher in the shipyard.

> ***Preliminary Assessment:*** *Other factors being equal, POD will be lowest for inspections done while underway, higher for inspections carried out while moored or at dockside, and highest for inspections carried out in drydock.*

2.4.2 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)

2.4.2.1 Lighting

Lighting has as significant impact on the quality of 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." [Williams and Sharpe 1992].

Inspectors interviewed as part of this study and for other studies [Holzman 1992, Goodwin and McClave 1993] consistently mention lighting as a critical issue in inspections. Current work by the U.S. Coast Guard investigates improvements in inspection lighting [Allen 1993].

> ***Preliminary Assessment:*** *Other factors being equal, POD will be higher when better lighting is available to inspectors.*

2.4.2.2 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." [Williams and Sharpe 1995].

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

> ***Preliminary Assessment:*** *Other factors being equal, POD will be higher when the tank is thoroughly cleaned. An exception may be if tell-tale rust streaks are cleaned away.*

2.4.2.3 Temperature/Humidity

Weather conditions and inadequate ventilation can lead to 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 [Exxon 1982]. Even under less harsh conditions, temperatures outside the optimal comfort range can accelerate inspector fatigue.

Other industries have attempted to quantify the impact of temperature and humidity on performance. For example, Figure 6 shows the effect on productivity for a variety of construction tasks. Tank inspection presents greater physical demands than bricklaying, and would therefore be expected to be even more sensitive to extremes of temperature and humidity. While there is not necessarily a direct relationship between the productivity of a construction task and the probability that an inspector will detect a defect, extremes of temperature and humidity clearly have the potential to negatively impact POD.

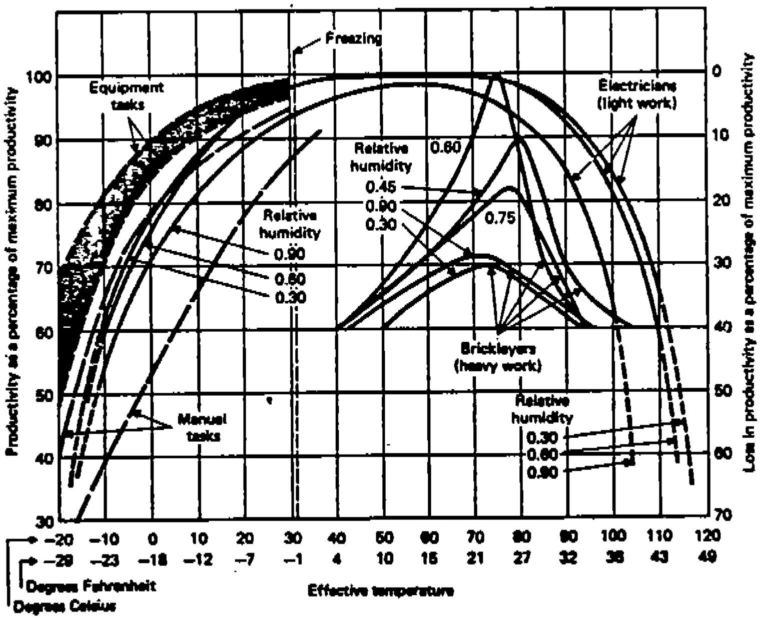

Figure 6. Effect of Temperature and Humidity on Productivity [Ogelsby *et al.* 1989]

> ***Preliminary Assessment:*** *Other factors being equal, POD will be lower when the tank is at extreme levels of temperature or humidity.*

2.4.2.4 Ventilation

Proper ventilation of the tank is essential for inspector safety, to ensure that there is adequate oxygen and no hazard of explosion [Williams and Sharpe 1992]. Half-mask filter respirators are required when benzene levels are not reduced to an acceptable level [Holzman 1992]. 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 [Holzman 1992]. Although ventilation was not mentioned by the inspectors interviewed, 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.

> ***Preliminary Assessment:*** *Other factors being equal, POD will be lower when the tank is not well ventilated or when ventilation results in excessive noise levels.*

2.4.2.5 Access method

Access is a critical factor in the probability of detection; it is difficult to detect a flaw of modest size from afar. Based on a variety of sources, 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. Each of these methods has benefits and drawbacks; the "best" method is the one which allows closest access given the constraints on time, cost, and safety. Figure 7, from [Holzman 1992], summarized the advantages and disadvantages of various access methods.

The primary access method used by U.S. Coast Guard inspectors is bottom walking (90%), with limited use of staging (8%) and rafting (2%) [Goodwin and McClave 1993]. Commercial and class society inspectors make much greater use of staging, rafting, and alternative methods.

The effect of access on probability of detection was summed up by one of the inspectors 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.

> ***Preliminary Assessment:*** *Other factors being equal, POD will be higher when there is better access to the tank structure.*

2.4.2.6 Inspection Method

Currently, 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 [Holzman 1992, Goodwin and McClave 1993, Allen 1993]. 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. Therefore, no preliminary assessment is provided.

METHOD	ADVANTAGES	DISADVANTAGES
Tanker design	Safety, increased accessibility	Cost, weight, maintenance, unwanted structural detail
Walking the Bottom	Inexpensive	Poor accessibility, only line of sight view
Climbing w/o Fall Safety device	Increased accessibility	Unsafe
Physical Climbing w/ Fall Safety device	Increased accessibility, inexpensive	Initial rigging difficult, physically demanding
Access to Side Member w/ Ascender	Increased accessibility, inexpensive	Initial rigging difficult, training required
Fixed Staging	Access available to all members in party	Expensive, labor intensive
Rafting	Can be accomplished underway, inexpensive	Considered unsafe by some, expensive, time consuming
Binocular with High Intensity Light	Can be accomplished underway	Hands on Inspection not possible, only line of sight view
Portable Staging	Light repairs possible, relatively safe	Expensive, difficult initial rigging
Mechanical Arm	Increased accessibility	Difficult initial rigging
Divers	Can be accomplished underway	Diver inexperienced in ship inspections, time consuming

Figure 7. Access Methods Summary [Holzman 1992]

2.4.2.7 Inspection Strategy

Inspection strategy refers to the extent to which the inspection is guided by previous information about problem areas. Experienced inspectors report that their inspections 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 in Section 2.2.2.2 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 2.3.1. No reliable information exists on the impact of a CAIP on POD. Therefore, no preliminary assessment is provided.

2.4.2.8 Area to be Inspected

The probability that a defect will be found may 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" factor is closely related to other environmental factors (including access method, inspection type, inspection method, and inspection strategy) and to vessel factors (including structural layout and defect location).

> ***Preliminary Assessment:*** *Other factors being equal, POD will be lower in hard to inspect areas.*

2.4.2.9 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. Depending on the type of inspection, the crew may also provide lighting and the means of access. A supportive crew should have a positive impact on POD.

> ***Preliminary Assessment:*** *Other factors being equal, POD will be higher when the vessel's crew provides good inspection support.*

2.4.2.10 Time Available

A recent survey of U.S. Coast Guard inspectors found that the time available for inspection was considered by inspectors to have 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..." [Goodwin and McClave 1993].

Ayyub and White note that

> "[t]he amount of 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." [Ayyub and White 1992].

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".

Preliminary Assessment: *Other factors being equal, POD will be higher when there is more time available for inspection.*

2.4.2.11 Inspection Type and Objectives

Classification societies, regulatory agencies such as the U.S. Coast Guard, and owner/operators each carry out tanker inspections with their own inspectors. Classification societies require an overall survey of the condition of the tank's structure at specified intervals (with close-up surveys of any problem areas and of selected details) and periodic close-up surveys of typical portions of the structure. The U.S. Coast Guard conducts periodic structural surveys. Owner/operators often carry out additional inspections to ensure safety and cost effective maintenance.

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.

No investigation of the extent or direction of these differences was found in the literature or through interviews, so no preliminary assessment of the influence on POD is made at this time.

2.5 SUMMARY

The sections above address the wide variety of factors that may influence the probability of finding defects during the inspection of a tanker. The available information on POD is qualitative at best. However, 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. The next section of this report describes related work on POD in other industries. Section 4 describes several procedures for obtaining data that could lead to the derivation of more accurate representations of POD.

3. INSPECTION PERFORMANCE IN OTHER INDUSTRIES

This section summarizes a review of inspection performance in the aviation, nuclear power, manufacturing, and off-shore structures industries. The review was carried out to determine (1) whether factors in addition to those described in Section 2 have been found to have an impact on probability of detection; (2) what procedures have been used to develop probability of detection information and POD curves; and (3) whether POD information in other industries could be applied to tanker inspection.

3.1 AVIATION

The high visibility and potentially high cost in human life associated with aviation accidents has motivated the development of thorough inspection procedures for aircraft structures. Methods of inspection currently employed by inspectors in this industry include eddy current testing, ultrasonic testing, fluorescent penetrant testing and radiographic testing. The aviation industry has a relatively long history of assessing the reliability of nondestructive inspection processes.

Early work comparing different methods of non-destructive evaluation (NDE) was carried out by Packman. Figure 8 shows a comparison of the reliability index for four NDE methods when used to detect flaws in steel cylinders. Although there is general increase in reliability as the size of the flaw increases, large variations are evident, both within and between methods.

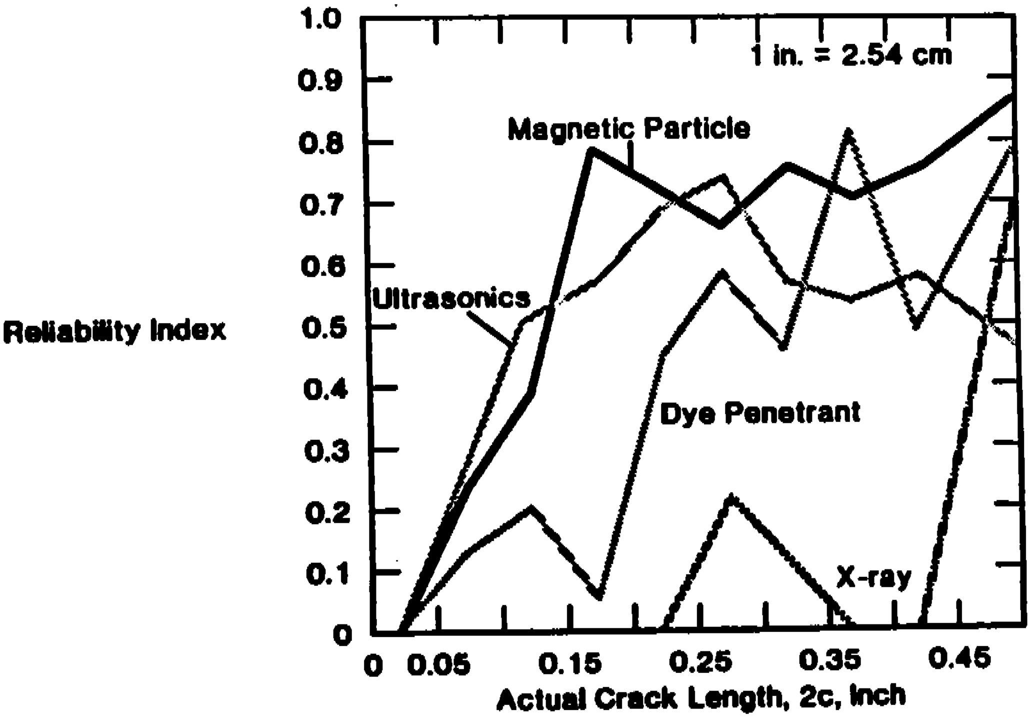

Figure 8. Comparison of Four NDE Methods Used on Steel Cylinders
(source: [Packman 1968] reported in [ASME 1991])

One interesting aspect of aircraft reliability is the introduction of a usage factor that reflects the conditions under which the aircraft has flown. The usage factor is combined with flight hours to allow comparisons between aircraft that have been subjected to different conditions. Similar factors, reflecting the harshness of service, could be applied to tankers.

Early attempts at quantifying inspection performance were included in the development of the B-1 aircraft, and are described in [Rummel 1989]. The procedure consisted of (1) the identification of critical structural components, (2) the identification of high stress areas of those components, (3) the identification of the largest size defect that could exist without growing to critical length in twice the design life. A controlled test was then carried out to determine the frequency with which inspectors could detect such a defect. It was found was that the inspection processes were not sufficient to detect the defect defined in step 3. The inspection processes were improved, and the test became part of the qualification requirements for the inspector [Rummel 1989].

Subsequent work in aviation inspection involved controlled tests in which a series of specimens were constructed with desired defects, and then inspected by a number of inspectors to determine the likelihood that a particular defect would be detected. Factors other than length were observed to affect this likelihood; for a given crack length, the fraction of times a defect was detected varied from defect to defect [Berens 1989].

In support of a software development effort designed to simulate structural defects, failures, and inspections, probability of detection curves for four types of inspections were derived from eleven years of inspection data covering an equivalent of over 1400 jet aircraft [Dinkeloo 1978]. Probability of detection curves were developed for, in order of increasing rigor of inspection, pre-flight inspection, service inspection, phase inspection, and overhaul inspection. These are shown schematically in Figure 9. Each curve was developed by comparing the number of defects that were found at a particular inspection level on aircraft in service with the number of defects that should have been found based on the results of the next more stringent inspection level.

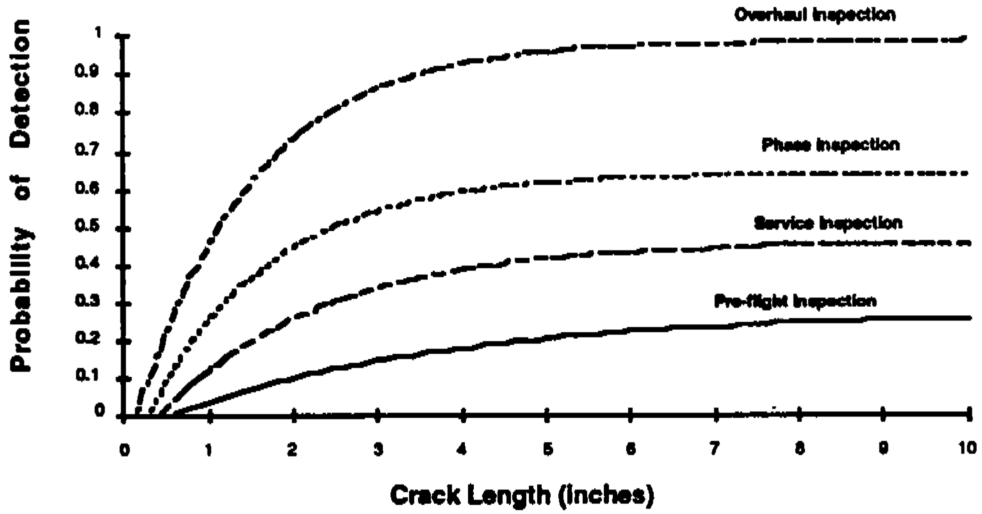

Figure 9. Probability of Detecting Cracks in Aircraft, after [Dinkeloo 1978].

Two aspects of the Dinkeloo study are of interest. First is the idea of developing probability of detection curves from successive inspections. Section 5.3.4 describes a similar effort in which the probability of detection for tanker inspections conducted underway is investigated by comparing the results of the underway inspection with results of a subsequent drydock inspection. Second is the vast quantity of data used to develop the curves: all mechanical reliability reports and all service difficulty reports submitted to the FAA from 1963 to 1973, data equivalent to 45,791,114 flight hours. [Dinkeloo 1978].

In another experiment considered by the Federal Aviation Administration, a retired commercial aircraft was to have been used to better understand the probability of detection [FAA 1988]. The experiment would have used the entire aircraft to better understand problems of inspection associated with various sections of the aircraft, and compared multiple inspectors to examine human factors issues. Due in part to the fact that any results could only have been considered "one point" in understanding the inspection problem, with limited engineering value, the test was never carried out.

In summary, most of the POD work in aviation has been based on controlled tests of specimens with preconstructed flaw characteristics. However, one study developed POD curves by comparing subsequently more rigorous inspections over a large body of data. Another study, based on multiple inspections of an out of service aircraft, was never carried out, in part due to concerns over the limited ability to extrapolate results from the single craft that was to have been used.

3.2 NUCLEAR POWER

The high consequences of structural failure have prompted extensive use of non-destructive evaluation in the nuclear industry. In the operation of power plants, inspection information is shared among utilities through channels such as the Edison Electric Institute or the Electric Power Research Institute (EPRI). In one recent project sponsored by EPRI and the U.S. Nuclear Regulatory Commission, a series of controlled tests were carried out to quantify the difference in detection rates for different length cracks and to gain insight into the human factors issues involved in inspection [Taylor 1989]. Samples were prepared with known flaws and presented to technicians for inspection using ultrasound. Each technician was observed during the inspection process, and asked questions about the decision made during the process. In addition, each technician completed an interview and a questionnaire relevant to human factors issues. The interview focused on good or bad inspection experiences. Similarly, the questionnaire asked about inspector's experience and background, inspection equipment and procedures, and factors in the work environment which effect performance [Taylor 1989].

For the test samples used, no difference in detection rate was observed between the two sizes of cracks considered, those longer than 3 inches and those shorter than 2 inches. However, a wide variation in performance was observed between the "best" inspectors and the "worst" inspectors. Figure 10 shows this variation as a plot of POD vs. false call probability (the probability that a defect was reported when there was in fact no defect). Ideal performance would be a POD of 1.0 and a false call probability of 0.0. In addition to the wide variation in performance, the Taylor study found that the majority of inspectors were not able to perform at levels deemed acceptable by industry standards. The human factors study found that no single factor could explain the wide variation in observed performance [Taylor 1989].

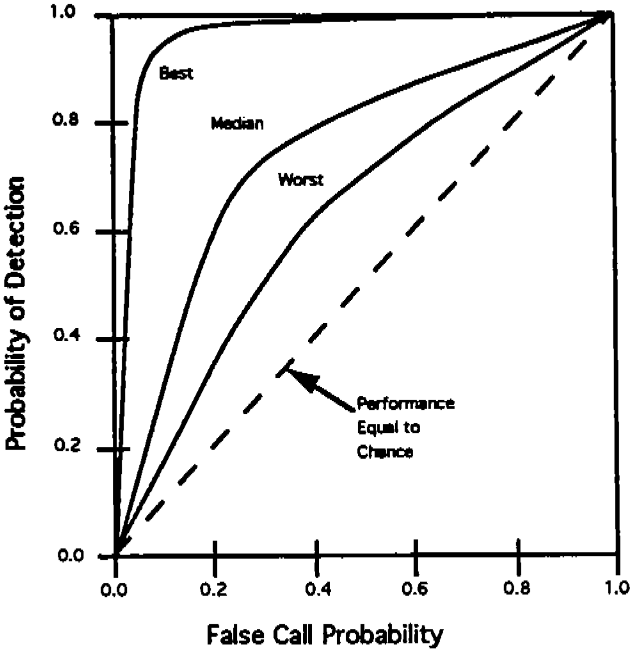

Figure 10. Probability of Detection vs. False Calls for Controlled NDE, after [Tayler 1989]

The combined effect of defect size and detection method used to detect cracks in reactor pressure vessels is shown in Figure 11. The substanial differences between the best and the worst methods are apparent for the entire range of defect sizes.

