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SSC-394

STRENGTH ASSESSMENT OF PITTED PLATE PANELS

SHIP STRUCTURE COMMITTEE
1997

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STRENGTH ASSESSMENT OF PITTED PLATE PANELS

In years past, the evaluation of adequacy of ship hull plates during drydocking has been highly based upon personal judgement of the evaluator. In general the situation was usually obvious as to whether adequate strength remained in the plate or that the plate had to be replaced. Initial scantlings were much greater in older ships, leaving a larger margin for error. Borderline cases were generally treated conservatively by replacing the plate even if it was only deemed marginal. However, with the current climate in the marine industry, unnecessary repairs are not taken on as quickly. On the other hand a small crack causing what may once have just been regarded as a "nuisance leak" may well result in a significant oil spill today. In general, there is less margin for error in judgment than there was before.

This project provides a