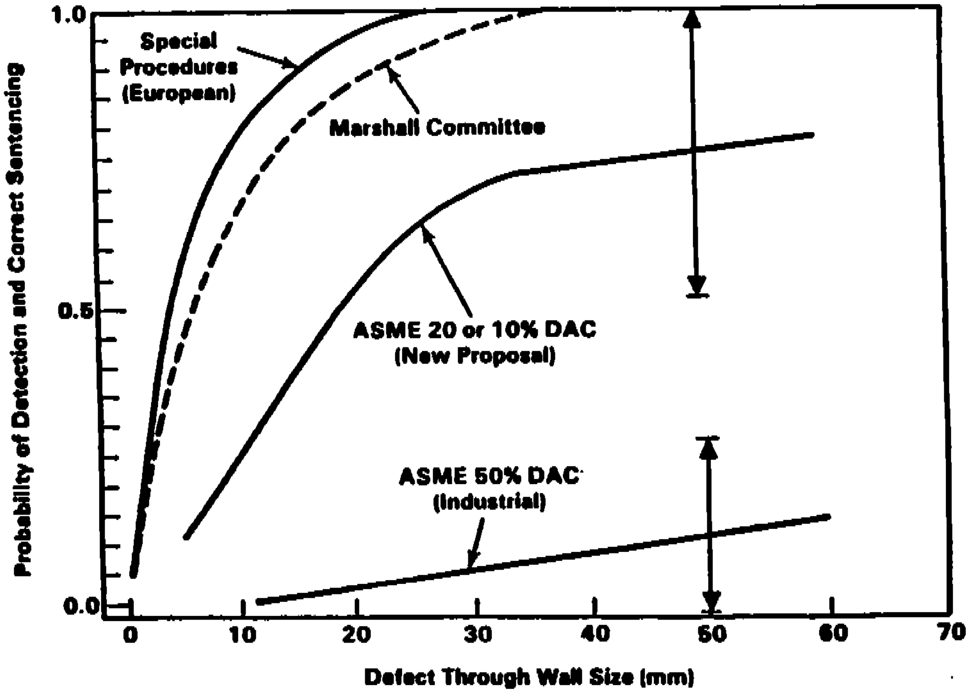

Figure 11. Probability of Detection vs. Defect Size for Different Procedures (source: [Doctor 1990] reported in [ASME 1991])

3.3 MANUFACTURING

Probability of detection is frequently of interest in manufacturing industries, where a minimum level of performance is sometimes used to qualify inspectors. Probability of detection curves are generated using test samples and recording the results of the inspectors under controlled conditions and procedures [Rummel 1989]. However, the conditions under which inspections are carried out and the flaw sizes of interest are generally quite different from those in tanker inspection.

3.4 OFFSHORE STRUCTURES

Most closely related to tanker inspections are inspections of other marine structures. The paragraphs that follow describe two studies of marine inspections: a review of the mobile offshore drilling unit (MODU) inspections, and a controlled study of the non-destructive evaluation of offshore platform sections. An unpublished study by a tanker owner/operator is also described.

A summary of the results of one owner's inspection of MODUs in the mid-1980s is provided in [Cole 1987]. From 20 to 300 cracks per drill rig were found. Cracks were found in MODUs that had seen severe service, those that had seen mild service, and in new rigs that had not yet seen service. "Twenty percent of the cracks at major connections were longer than 4 inches." [Cole 1987].

More insight into this situation can be found in the report of an industry study group [API 1986]. First, it is noted that "it has not been established whether the cracks found during these inspections have a negative impact on the structural integrity of the vessels" [API 1986]. Of more significance for the work described in this report is the comparison of owner/operator inspections with classification society inspections. The task force concluded that "Classification Societies are either not detecting, failing to document, and/or accepting a number of cracks in a substantial number of rigs" [API 1986]. For those particular structures at that particular time, a significantly different probability of detection existed for owner/operator inspections than for Classification Societies inspections.

More recent work of interest has been carried out at the Underwater NDE Centre in the United Kingdom, a combined venture of University College London, City University, and industry and government sponsors. The center has developed a sophisticated testbed for an ongoing evaluation of performance in underwater inspections of offshore structures. A variety of structural node configurations are fabricated with a variety of defects intentionally included. Thorough inspection out of the water is used to determine the characteristics of each defect. Selected nodes are then combined to define a library of cracks for a particular test. The results of one such test, comparing four different non-destructive evaluation methods, are presented in [Rudlin 1992].

Although the effect of the inspector was deliberately removed from this experiment, the experiments are of interest for several reasons. First, they represent an attempt to duplicate, for portions of a large structure, field conditions in a controlled setting with known defects. The conditions are not identical to the conditions facing an inspector working on an offshore structure, but are as similar as possible in a lab setting. Second, the results presented in [Rudlin 1992] show that the choice of inspection method can have a noticeable effect on probability of detection. Finally, the procedure used demonstrates one way of estimating the number of samples needed to obtain a specified confidence level. For example, for the conditions described in [Rudlin 1992], to obtain a 95% confidence level in 90% of the population would have required 87 cracks if it was anticipated that each crack would be detected. When it is anticipated that cracks will be missed, the number of cracks that must be inspected to reach the desired confidence level increases [Rudlin 1992].

3.6 SUMMARY

The sections above describe selected studies in related industries. Of note are the various methods that have been used to assess probability of detection: controlled experiments on small scale samples, controlled experiments on large scale samples in simulated field conditions, use of historical data, and proposed use of an out-of-service structure. Also of interest are the variety of factors that appear to affect probability of detection, including inspection method and various human factors, and the tendency for *a priori* estimates of inspection performance to be better than actual performance under test conditions.

4. ISSUES IN QUANTIFYING PERFORMANCE

Before turning to an assessment of the different approaches that might be used to evaluate probability of detection in tankers, it is useful to review issues that are important in quantifying performance. This section provides a brief summary of the issues that will help determine which method of quantifying performance is most effective. These include motivation, confidence in results, ability to isolate factors, data management, resource requirements, time requirements, and cost.

4.1 MOTIVATION

There are at least four motivations for determining the probability of detection for tanker inspection: to improve safety of cargo, crew, and the environment; to provide feedback to design; to allow the rational scheduling of inspections; and to facilitate a comparison of different inspection methods. Probability of detection information in and of itself will not improve safety; the information must be used to guide the allocation of resources to inspection and to provide feedback to design. For feedback to design to be most effective, more information than just the variation in POD with flaw size will be desired; knowledge of the impact of vessel design factors will be important as well. To allow the rational scheduling of inspection, POD information must be combined with information on defect growth rates under various loading conditions. Finally, to facilitate the comparison of different inspection methods, it is desirable to be able to isolate the effect of the method from the many other factors than can impact the likelihood that a defect is found.

4.2 CONFIDENCE IN RESULTS

Confidence in an assessment of probability of detection can be considered to have three components: accuracy, repeatability, and fidelity. Accuracy is an indication of how close the derived POD is to the true probability of detection *for the situation being measured*. Repeatability is the extent to which results can be replicated. It is repeatability that allows the establishment of confidence intervals. Fidelity is an indication of how closely the situation being measured replicates conditions *in the field*.

4.3 ABILITY TO ISOLATE FACTORS

The wide variety of factors described in Section 2 of this report each have an impact on probability of detection. To arrive at results that have a small enough variance to yield suitable confidence levels will require a method of determining POD that can isolate the effects of at least some of these factors.

4.4 DATA MANAGEMENT

Data management issues include the amount of data required, the manner in which the data is handled and transferred, and the analysis that is carried out on the data to determine probability of detection. An extreme example of the large quantity of data that may be required is provided by the aviation study that derived POD curves for successively more detailed inspections, in which 11 years worth of report data was gathered for all aircraft under Federal Aviation Agency authority [Dinkeloo 1978]. For tanker inspection, a more likely scenario is that a particular approach to deriving POD curves will require more data than is available.

Data handling will be an important issue if actual or simulated inspections are carried out. The defects that are recorded by the inspector must be accurately and efficiently transferred to an electronic form for storage and analysis. Possible storage formats include those used by various owner operators (*e.g.*, CATSIR). Existing databases of this sort are reviewed in [Schulte-Strathaus and Bea 1995]. The format selected for data storage should promote efficient analysis of the data.

4.5 RESOURCE REQUIREMENTS

The resources required will be a critical issue in selection of an approach for deriving POD curves. Consider, for example, the considerable resources that are being applied at the Underwater NDE Centre in the United Kingdom. Because the experience of the inspector has such a large impact on the probability of detection, any approach that involves the inspection of an *in situ* or in lab structure will require significant inspector manhours. For *in situ* experiments, a suitable vessel must be available. For a lab experiment to come at all close to capturing the tank inspection environment in terms of access, lighting, and cleanliness will require samples that resemble large portions of a tank.

4.6 TIME REQUIREMENTS

Time requirements come into play in two ways. First, there is the time required to carry out the actual experiment and analyze the date. Second, for methods that require access to in-service or out-of-service vessels, there may be a significant delay before an appropriate vessel is available.

4.7 COST

Cost will of course be a factor in selecting an appropriate method. The greater the reliance on physical resources, particularly in-service vessels, the greater the cost of determining probability of detection.

4.8 SUMMARY

The variety of issues that must be considered in selecting an appropriate method to investigate probability of detection include motivation, confidence in results, ability to isolate factors, data management, resource requirements, time requirements, and cost. In the next section, these issues are evaluated in the context of four options for quantifying inspection performance.

5. OPTIONS FOR QUANTIFYING PERFORMANCE

This section assesses four strategies for quantifying inspection performance: solicitation of experts, laboratory experiments, benchmarked inspection data, and *in-situ* experiments. Two of these methods were described in [Ayyub and White 1992], solicitation of experts and *in-situ* experiments. Laboratory experiments have been proposed elsewhere, and are currently being used to help assess the feasibility of vibration testing as an inspection method [Allen 1993]. The fourth approach, benchmarked inspection data, is new. A case study of benchmarked inspection data was carried out as part of this project. The procedure and results are summarized in Section 5.4.4.

5.1 SOLICITATION OF EXPERTS

5.1.1 Solicitation of Experts: General Approach

One approach to determining the probability of detection is to ask "experts" what they think the POD is under a variety of circumstances. Ayyub and White refer to this approach as expert elicitation and define seven steps that comprise the process: selection of issues, selection of experts, issue familiarization of experts, training of experts, elicitation of expert opinion, aggregation and presentation of results, discussion and revision by experts, revision of results and reporting [Ayyub and White 1992]. Several formal approaches exist that can help experts reach a consensus, among them the Delphi approach (for a concise description, see [Pahl and Beitz 1988]).

In a sense, solicitation of experts regarding tanker inspection overall has been carried out informally as a part of several studies (*e.g.*, [Holzman 1992], [Goodwin and McClave 1993]). The interviews carried out as a part of this study went farther, and actually requested experienced inspector's assessment of probability of detection. For the most part, the inspectors interviewed, including some of the most senior in the profession, were unable or unwilling to provide anything more than a typically detectable crack length (2 to 3 inches) and their comments on the various factors that influence inspection performance.

5.1.2 Solicitation of Experts: Advantages & Disadvantages

Solicitation of experts as a means of determining POD has several advantages. Compared to other approaches, it is low cost, has fewer time constraints, requires fewer resources, and presents a much simpler data management task. However, the disadvantages are significant. Expert inspectors, even those with many years of experience, are unable or unwilling to provide anything more than a qualitative assessment of POD and the factors that influence it. The qualitative information is of some use in providing feedback to ship designers, in making changes to enhance safety, and in comparing new inspection methods with current practice, but it is does not support these applications as well as quantitative data would. Furthermore, the qualitative data available via solicitation of exerts is not sufficient to support a more rational scheduling of inspections.

5.1.3 Solicitation of Experts: Summary

Solicitation of experts has been carried out on an informal basis as a part of this and other studies. The results have helped guide new developments and research on tanker inspection. Continued informal solicitation of expert opinion is worthwhile, but it is unlikely that a formal solicitation exercise would yield significant new information.

5.2 LABORATORY EXPERIMENTS

5.2.1 Laboratory Experiments: General Approach

Laboratory experiments are the primary approach used in other industries to assess probability of detection. In a laboratory experiment, test specimens are constructed (or otherwise obtained) that contain the range of defects that are of interest. These specimens are then inspected, with the procedure controlled to derive information about the factors of interest. For example, in the nuclear power inspection application described in Section 3.2, the factors of interest were crack length and various human factors related to the inspector and the inspection environment [Taylor 1989]. The marine inspection work currently being carried out at the Underwater NDE Centre in the United Kingdom is another example of a laboratory experiment. The test conditions have been designed to be as close as possible to field conditions. However, the structures being inspected are specimens, not the "real" structure. The specimens have been fabricated to contain the defects of interest; there is no guarantee that such defects would be available in a particular "real" structure.

5.2.2 Laboratory Experiments: Advantages & Disadvantages

The major benefit of laboratory experiments is the control provided over test conditions. The true condition of the specimens is known. Selected factors of interest can be varied (within the constraints of the test specimen and test environment) and their impact on probability of detection readily determined. Specimens can be constructed to contain the desired type and distribution of defects. Because the specimens are not part of an operational facility, the time constraints are less stringent than in an *in situ* experiment. Data management is not as straightforward as in solicitation of experts. However, because the existing defects are known to the experimenters, an electronic "tally sheet" can be developed to allow quick transfer of the "hits and misses" that result from a particular test.

The disadvantages of laboratory experiments derive from the significant influence of environmental factors such as access, lighting, and cleanliness on probability of detection for tanker inspection. A laboratory specimen that accurately portrayed these aspects of the inspection environment would have to be quite large, and quite expensive to construct (especially if flaws are to be built in). For tanker inspection, laboratory experiments appear to be either too costly or, if smaller, less representative specimens are used, unlikely to replicate the impact of important environmental factors.

5.2.3 Laboratory Experiments: Summary

Due to the anticipated cost and size of specimens, laboratory experiments do not appear to be a promising way to develop probability of inspection curves. A hybrid approach, in which an out-of-use vessel used as a full scale laboratory, is discussed in Section 5.3 on *in-situ* experiments.

5.3 *IN-SITU* EXPERIMENTS

5.3.1 *In-Situ* Experiments: General Approach

In-situ experiments are experiments carried out in a "real" structure, an in-service vessel. Several inspectors would in turn inspect the same portions of the vessel. Unlike a laboratory experiment, the true condition of the tank would not be known beforehand. The results of all inspections could be pooled to provide an estimate of the true condition. Alternatively, a final and extremely thorough inspection could be carried out to try to assess the true condition. The defects found by the individual inspectors would then be compared with the estimated true condition to determine probability of detection.

5.3.2 *In-Situ* Experiments: Advantages & Disadvantages

The major advantage of an *in-situ* experiment is the close replication of actual field conditions. Although the inspectors' motivation during the experiment may be slightly different from that in practice, other inspector factors and the vessel and environmental factors would be true to life.

There are, however, major disadvantages to *in-situ* experiments. The resource requirements are significant; a vessel and a group of inspectors must be brought to the same place at the same time. The associated costs include the cost of the inspectors and, most significantly, the potential cost of keeping the vessel out of service for several days. This cost could be greatly reduced if the experiment were carried out while the vessel was in drydock using a portion of the vessel that was not cleaned and staged for repairs. A major disadvantage is that the condition of the vessel is unknown before the experiment starts. It may turn out that the vessel has few defects of interest, and that the experiment, while executed correctly, does not yield useful probability of detection data. Careful prescreening of candidate vessels can minimize this risk, but not eliminate it. Another disadvantage is that is that only one set of vessel factors can be examined per experiment. Data management is not as straightforward as in laboratory experiments, because defect types and locations are not known beforehand.

Two variations of *in-situ* experiments warrant consideration. In the first, the experiment would be carried out as described above, but on an out-of-service vessel. This would reduce the time constraints and the cost of a several day experiment. The drawback might a difference between the condition of an in-service and an out-of-service vessel, for example, in terms of cleanliness. The second variation would be to have inspectors look for some sort of tag or marker in addition to the actual defects. The markers would be designed to look as similar to real defects as possible, and could be placed at any area of interest within the tank. POD for markers would not be identical to POD for defects, but the marker detection rates could provide useful information, for example on the impact of defect location.

5.3.3 In-Situ Experiments: Summary

In-situ experiments present significant advantages due to the use of a real structure. However, the associated disadvantages are also significant in terms of cost and the risk of insufficient results. Candidate vessels should be carefully pre-screened to ensure that a significant population of defects exists. As many inspections of the vessel as possible should be carried out during the time it is out-of-service. If time permits, at least some of the inspectors should be subjected to a version of the marker experiment.

5.4 BENCHMARKED INSPECTION DATA

5.4.1 Benchmarked Inspection Data: General Approach

An alternative the use of experimental data is the use of inspection reports of vessels currently in service. The basic approach is the same as that found in [Dinkeloo 1978]; compare the results of subsequent inspections, where one inspection is more thorough than the other. For tankers, the results of inspections performed underway could be compared with the results of drydock inspections carried out a short time thereafter. The drydock inspection serves a "benchmark" against which the performance of other inspections can be compared. The assumption is that the drydock inspection is more thorough and therefore a better approximation to the true state of the vessel. The benchmarked inspection approach is only possible when two inspections of differing quality are performed within a relatively short time of each other. Not all operators carry out underway inspections shortly before going in for repairs, so the amount of data available may be somewhat limited. The drydock inspection itself is not perfect. Because some defects may not be detected even in drydock, using drydock data as a benchmark will yield an upper bound on probability of detection.

5.4.2 Benchmarked Inspection Data: Advantages & Disadvantages

The major advantages of benchmarked inspection data are low cost and low demand on resources. The primary resources required are the results of inspections that are carried out anyway. Once a data analysis procedure is established, it should be straightforward to apply the approach to additional vessels. In addition, the conditions under which the data were obtained are true field conditions.

There are several disadvantages of benchmarked inspection data. First, the "experimenter" (or data analyst) may have little or no control over the inspection conditions. This makes it difficult to isolate the impact of particular factors. Furthermore, unless additional resources are applied to the drydock inspection, even it is only an approximation of the "true" condition of the tank. As with the *in situ* inspection, the condition of the tank may be such that there are few defects, and little or no POD information is obtained. A final disadvantage, the lack of information on various factors, can be overcome through the use of a simple questionnaire described in Section 5.4.4 below.

5.4.3 Benchmarked Inspection Data: A Case Study

Despite the disadvantages noted above, the low cost and low risk of the benchmarked data approach make it appealing. This section describes a sample application of the approach.

5.4.3.1 Background

Two sister ships belonging to the same owner/operator form the basis of the case study. This owner/operator 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. The purpose of the underway inspection is to determine the approximate scope of repair work so that a budget and schedule can be developed. 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 for the owner, with different companies and different inspectors involved in the various inspections.

The configuration of the ships iss summarized in Figures 12-14. Figure 12 shows the general arrangement and tank locations. The vessel has six center cargo tanks and four wing cargo tanks on port and starboard. Wing tanks 3 and 5 are water ballast tanks. The vessel particulars are shown in Figure 13. The midship section is shown in Figure 14. The vessel has a standard single-hull construction with center cargo tanks and two tie beams across the wing tanks.

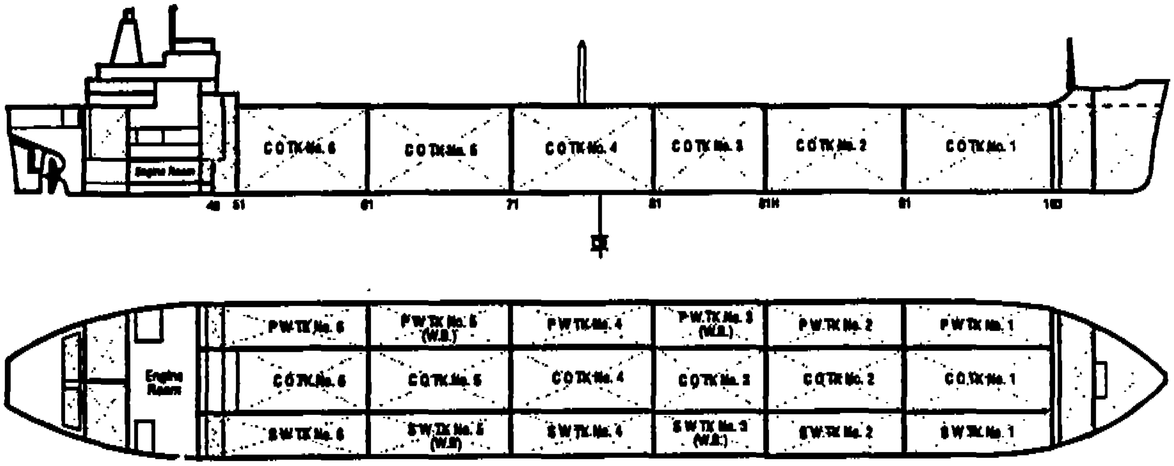

Figure 12. General Arrangement of Ship

Length (O.A.)	810.00'
Length (B.P.)	786.00'
Breadth (MLD)	57.00'
Depth (MLD)	105.00'
Deadweight	70,000 LT
Segregated Ballast Tanks	YES
Cargo Type	CRUDE OIL

Figure 13. Characteristics of Vessel

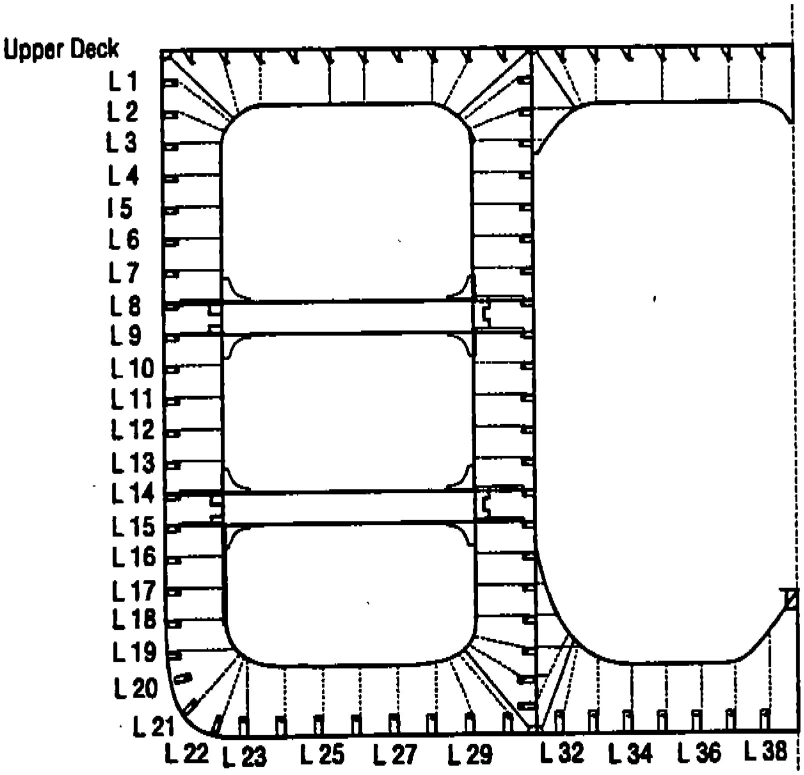

Figure 14. Midship Section

5.4.3.2 Data Acquisition

Survey reports from the six inspections listed above were reviewed. For this case study, cracks were the only type of defect considered. 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/operator 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.

5.4.3.3 Data Analysis: General

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

The initial inspection reviewed for the case study was the November 1986 underway inspection of Ship A. The owner/operator was particularly 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. This inspection revealed sideshell cracks throughout the length of the ship at the locations where the tie beams meet the side shell and the longitudinal bulkhead: L8, L9, L14, and L15. The 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 are summarized in Appendix C.

The results of the drydock inspection of Ship A were a surprise, given that the inspection carried out underway had found no fractures in Tank 3 at L8 and L9. The owner/operator 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 yet 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.

5.4.3.4 Data Analysis: Specific

The general data analysis above provides an overview of the case study inspections. As a trial application of the use of benchmarked historical data, the results of the drydock inspections were used as benchmarks against which to compare the corresponding underway inspection. Inspection reports were reviewed and crack information (location, length, type) extracted. From this information, "benchmarked" inspection plots comparing underway and drydock inspections were developed.

Benchmarked inspection plots are presented for the 1987 and 1990 underway and drydock inspections of Ship B. For each pair of inspections, a comparison of the cracks found underway with those found in drydock is shown for four views of the tank structure: port side shell, port longitudinal bulkhead, starboard side shell, and starboard longitudinal bulkhead. 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).

As a preliminary investigation of the effect of crack length on detection, similar plots are provided showing only those cracks with length ≥ 100mm. For cracks that were found both underway and in drydock, the drydock length is assigned to the underway measurement. For example, for a crack reported as 150mm in drydock and 75 mm underway, both the "underway" and "drydock" symbols will be in included on the "crack length ≥ 100 mm" plot.

Figures 15 - 18 show the results of the 1987 inspections of Ship B, with cracks along the port side shell shown in Figure 15, those along the port longitudinal bulkhead in Figure 16, those along the starboard side shell in Figure 17, and those along the starboard longitudinal bulkhead in Figure 19. Similarly, Figures 19 - 22 show the results of the 1990 inspections of Ship B: port side shell in Figure 19, port longitudinal bulkhead in Figure 20, starboard side shell in Figure 21, and starboard longitudinal bulkhead in Figure 22. Results for the 1987 inspection of Ship A are not shown. Because there were few cracks found in the April/May 1987 underway inspection of Ship A, and many cracks found in the subsequent drydock inspection, the detection rate that would be obtained by comparing the two is close to zero, and plotting the results would yield little additional information.

At a particular location, one of four conditions holds: no crack was reported in either the underway or the drydock inspection; a crack was reported in the underway inspection and in the drydock inspection (a "hit"); a crack was reported in drydock but not underway (a "miss"); or, in a few cases, a crack was reported underway but not in drydock. The comparison between underway and drydock inspections is based on location only, and does not take into account crack length. Thus, if a crack was found in the same location both underway and in drydock, it shows up as a "hit" whether or not the same length was reported.

Consider first the data from the 1987 inspections. A quick glance at Figures 16 - 19 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

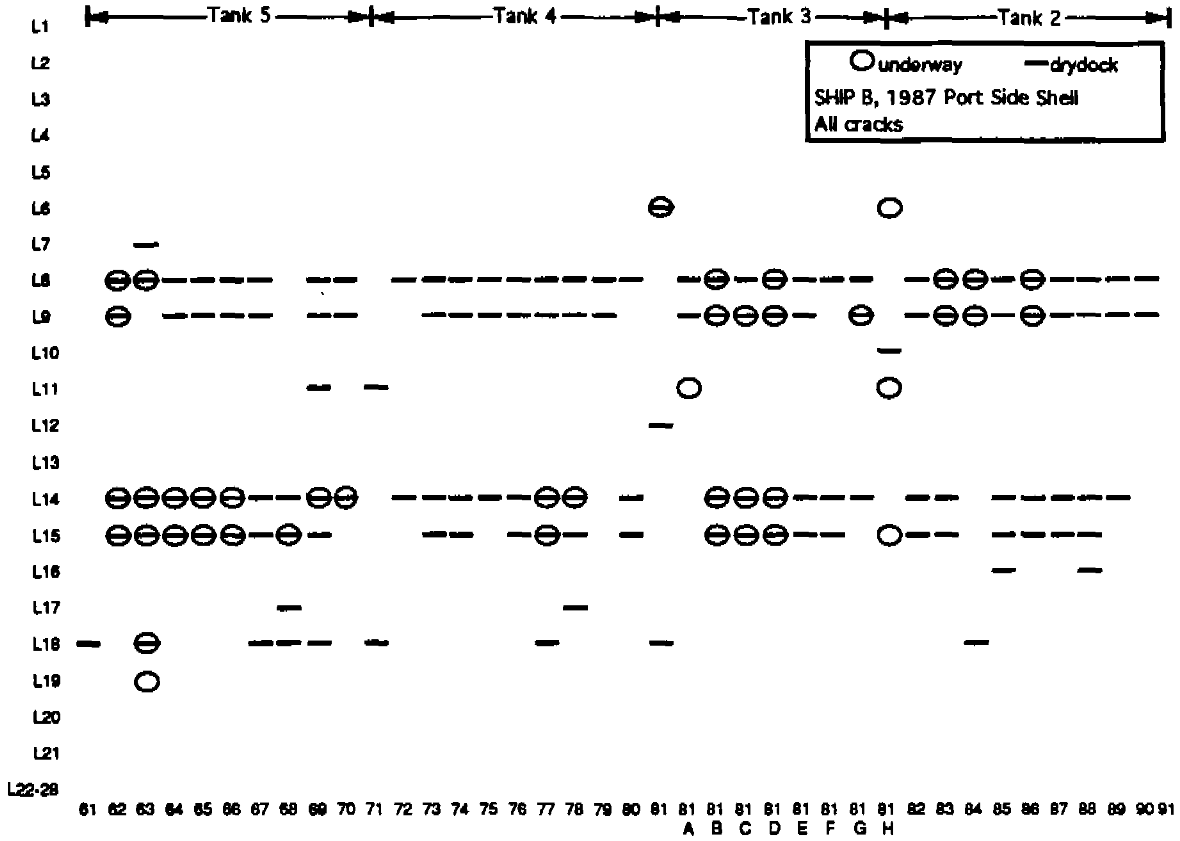

Figure 15a. Ship B 1987 Inspections, Port Side Shell Cracks

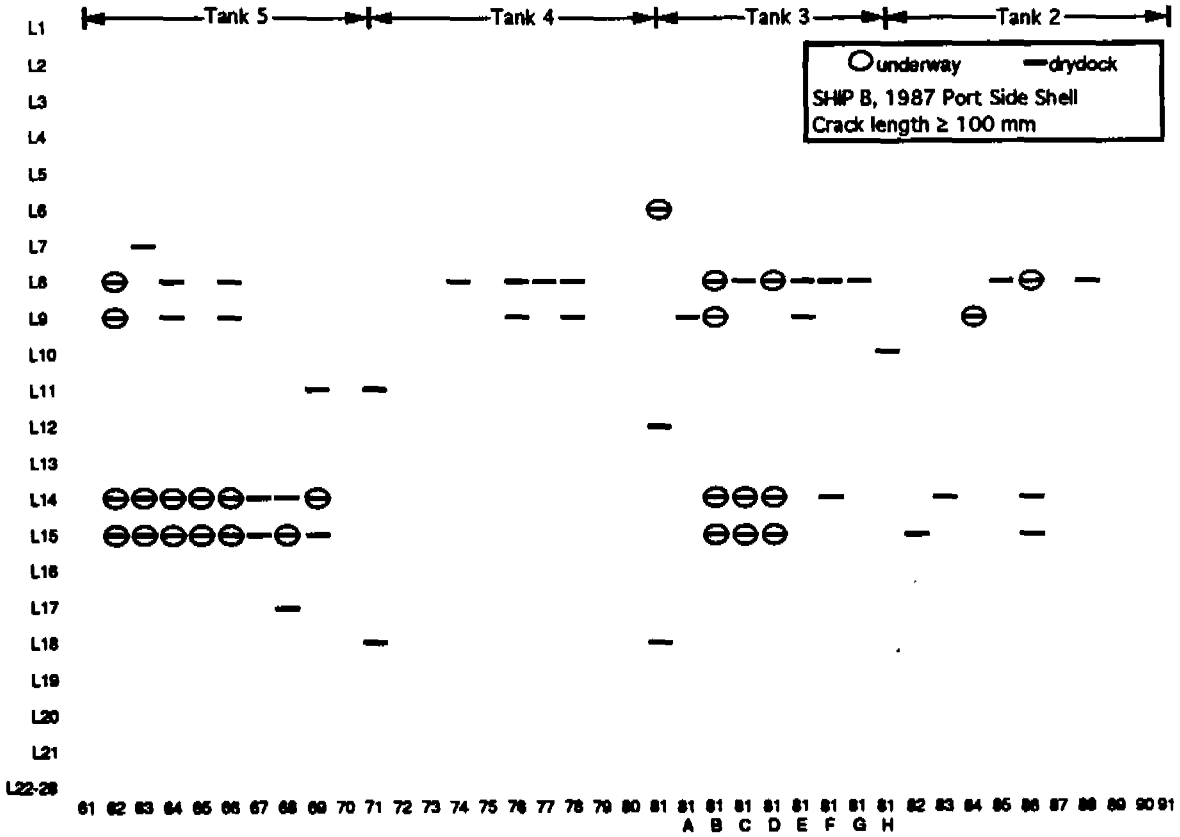

Figure 15b. Ship B 1987 Inspections, Port Side Shell Cracks ≥ 100mm

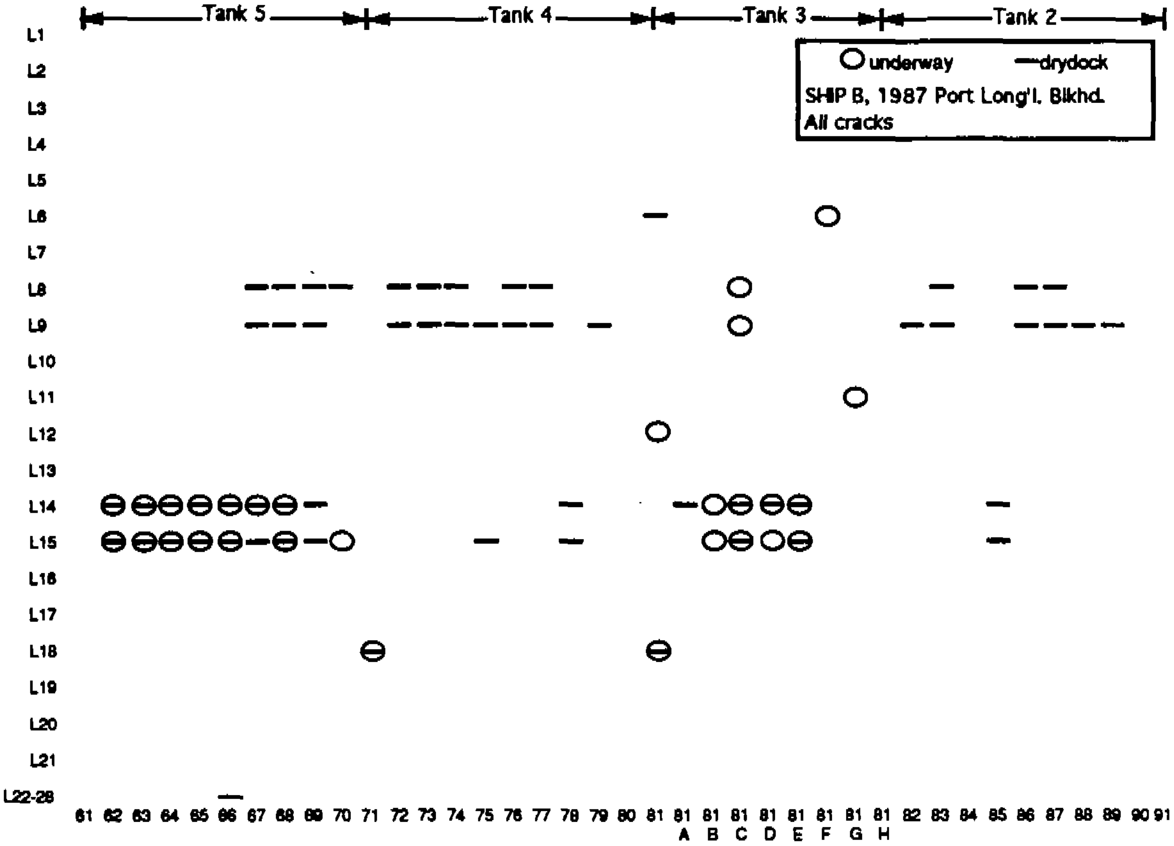

Figure 16a. Ship B 1987 Inspections, Port Longitudinal Bulkhead Cracks

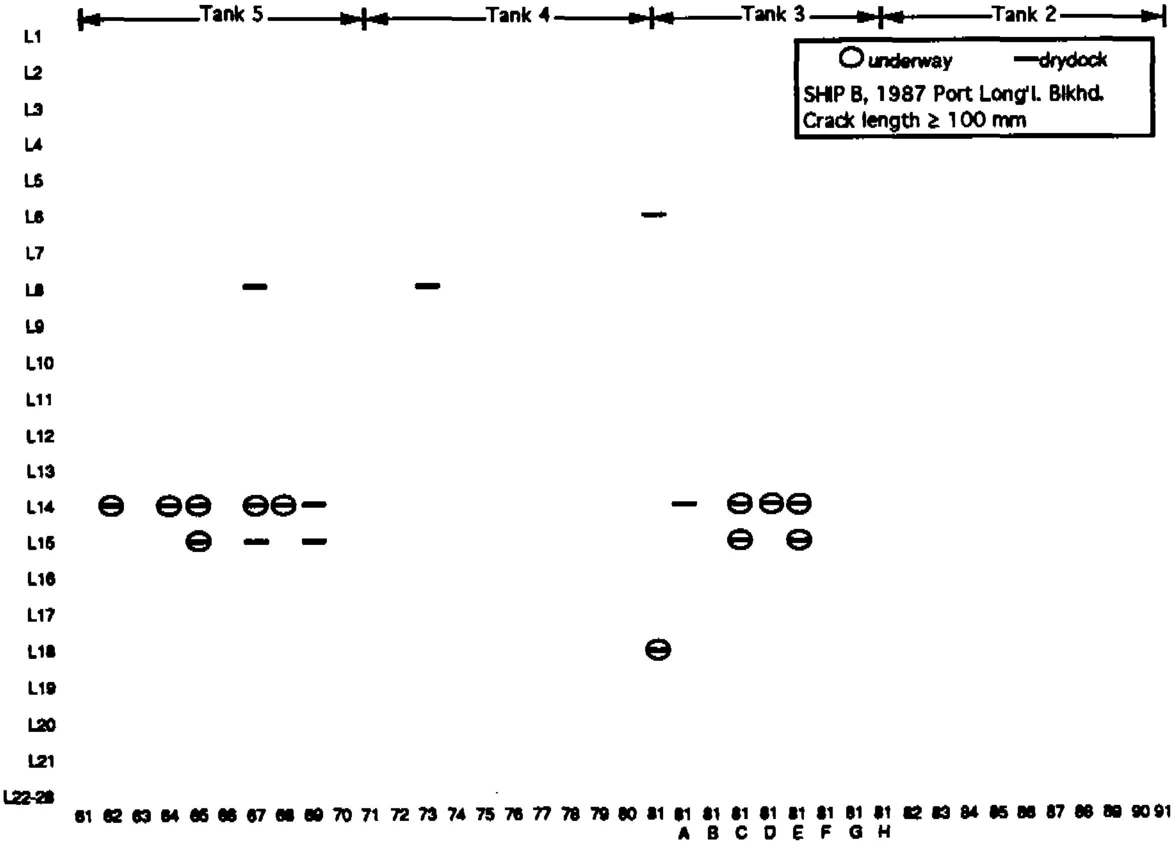

Figure 16b. Ship B 1987 Inspections, Port Longitudinal Bulkhead Cracks ≥ 100mm

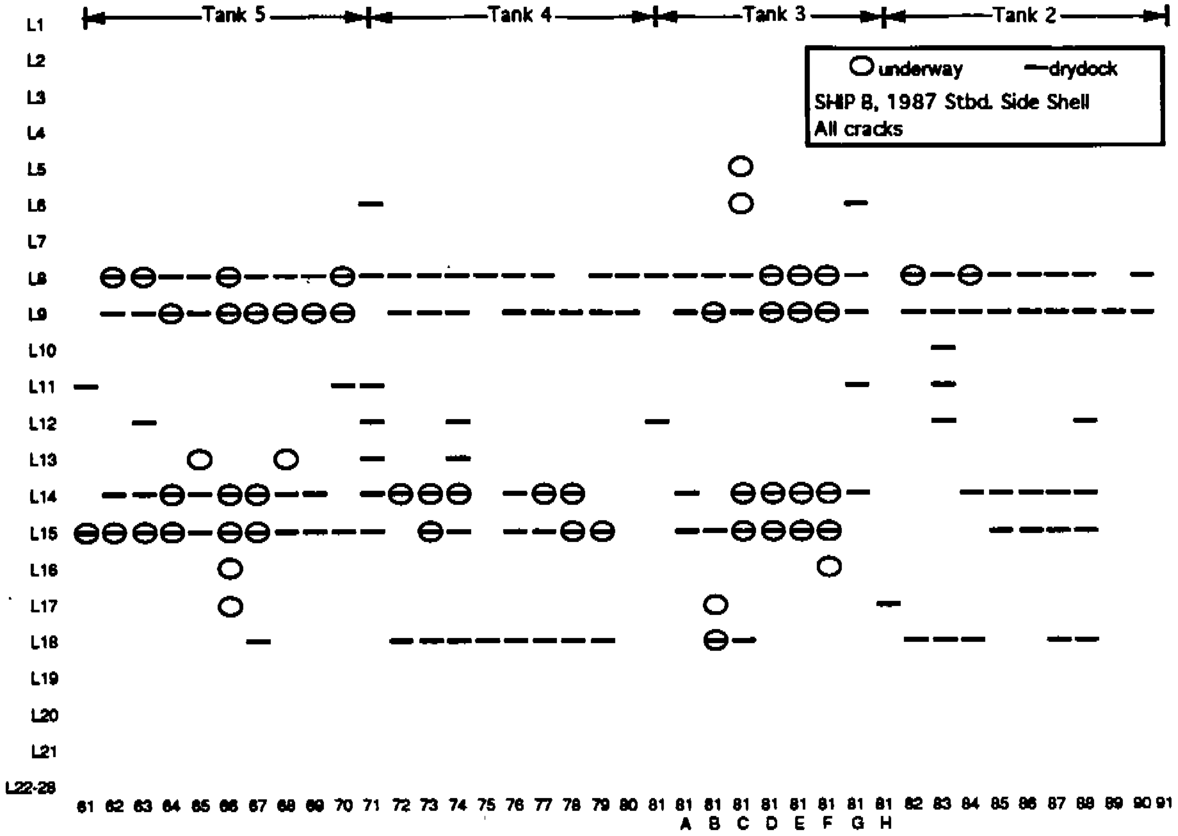

Figure 17a. Ship B 1987 Inspections, Starboard Side Shell Cracks

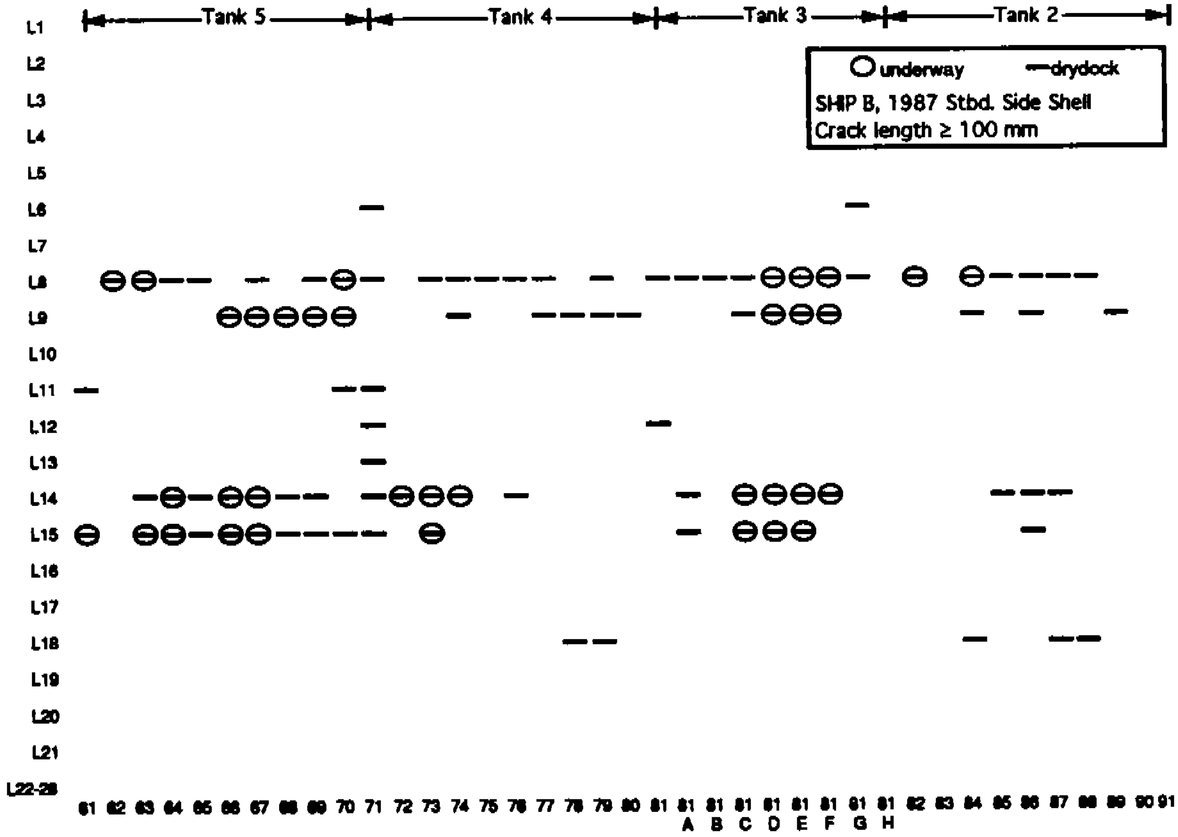

Figure 17b. Ship B 1987 Inspections, Starboard Side Shell Cracks ≥ 100mm

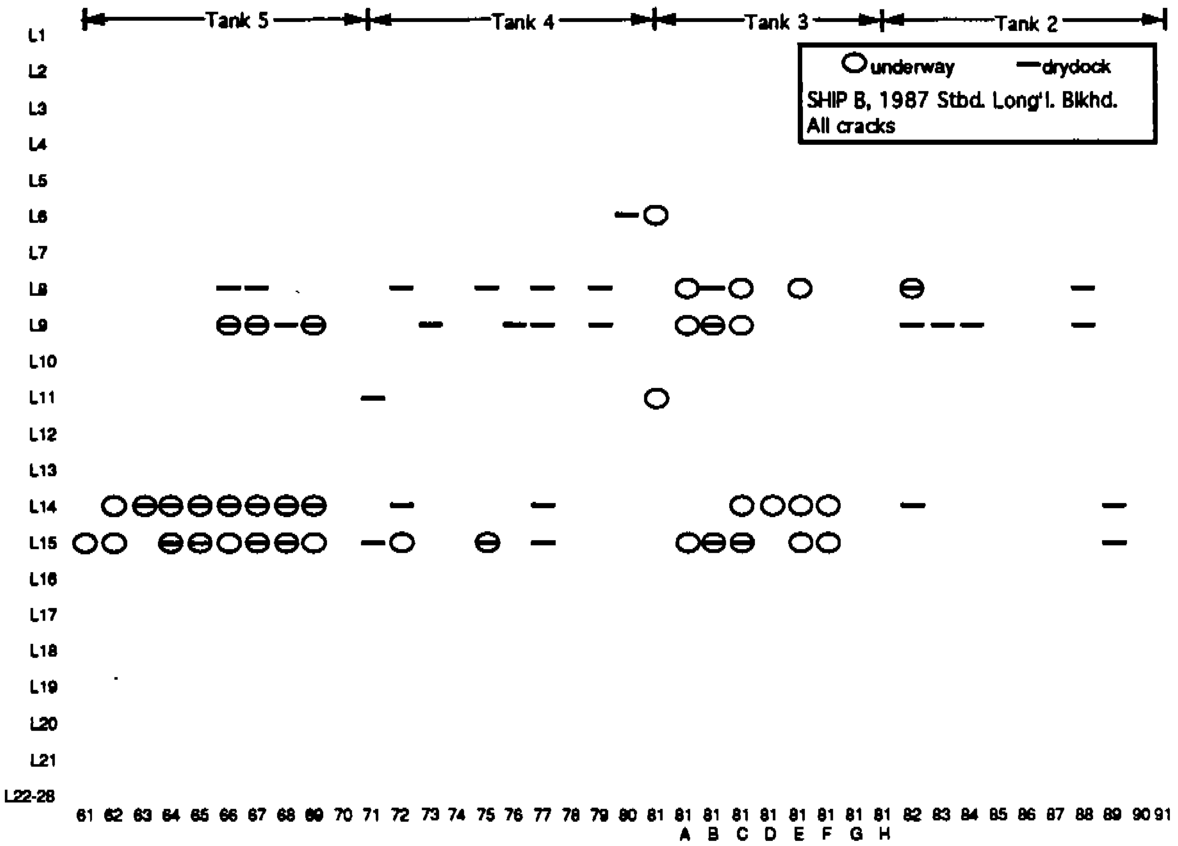

Figure 18a. Ship B 1987 Inspections, Stbd. Longitudinal Bulkhead Cracks

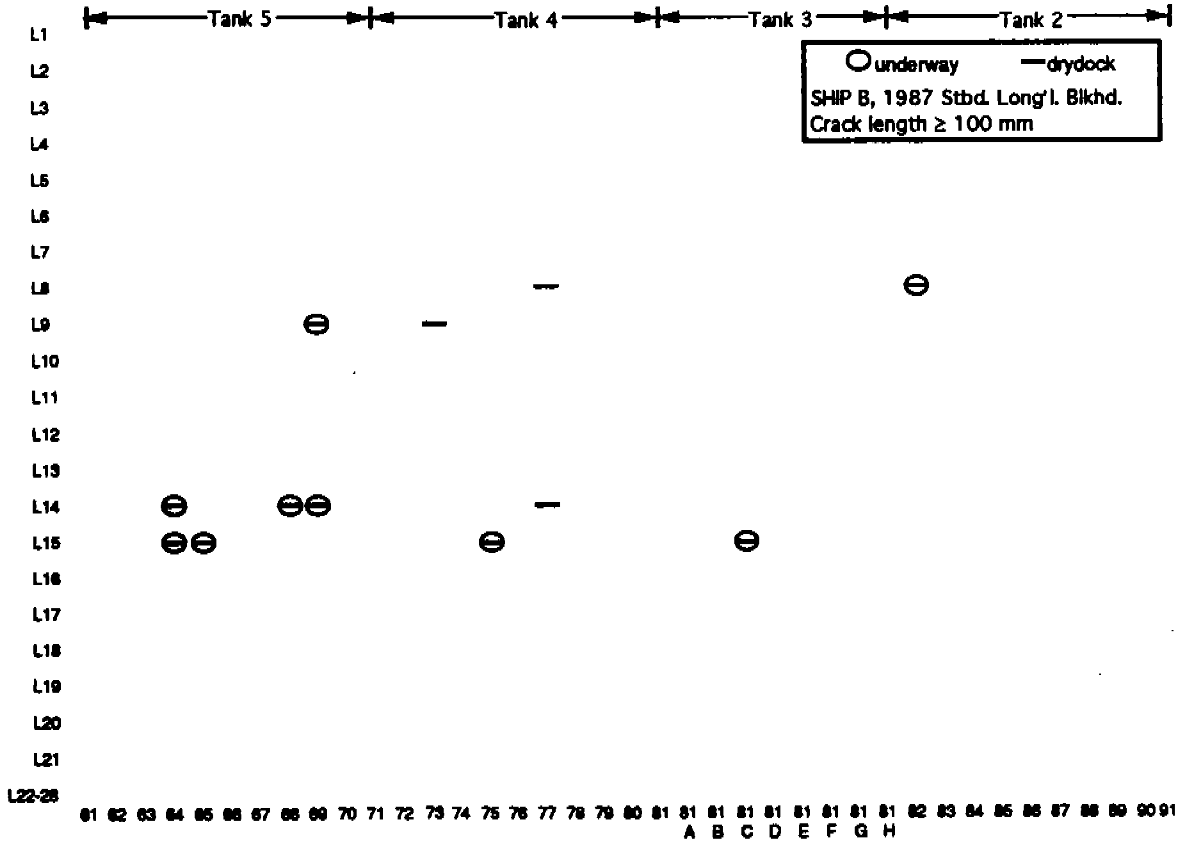

Figure 18b. Ship B 1987 Inspections, Stbd. Longitudinal Bulkhead Cracks ≥ 100mm

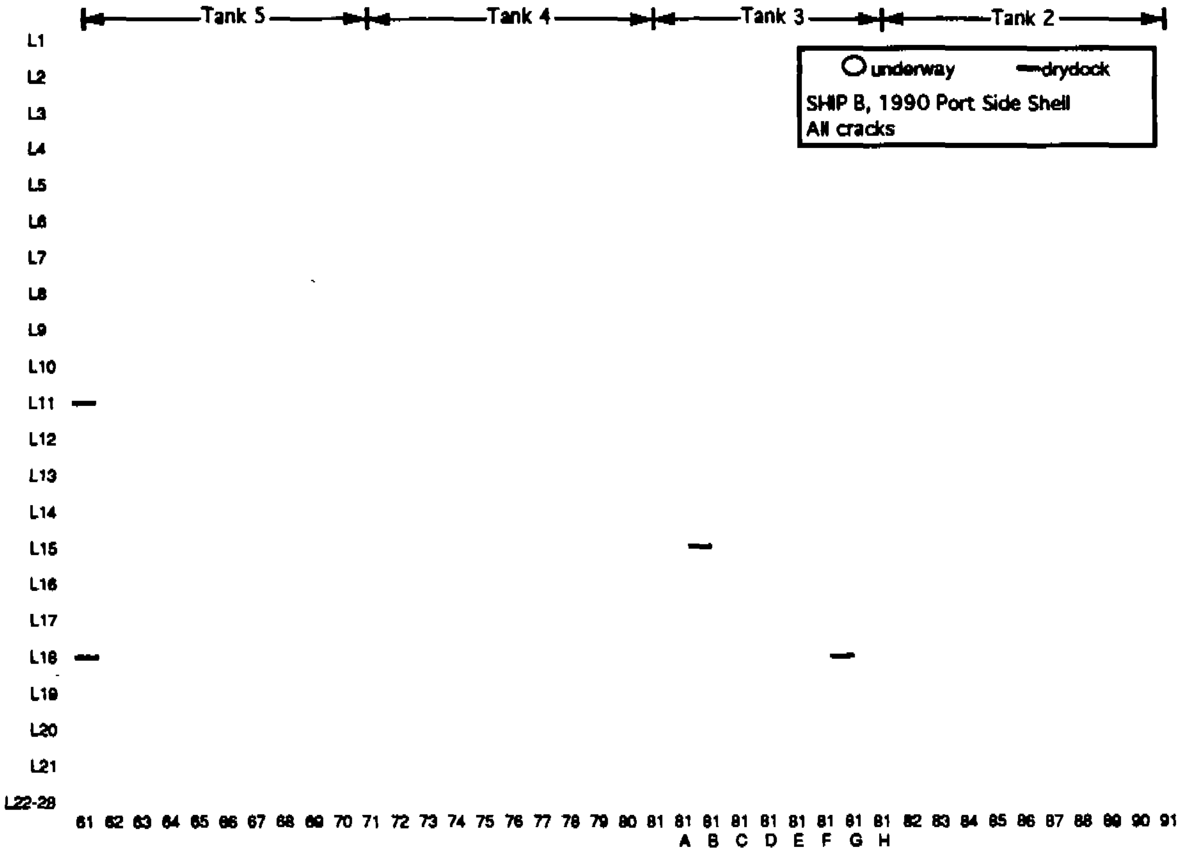

Figure 19a. Ship B 1990 Inspections, Port Side Shell Cracks

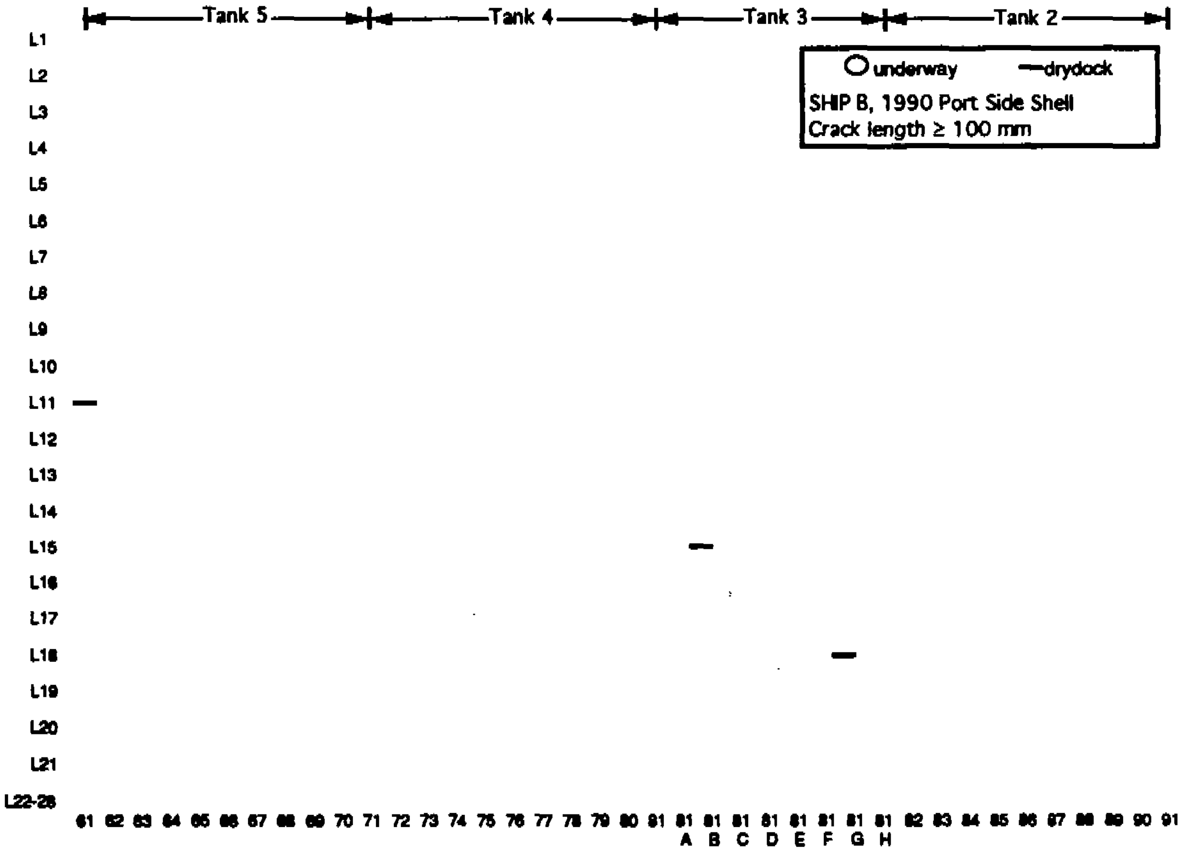

Figure 19b. Ship B 1990 Inspections, Port Side Shell Cracks ≥ 100mm

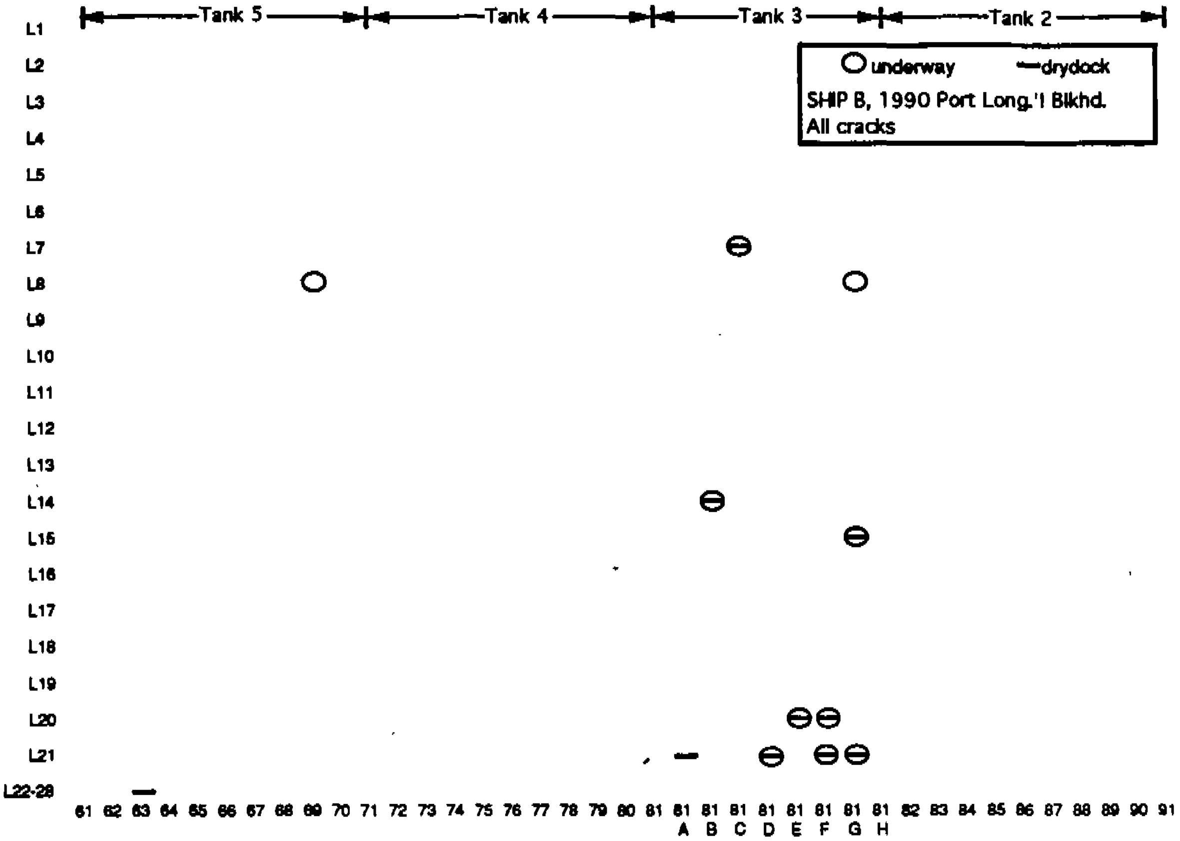

Figure 20a. Ship B 1990 Inspections, Port Longitudinal Bulkhead Cracks

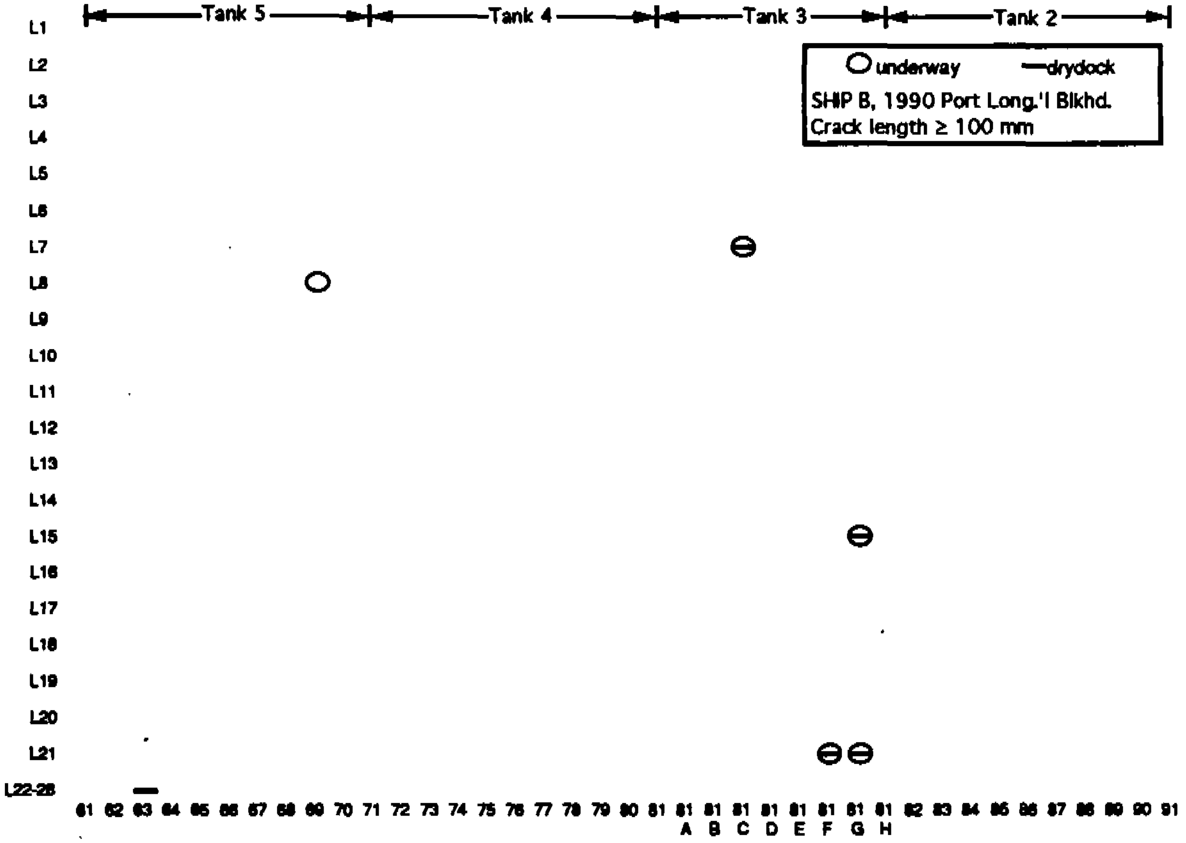

Figure 20b. Ship B 1990 Inspections, Port Longitudinal Bulkhead Cracks ≥ 100mm

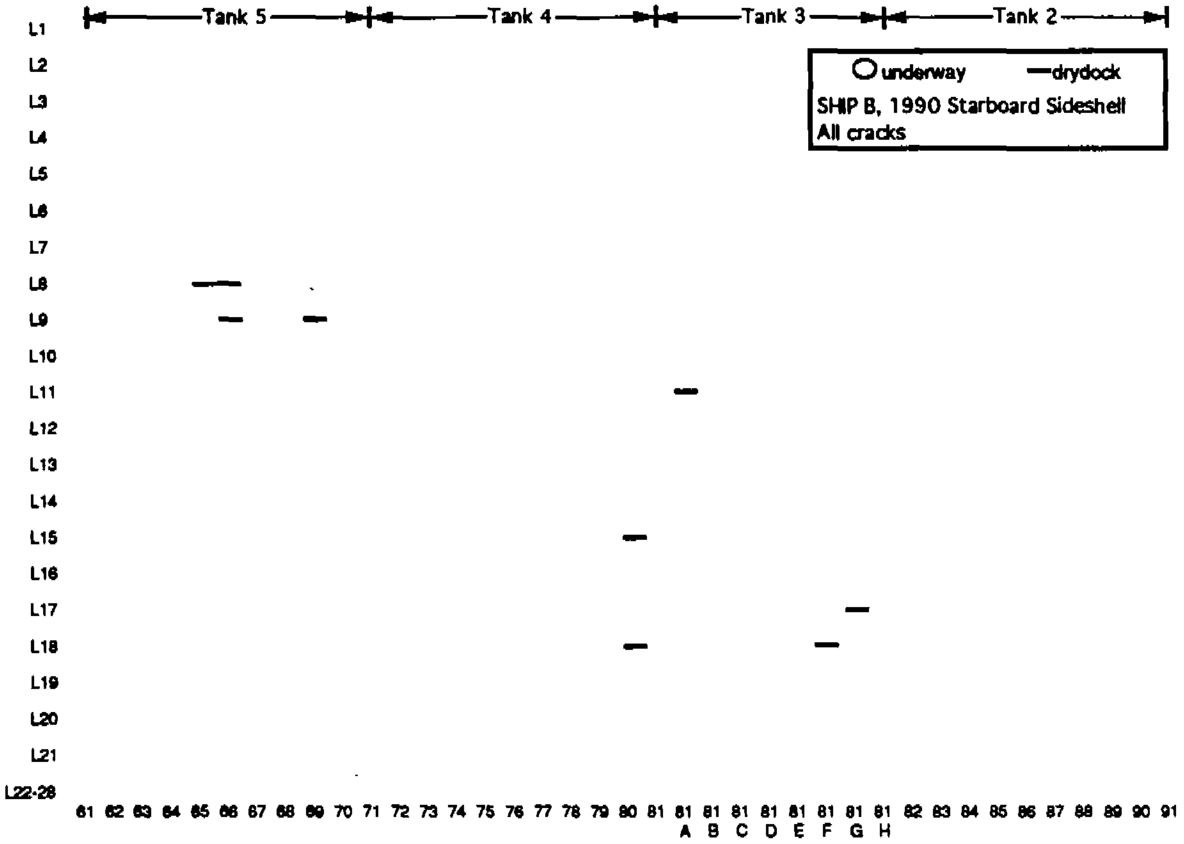

Figure 21a. Ship B 1990 Inspections, Starboard Side Shell Cracks

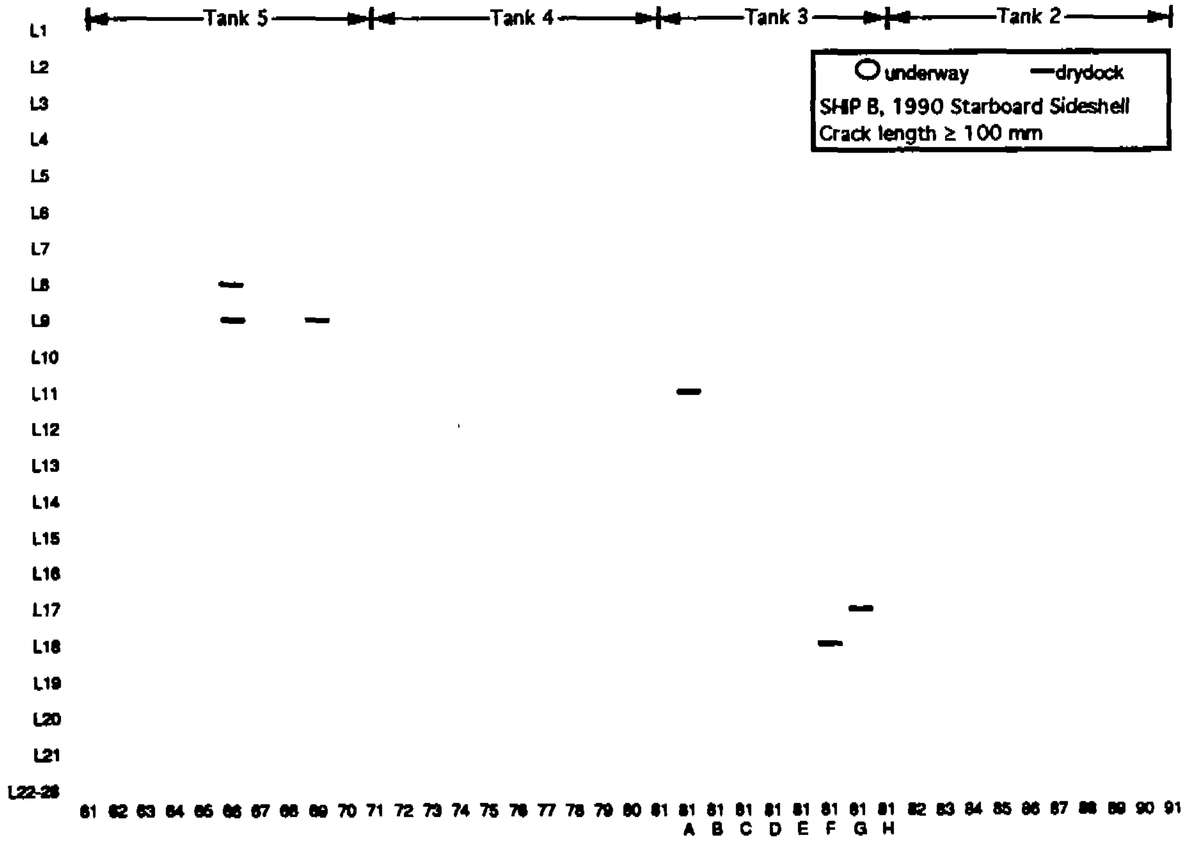

Figure 21b. Ship B 1990 Inspections, Starboard Side Shell Cracks ≥ 100mm

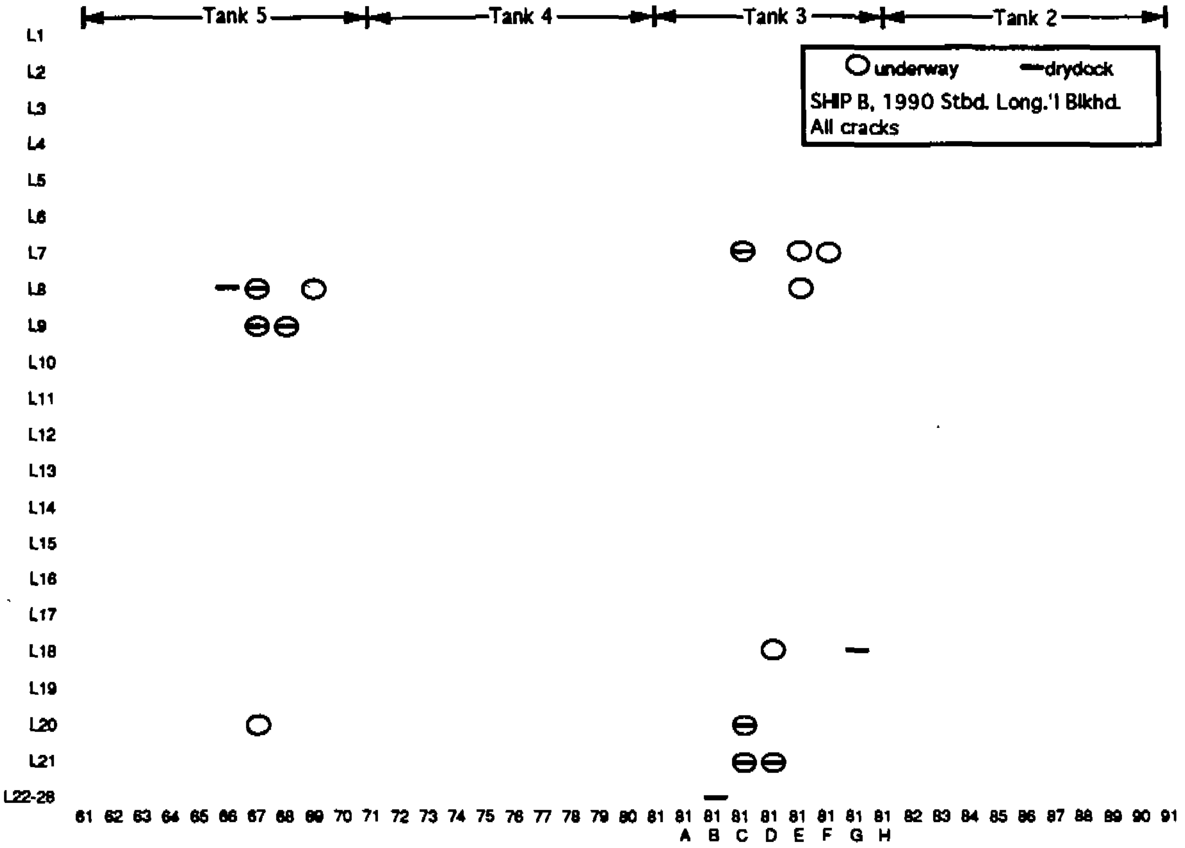

Figure 22a. Ship B 1990 Inspections, Starboard Longitudinal Bulkhead Cracks

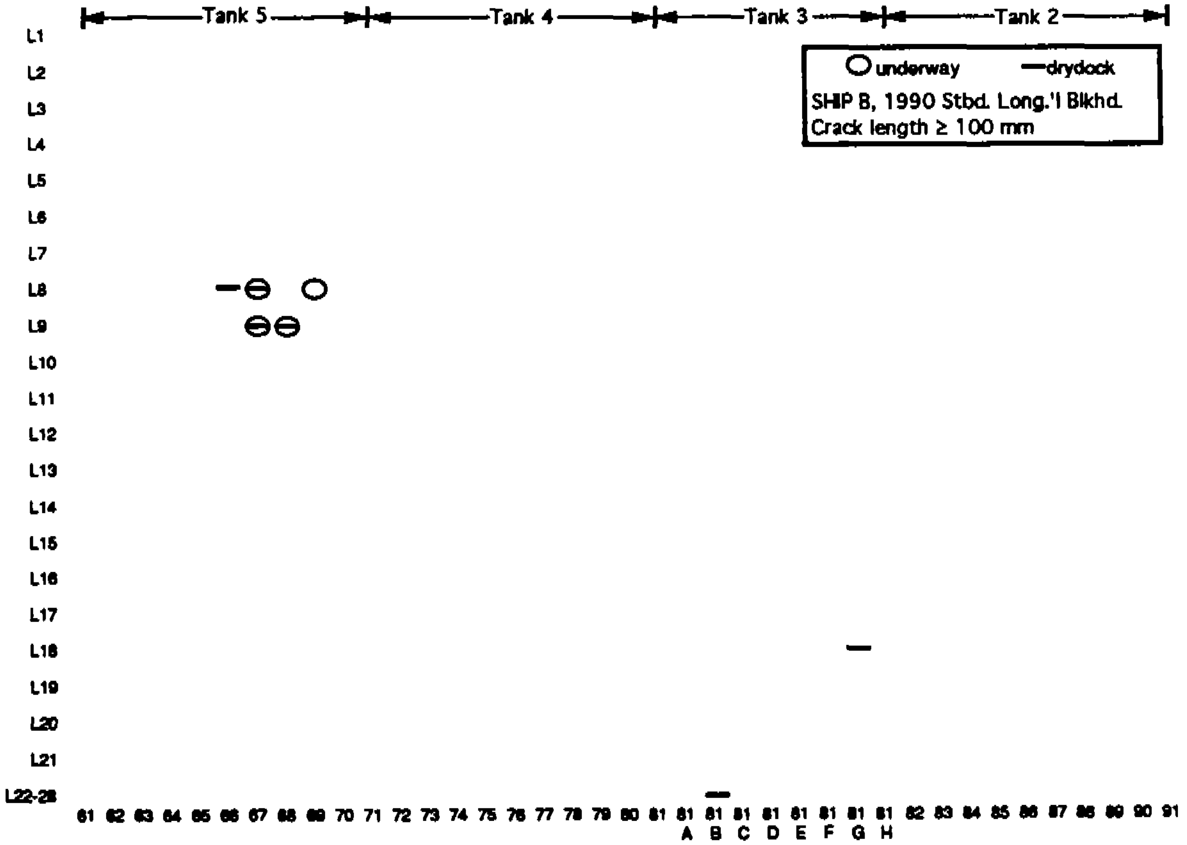

Figure 22b. Ship B 1990 Inspections, Stbd. Longitudinal Bulkhead Cracks ≥ 100mm

also present in Ship B. To do this requires not that every crack be detected, but that a general sense of condition at the locations in question be obtained. In Tank 3 P, for example, 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 knowledge affected the inspector's performance. However, a reasonable course of action in light of time pressures would have been to inspect at the L8/L9 and L14/L15 levels only until cracks had been found at several web frames, and then to conclude that a problem existed in that tank.

For the 1987 inspections three types of performance can be observed through the benchmarked plots: very good, mixed, and poor.

> Very Good Performance There are regions, such as the longitudinal bulkheads in Tanks 5P and 5S, where nearly all the cracks found in drydock were also detected underway. This indicates that at least under certain conditions (in this case, an inspection carried out with knowledge of what had recently been found in a sister ship), the probability of detection in tanker inspection can be quite good.
>
> Mixed Performance In regions such as the side shells in Tanks 5P and 5S, performance is mixed. Some cracks are detected, but many are missed. As discussed above, 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 Tanks 4P and 4S, where no cracks were found underway, despite the presence, in Tank 4P, of many cracks with length ≥ 100 mm. It may be that there was no opportunity to raft at this level during the underway inspection, though that is not clear from the information available.

A review of the results of the 1990 inspections of Ship B, shown in Figures 19 - 22, indicates that the problem observed at L8, L9, L14, and L15 in 1987 seems to have been solved, although there are still a few cracks 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 each of Figures 15-18. In each case, performance is better, that is, the detection rate is higher, for cracks with length ≥ 100 mm than it is for all cracks. The 1987 inspection of Tanks 3 and 5 produced the greatest number of cracks in regions other than those with poor performance, so the effect of length is best seen through the 1987 data from these tanks.

Figures 23-26 show "hits" *vs.* all cracks found in drydock for various crack lengths. Figures 23 and 24 show this comparison for the 1987 inspection of Tank 3. Figures 25

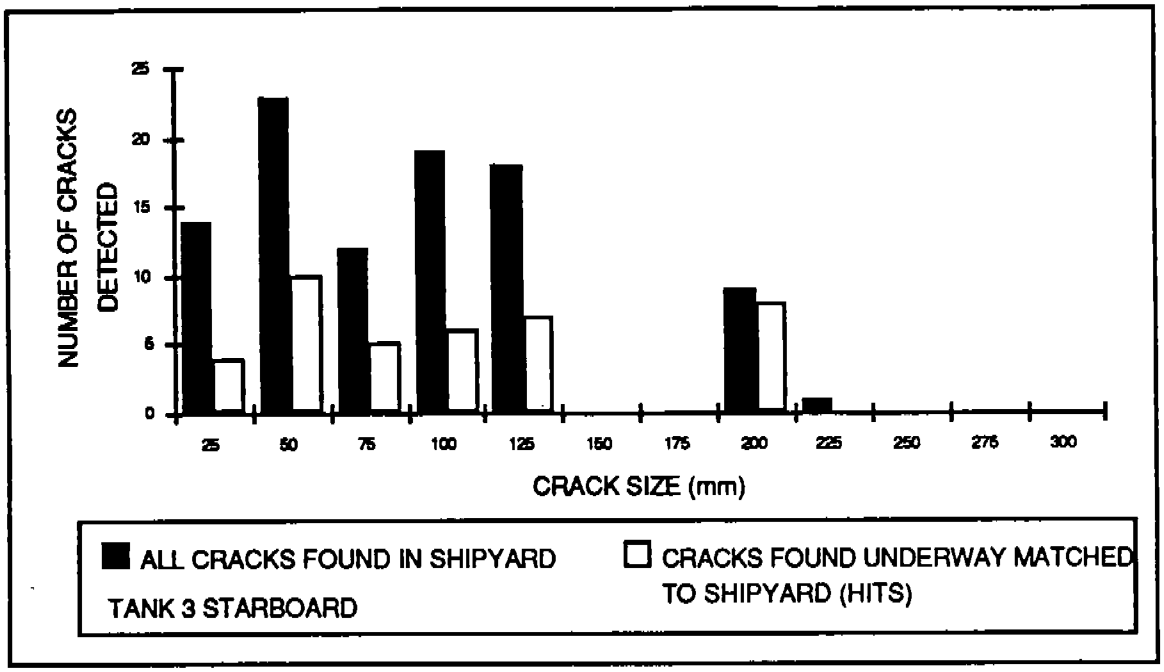

Figure 23. "Hits" and All Drydock Cracks, 1987 Inspection, Tank 3 Starboard

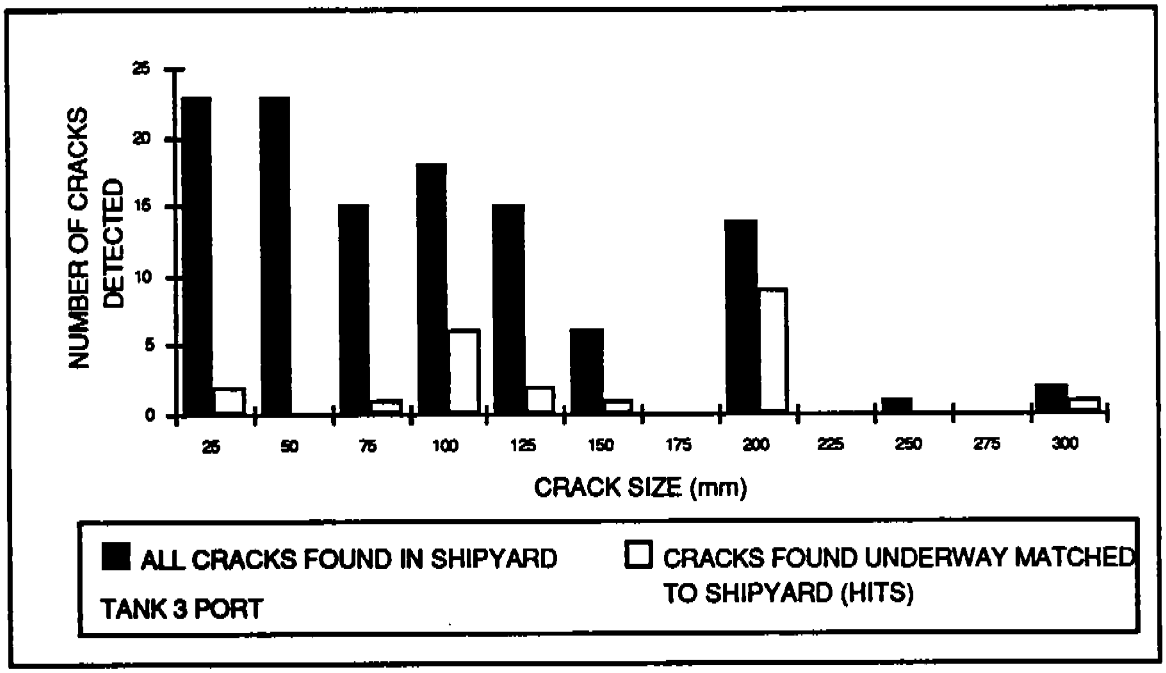

Figure 24. "Hits" and All Drydock Cracks, 1987 Inspection, Tank 3 Port

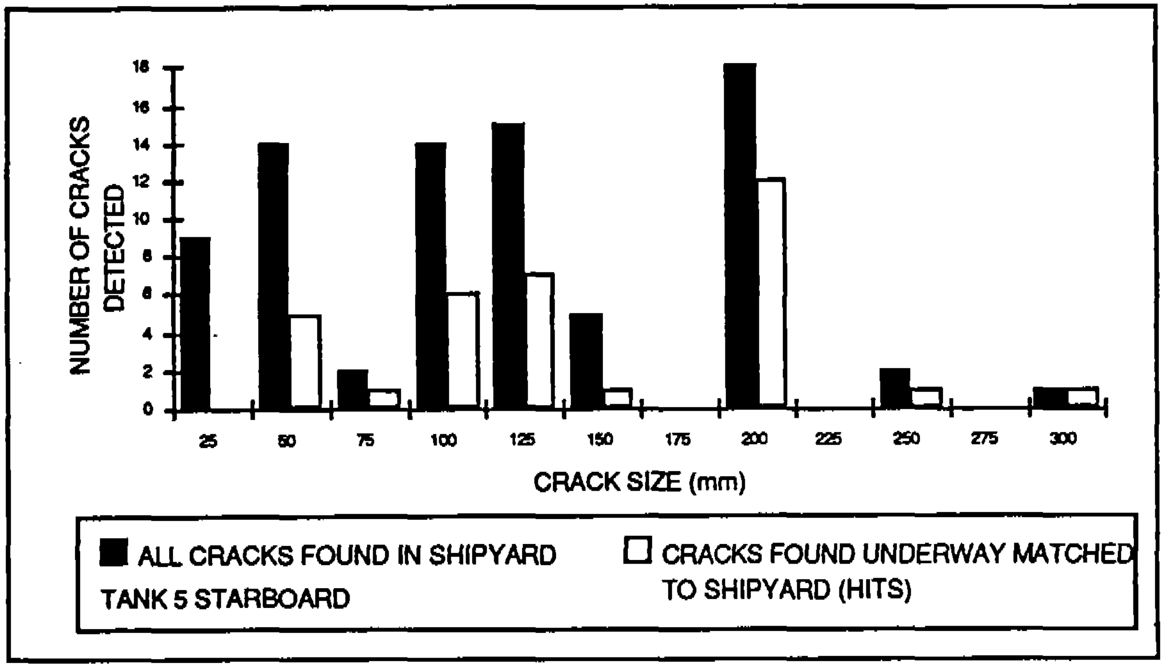

Figure 25. "Hits" and All Drydock Cracks, 1987 Inspection, Tank 5 Starboard

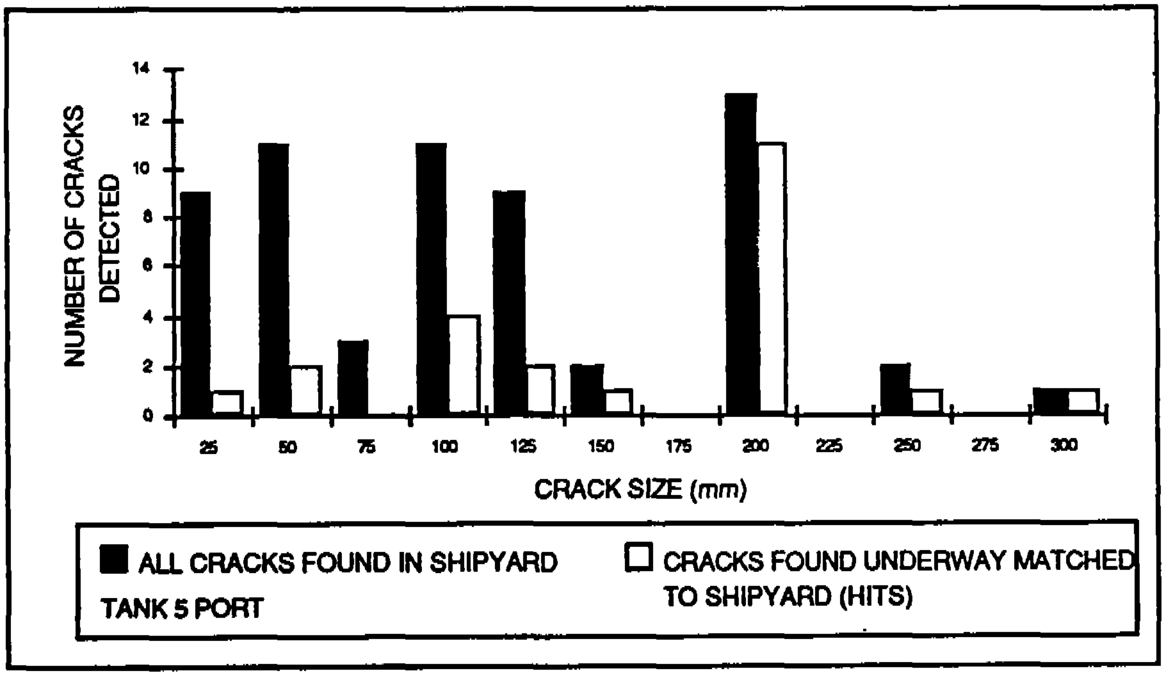

Figure 26. "Hits" and All Drydock Cracks, 1987 Inspection, Tank 5 Port

and 26 show the same information for Tank 5. The ratio of hits to all drydock cracks is, for each crack length, a single POD data point. However, due to the limited pool of data considered here, it would be misleading to express these results in the form of a POD curve. Based on Figures 23-26, it appears that a reasonably large percentage of cracks 200 mm (7.9 inches) or larger are detected, and that a much smaller percentage of cracks 150 mm (6.0 inches) or less are detected. These results are somewhat at odds with inspectors' comments during the interviews, which indicated that most cracks larger than 2 or 3 inches would be detected. However, the special circumstances of the 1987 underway inspection (that is, the focus on cracks at L8, L9, L14, and L15) may have caused inspectors to overlook large cracks once they had determined that the cracking problem was indeed evident in a particular tank.

5.4.3.5 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. In the 1987 inspections, with many cracks reported, 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 be such that the inspector's performance varies within a tank.

Although there were not sufficient data to allow the development of probability of detection curves, 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 2 to 3 inch 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 150 mm in length. This may in part be due to the specific conditions of the case study inspections.

5.4.4 Modifications to Support Data Collection

In carrying out the benchmarked inspection data case study described here, it became apparent that two modifications would greatly facilitate data collection and analysis. For typical historical data, little or no information will available regarding the many factors that can affect inspection performance. The comments of the owner/operator representative provided insight into some factors important in the case study, but even so, no information was available regarding others (such as lighting, the experience of the inspectors, etc.). If a larger body of benchmarked data is collected, it will be useful to have information on environmental factors and inspector factors, in addition to the vessel factors (which are generally available from the owner/operator). Much of this information could be obtained directly from the inspector at the time of the inspection, and then stored with the inspection data. To facilitate this process, a brief questionnaire was developed. The intent is that this form would be completed by the inspector immediately following the inspection. The format and content of the questionnaire represent a compromise between the desire for complete information and the need for a brevity. The current draft of the questionnaire is provided as Appendix A. This draft incorporates the comments of several experienced inspectors. The questionnaire has not been "tested"; that is, it has not been filled out by inspectors just completing an inspection. Until feedback from such "tests" is incorporated into the questionnaire, it should be viewed as a draft.

The process of matching cracks found underway with those detected in drydock was arduous. Currently, the data are recorded in two separate reports, and must be manually extracted from each and then compared. Two changes could make this process easier. First, if inspection results were stored in a database that could be sorted by location, defect type, and defect size, the matching process would be close to effortless. Existing and proposed database representations of tanker structure and history are described in [Shulte-Strathaus and Bea 1995]. Second, if the inspector carrying out a drydock inspection had access to the results of the prior underway inspection, perhaps in the form of locations marked on drawings, data for the two inspections could be archived together. There is a potential drawback to this approach; the drydock inspector might be inclined to look only (or primarily) where defects had been detected in the underway inspection.

5.4.5 Benchmarked Inspection Data: Summary

The case study carried out here shows that benchmarked inspection data can provide useful information on the probability of detection. The process of obtaining and analyzing data was relatively straightforward. Benchmarked inspection data has the advantage of drawing on data from real inspections in true field conditions, yet remaining relatively inexpensive and free of time constraints. However, the approach has several drawbacks. First, the amount of data available may be limited; only a few operators carry out underway inspections followed shortly by drydock inspections. In addition, the method provides no assessment of the quality of the drydock inspections, and no means to control the various factors that affect performance Two additional drawbacks, the lack of information on factors affecting performance and the tedious data collection process, could be minimized by the steps proposed in Section 5.4.4. In addition, knowledge of the purpose of an inspection and the conditions under which it is carried out can shed light some light on observed performance, and should be obtained whenever possible.

The results of the experiment carried out here also indicate that inspection performance can vary greatly in different regions of the same vessel. Furthermore, the limited results presented here suggest that the "readily detected" crack size is significantly larger than that estimated by most inspectors. This calls into question the ability of inspectors to provide the information needed for the solicitation of expert opinion approach recommended in [Ayyub and White 1992].

5.5 SUMMARY

Of the four approaches to quantifying performance, two do not appear to warrant further attention at this time: solicitation of expert opinion and laboratory experiments. Solicitation of expert opinion is not a feasible approach; inspectors are reluctant to provide quantitative estimated of performance. Furthermore, at least for the ship analyzed here, the estimates that inspectors do put forward are much more optimistic than the observed detection record. Laboratory experiments, while they have the advantage of a working from a known and controllable set of flaws, are unlikely to be successful due to the difficulty in replicating in-tank conditions without incurring excessive costs.

The other two approaches, *in-situ* experiements and benchmarked inspection data, along with a hybrid approach do appear promising as means to assess inspection performance and derive POD information. *In-situ* experiments provide results based on a close-to-real inspection carried out under real conditions. The drawbacks that would have to be overcome for this approach to be successful are the high cost of inspector and vessel time, the reduced ability to isolate the effects of different factors, and the fact that any particular vessel may not yield a suitable number of defects to evaluate POD. Benchmarked inspection data also has the advantage of deriving results from real inspections carried out in real field conditions. Furthermore, it is relatively inexpensive and poses no time constraints. The drawbacks that have to be overcome include, once again, the reduced ability to isolate and modify various factors and the risk that any particular vessel may not yield a large number of defects. An additional drawback is the small number of organizations that carry out drydock inspections shortly after underway inspections. Finally, the hybrid approach of carrying out an *in-situ* experiment on an out-of-service vessel appears to be a promising means of avoiding some of the drawbacks associated with *in situ* testing and benchmarked inspection data. The use of markers to supplement the already existing defects in an *in situ* or hybrid test also has the potential to increase the information obtained.

6. SUMMARY AND CONCLUSIONS

A 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. This project has investigated the means of developing a better understanding of probability of detection in tanker inspections. 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 review of the literature in other industries, including aviation, nuclear power, manufacturing, and off shore structures was carried out. Selected studies are summarized in this report. Taken together, they provide examples of the various methods that have been used to assess probability of detection: controlled experiments on small scale samples, controlled experiments on large scale samples in simulated field conditions, use of historical data, and use of an out-of-service structure. In addition, these studies indicate that a variety of factors affect probability of detection, including inspection method and various human factors, and that there is a tendency for subjective estimates of inspection performance made by inspectors and others to be better than measured performance under test conditions. It is reasonable to anticipate that the same tendency for optimism exists in the marine field.

Four approaches to analyzing inspection performance were identified or developed for application to the tanker inspection problem: solicitation of experts, laboratory experiments, *in situ* experiments, and benchmarked inspection data. Each approach was assessed with regard to a variety of issues including ability to isolate factors, data management, resource requirements, time requirements, and cost. The results suggest that *in situ* experiments, benchmarked inspection data, and a hybrid (*in situ* test on an out-of-service vessel) are potentially useful tools for further work on POD.

An case study of the use of benchmarked inspection data was carried out. In addition to demonstrating the feasibility of the approach, the results showed the import influence that prior experience with 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 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. To overcome the issue of limited knowledge of the factors that affect inspection, a brief questionnaire was developed for use in future applications of benchmarked data analysis. The questionnaire should be completed by inspectors shortly after an inspection. The use of a database to archive both sets of inspection data is also recommended.

In conclusion, further efforts to understand probability of detection in the tanker inspection environment should be carried out through *in situ* tests of either an in-service or an out-of-service vessel and though analysis of benchmarked inspection data.

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APPENDIX A - INSPECTOR QUESTIONNAIRE

INSPECTOR QUESTIONNAIRE

VESSEL: ____________________ DATE: ____________________

---

1. Roughly how many hours have you worked in the past seven days?

   less than 35 hrs   35 to 50 hrs   51 to 70 hrs   more than 70 hrs

2. Number of years experience performing inspections on ships:

   less than 2 yrs   2 to 4 years   5 to 8 years   more than 9 years

3. Amount of classroom and formal in-field training you have received during your inspection career:

   none   less than 6 mo   6 mo to 1 yr   1 to 2 yrs   more than 2 yrs

4. Number of times you have inspected vessels in the same class as this ship:

   none   one or two   three or four   five or more

5. Number of times you have inspected this vessel in the past not including this time:

   none   once   twice   three or more

6. Prior to this inspection, were the past inspection reports of this vessel reviewed?

   yes   no

7. Was there as detailed written plan for areas to be inspected (such as CAIP)?

   yes   no

8. Where was the ship located when this inspection was performed?

   underway   dockside   in dry-dock

9. If this inspection was performed underway, how would you describe the sea condition?

   calm   moderate   rough

10. What type of access was used during this inspection?

    bottom waking   rafting   staging   other __________

11. How would you describe the overall lighting available in the tanks being inspected?

    poor   adequate   excellent

12. In addition to the overall lighting, did your portable flashlight provide suitable lighting?

    poor   adequate   excellent   not used

13. How would you describe the color of the coating used in the tank?

dark   light   none used

14. How would you describe the tank cleanliness?

poor   adequate   excellent

15. What was the temperature in the tanks being inspected?

cold   moderate (comfortable)   hot

16. How would describe the ventilation in the tank during this inspection?

poor   adequate   excellent

17. Did you use protective eyewear during this inspection?

yes, prescription glasses   yes, protective glasses   no

18. Did you have to wear a breathing respirator while performing the inspection?

yes   no

19. Please estimate the total time you were in the tank(s) during this inspection:

____________________hours

20. How would you describe the amount of time available to inspect the area required?

insufficient   limited but acceptable   time was not a problem

21. During the inspection, what was the longest you had to work without a break?

less than 1 hr   1 to 2 hrs   3 to 4 hrs   more than 5 hrs

22. In general, would you say the vessel was well prepared for the inspection?

yes   no

23. For what type of organization were you conducting this inspection?

regulatory agency   classification society   owner/operator   repair facility

APPENDIX B - SAMPLE INSPECTION DATA

SHIP "B - 1987 INSPECTION PORT CARGO WING TANK #2

Inspection Type	Crack Length, mm	General Location	Frame	Longitudinal
shipyard	10	side shell	82	8
shipyard	10	side shell	82	9
shipyard	10	long'l bkhd	82	9
shipyard	20	side shell	82	14
shipyard	200	side shell	82	15
shipyard	20	long'l bkhd	83	8
shipyard	60	side shell	83	8
underway	200	side shell	83	8
shipyard	10	long'l bkhd	83	9
shipyard	120	side shell	83	9
underway	200	side shell	83	9
shipyard	200	side shell	83	14
shipyard	30	side shell	83	15
shipyard	30	side shell	84	8
shipyard	30	trans web frame	84	8
underway	200	side shell	84	8
shipyard	100	side shell	84	9
underway	200	side shell	84	9
shipyard	30	side shell	84	18
shipyard	600	side shell	84.5	9
shipyard	100	side shell	85	8
shipyard	60	side shell	85	9
shipyard	10	side shell	85	14
shipyard	20	long'l bkhd	85	14
shipyard	10	side shell	85	15
shipyard	20	long'l bkhd	85	15
shipyard	40	side shell	85	16
shipyard	20	long'l bkhd	86	8
shipyard	120	side shell	86	8
underway	200	side shell	86	8
shipyard	10	long'l bkhd	86	9
shipyard	60	side shell	86	9
underway	200	side shell	86	9
shipyard	200	side shell	86	14
shipyard	200	side shell	86	15
shipyard	80	trans web frame	86	31
shipyard	20	long'l bkhd	87	8
shipyard	40	side shell	87	8
shipyard	10	long'l bkhd	87	9
shipyard	60	side shell	87	9
shipyard	60	side shell	87	14
shipyard	60	side shell	87	15
shipyard	100	side shell	88	8
shipyard	10	long'l bkhd	88	9
shipyard	60	side shell	88	9
shipyard	20	side shell	88	14
shipyard	10	side shell	88	15
shipyard	10	side shell	88	16
shipyard	30	side shell	89	8
shipyard	20	long'l bkhd	89	9
shipyard	30	side shell	89	9
shipyard	20	side shell	89	14
shipyard	10	side shell	89.5	14
shipyard	20	side shell	90	8
shipyard	20	side shell	90	9
shipyard	40	horiz strg #1	90	10

shipyard	80	horiz strg #2	90	17
shipyard	30	trans web frame	90	31
shipyard	40	trans web frame	90	31

SHIP "B" - 1987 INSPECTION STBD CARGO WING TANK #2

Inspection Type	Crack Length, mm	General Location	Frame	Longitudinal
shipyard	60	side shell	81H	17
shipyard	120	side shell	82	8
shipyard	120	long'l bkhd	82	8
underway	200	side shell	82	8
shipyard	20	long'l bkhd	82	9
shipyard	30	side shell	82	9
shipyard	30	long'l bkhd	82	14
shipyard	60	side shell	82	18
shipyard	60	side shell	83	8
shipyard	40	long'l bkhd	83	9
shipyard	60	side shell	83	9
shipyard	30	side shell	83	10
shipyard	10	side shell	83	11
shipyard	10	side shell	83	12
shipyard	60	side shell	83	18
underway	100	side shell	84	8
shipyard	120	side shell	84	8
shipyard	10	long'l bkhd	84	9
shipyard	20	side shell	84	9
shipyard	100	side shell	84	9
shipyard	20	side shell	84	14
shipyard	100	side shell	84	18
shipyard	30	trans web frame	84	31
shipyard	120	side shell	85	8
shipyard	20	side shell	85	9
shipyard	200	side shell	85	14
shipyard	20	side shell	85	15
shipyard	120	side shell	86	8
shipyard	120	side shell	86	9
shipyard	150	side shell	86	14
shipyard	100	side shell	86	15
shipyard	120	side shell	87	8
shipyard	20	side shell	87	9
shipyard	50	trans web frame	87	14
shipyard	200	side shell	87	14
shipyard	80	side shell	87	15
shipyard	120	side shell	87	18
shipyard	60	trans web frame	87	25
shipyard	50	long'l bkhd	88	8
shipyard	120	side shell	88	8
shipyard	10	long'l bkhd	88	9
shipyard	40	side shell	88	9
shipyard	20	side shell	88	12
shipyard	10	side shell	88	14
shipyard	50	side shell	88	15
shipyard	100	side shell	88	18
shipyard	120	side shell	89	9
shipyard	20	long'l bkhd	89	14
shipyard	10	long'l bkhd	89	15
shipyard	20	side shell	90	8

shipyard	20	side shell	90	9
shipyard	20	side shell	90	9
shipyard	20	horiz strg #1	90	10
shipyard	20	horiz strg #1	90	17
shipyard	100	horiz strg #2	90	19

APPENDIX C - SHIP A 1987 DRYDOCK INSPECTION

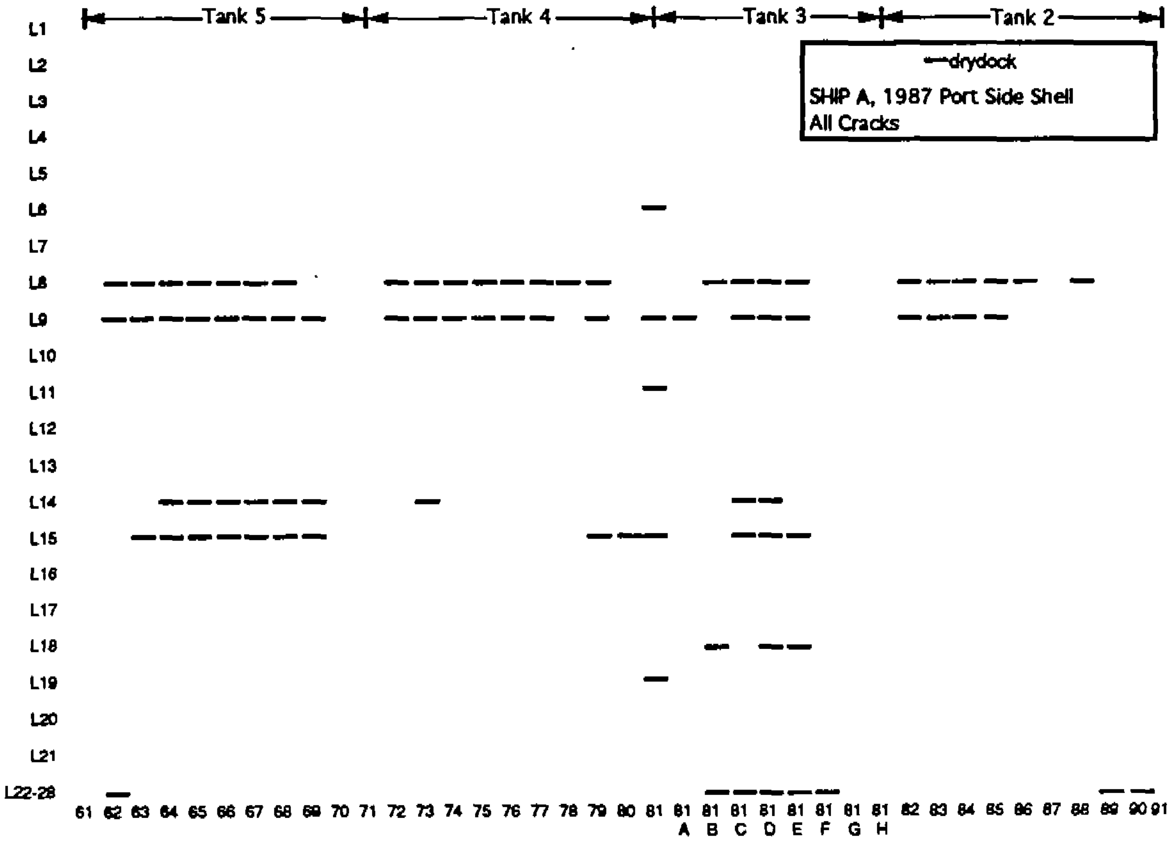


Figure C1a. Ship A 1987 Drydock Inspection, Port Side Shell Cracks

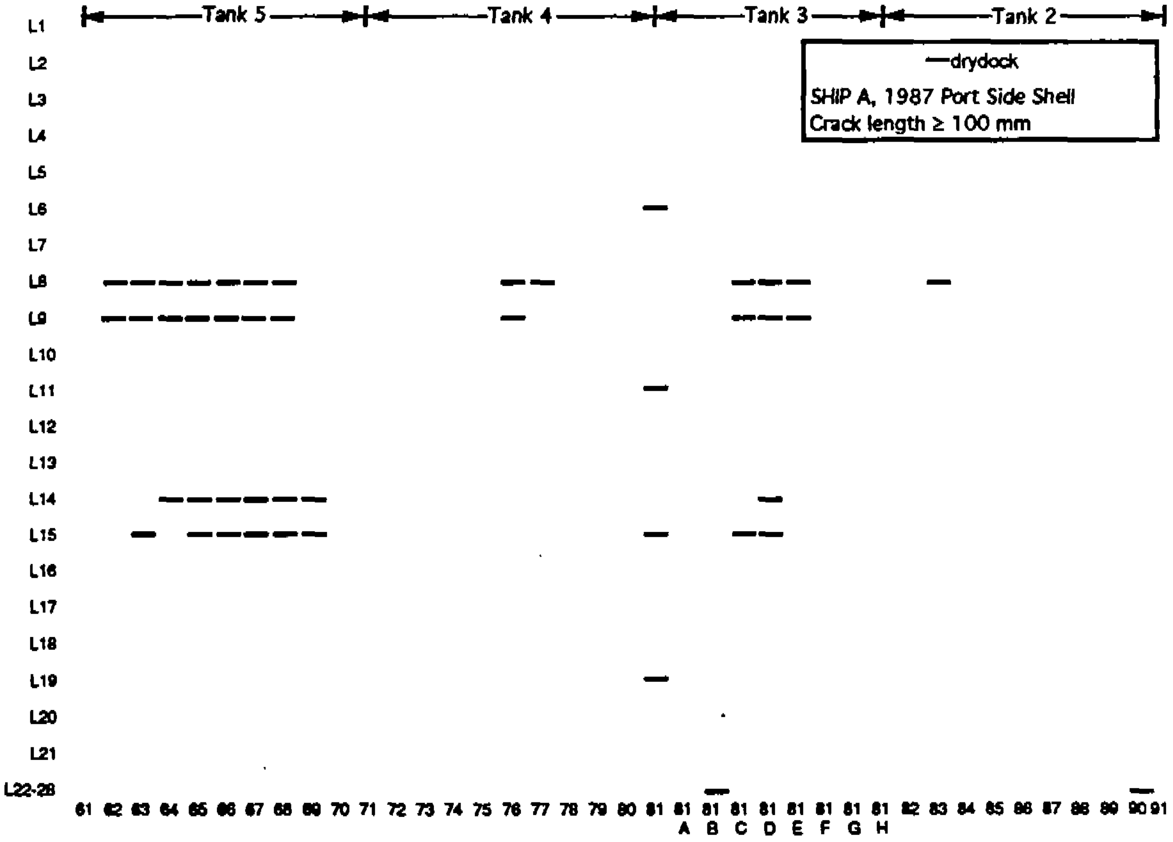


Figure C1b. Ship A 1987 Drydock Inspection, Port Side Shell Cracks ≥ 100mm

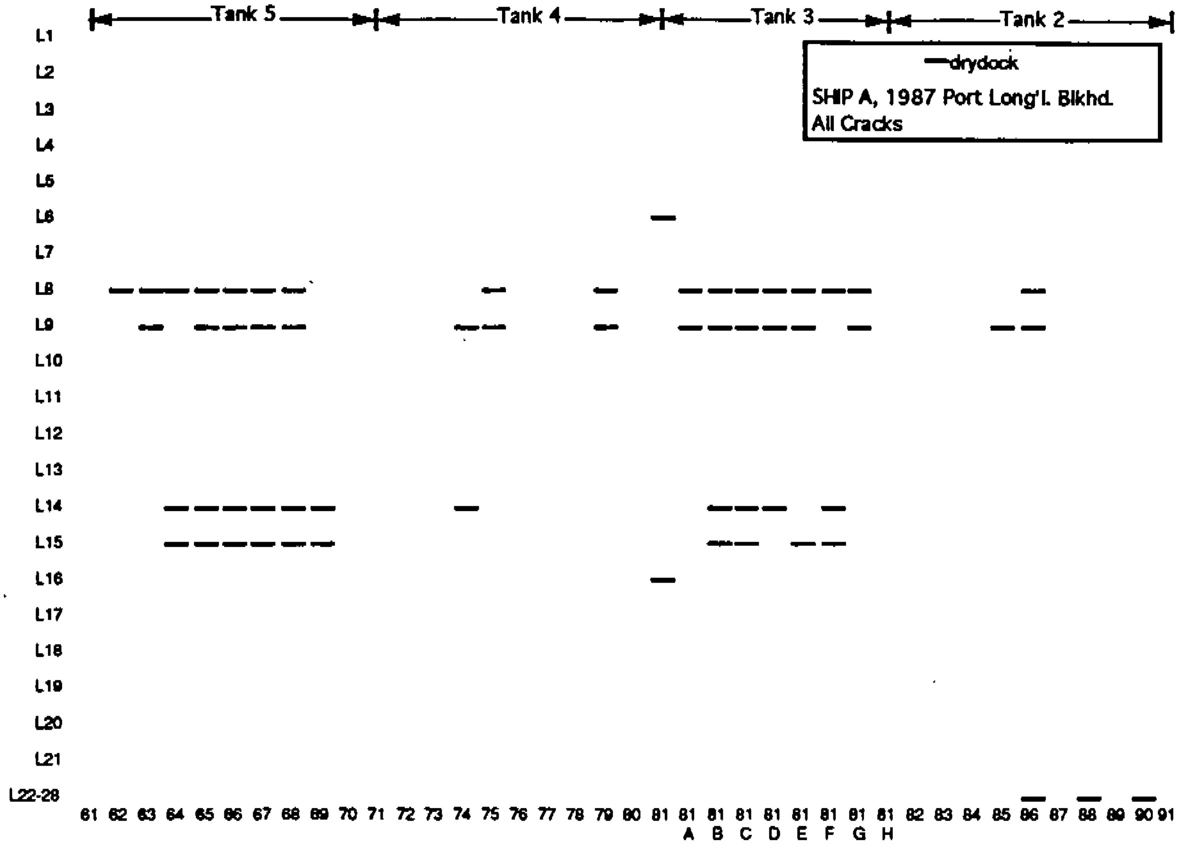


Figure C2a. Ship A 1987 Drydock Inspection, Port Longitudinal Bulkhead Cracks

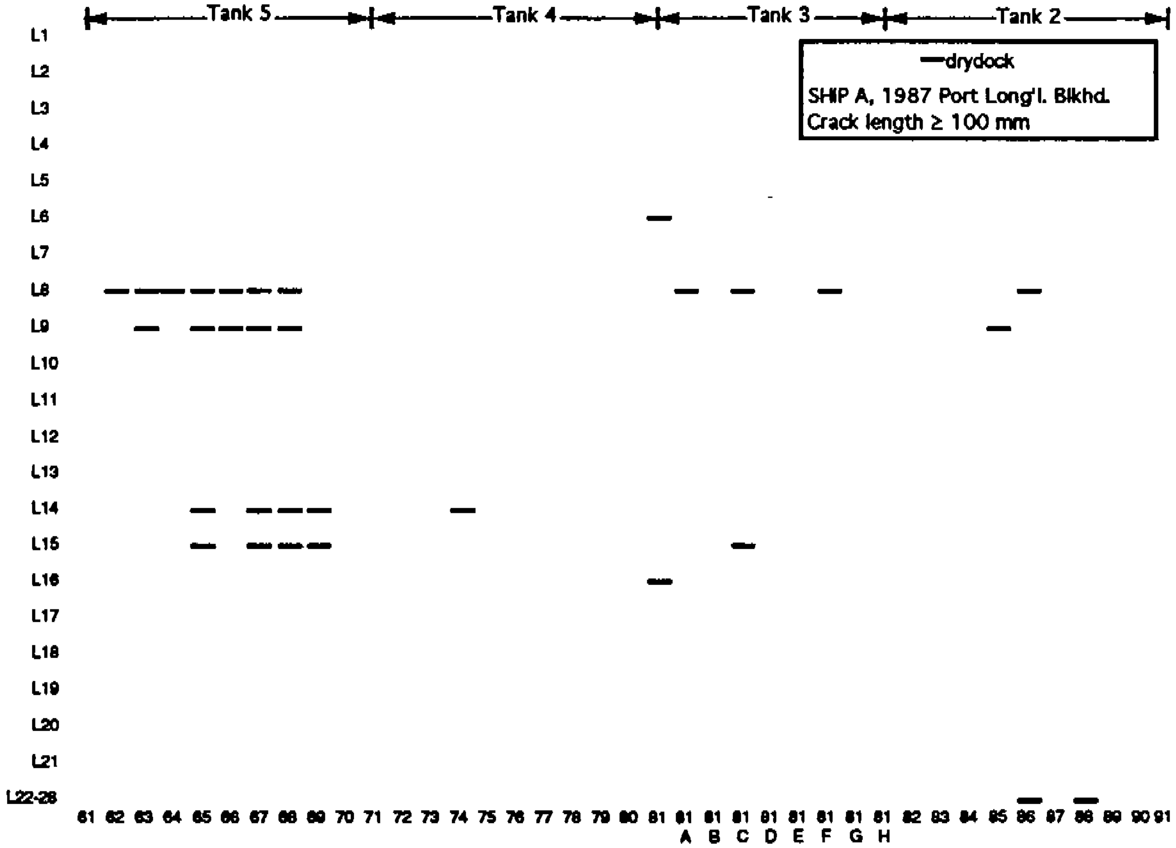


Figure C2b. Ship A 1987 Drydock Inspection, Port Long'l. Bulkhead Cracks ≥ 100mm

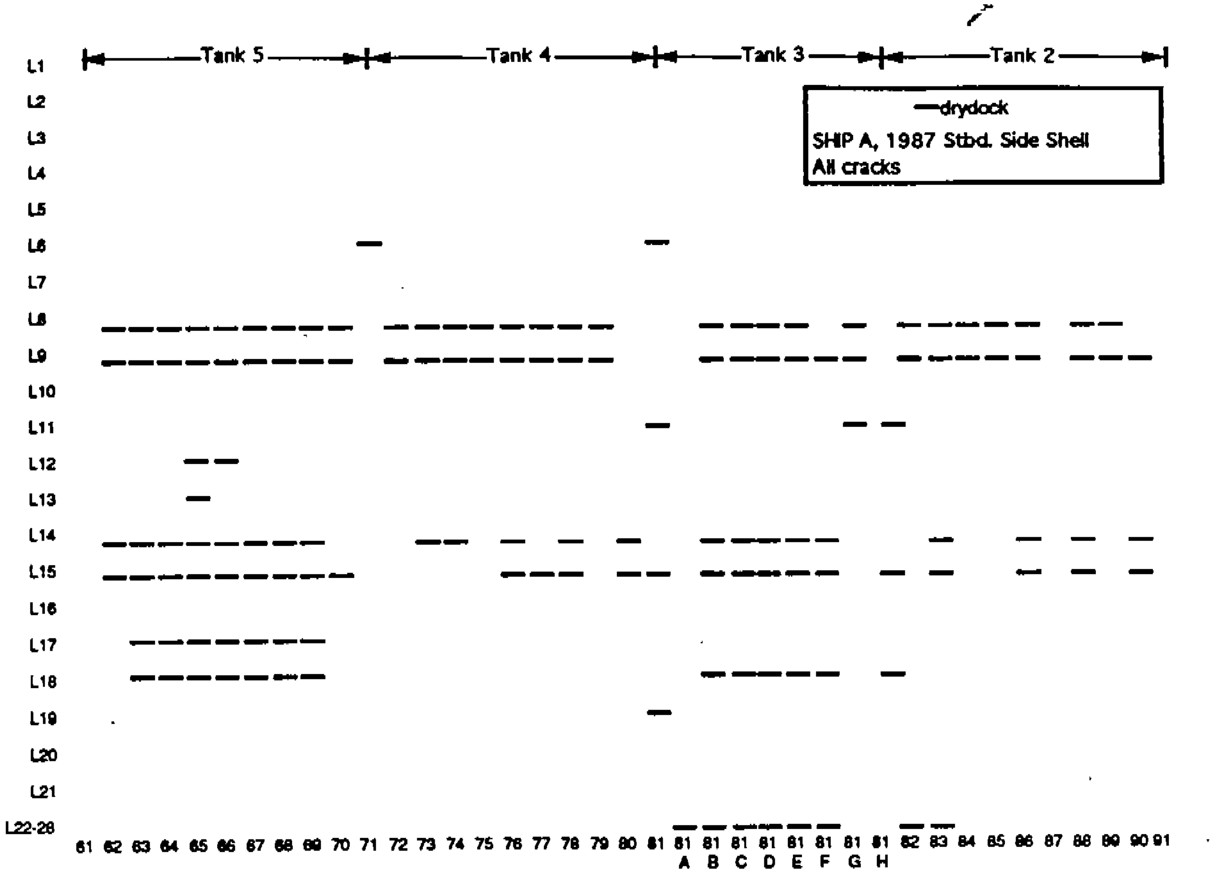


Figure C3a. Ship A 1987 Drydock Inspection, Starboard Side Shell Cracks

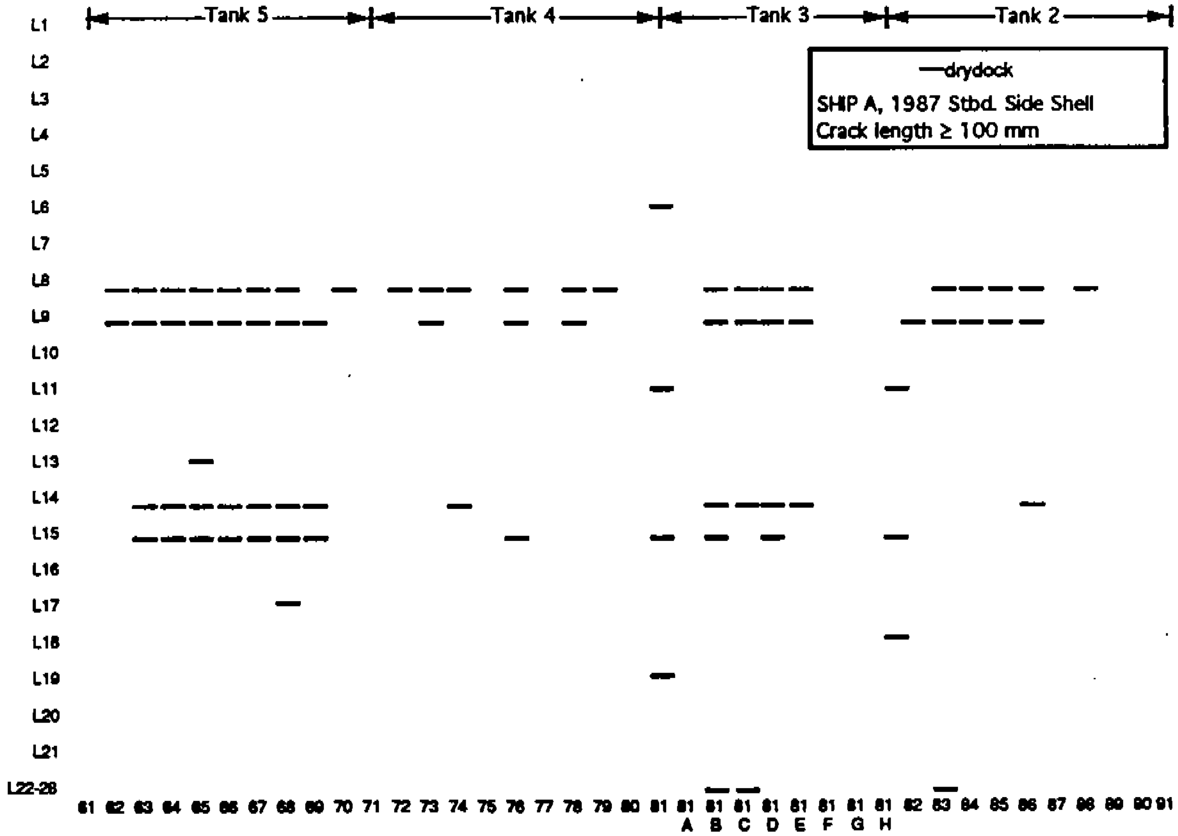
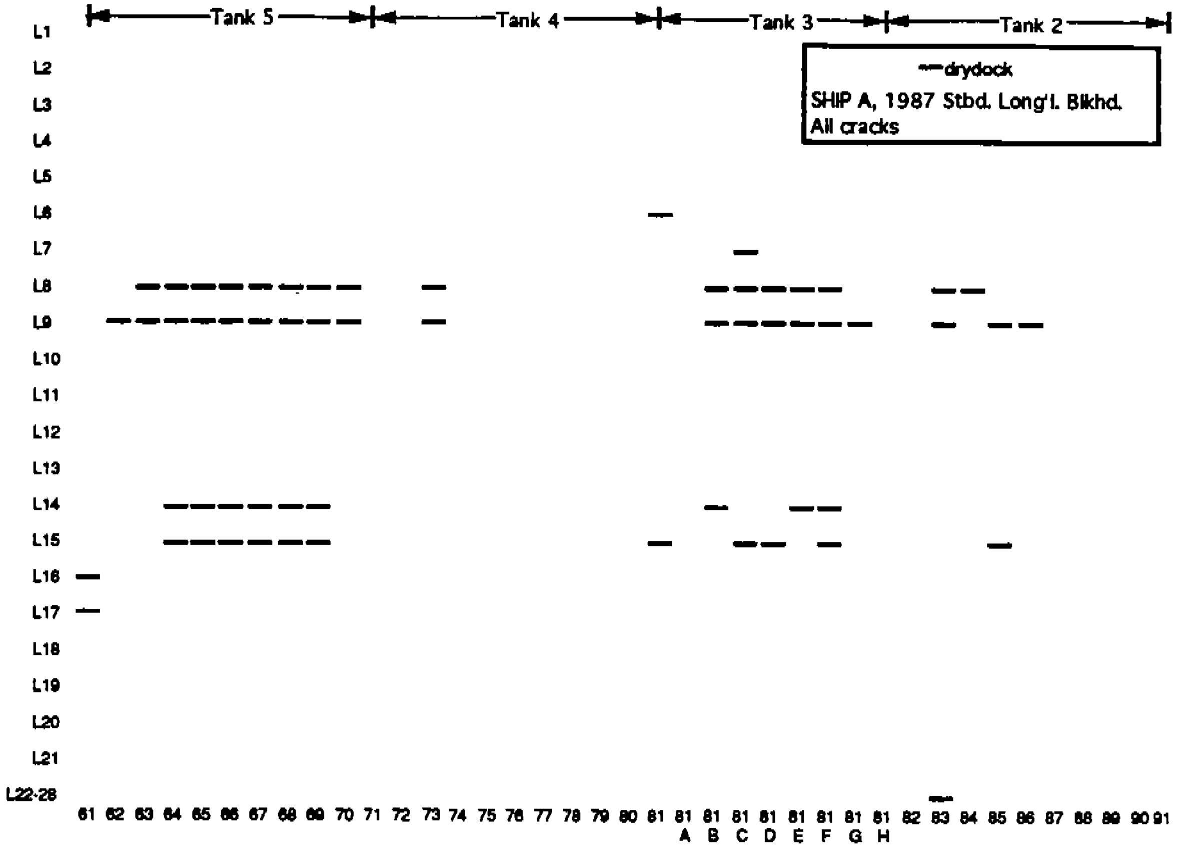


Figure C3b. Ship A 1987 Drydock Inspection, Starboard Side Shell Cracks ≥ 100mm



C4a. Ship A 1987 Drydock Inspection, Stbd. Longitudinal Bulkhead Cracks

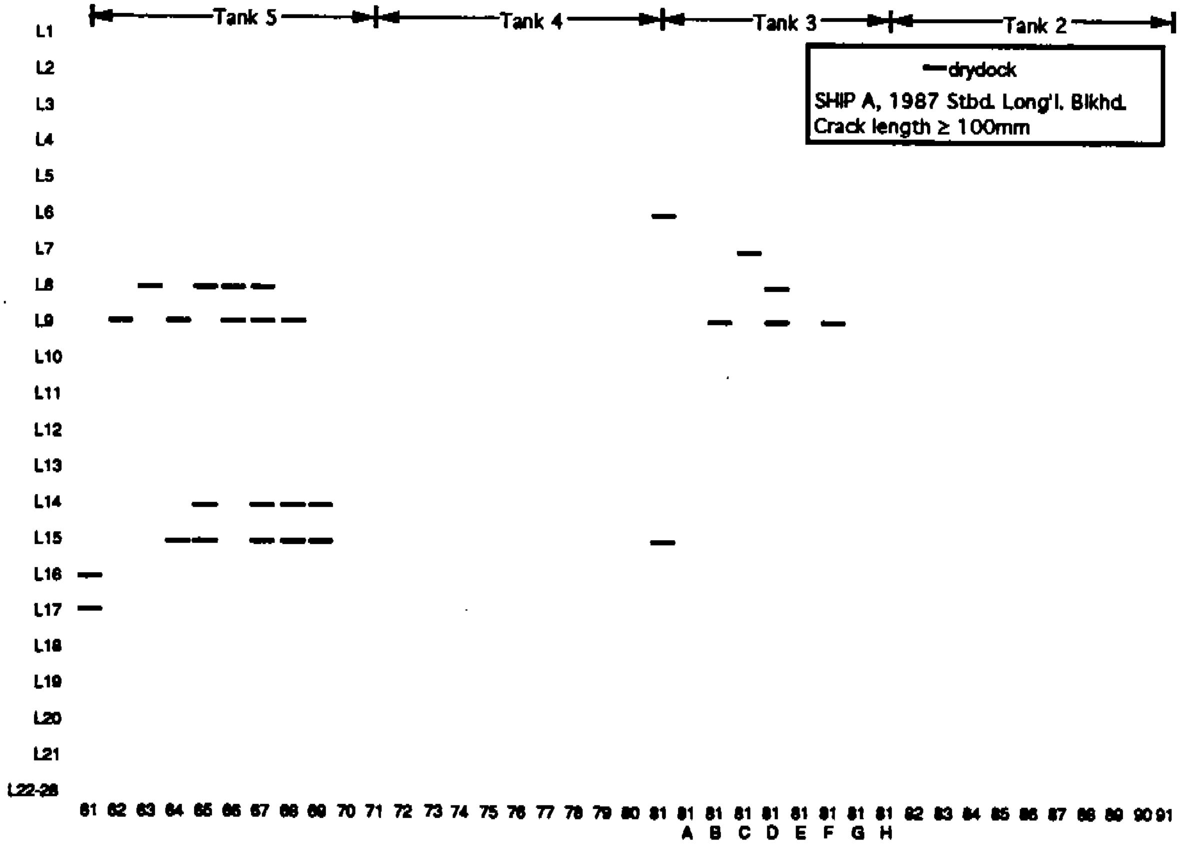


Figure C4b. Ship A 1987 Drydock Inspection, Stbd. Long'l. Bulkhead Cracks ≥ 100mm

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The following persons were members of the committee that represented the Ship Structure Committee to the Contractor as resident subject matter experts. As such they performed technical review of the initial proposals to select the contractor, advised the contractor in cognizant matters pertaining to the contract of which the agencies were aware, and performed technical review of the work in progress and edited the final report.

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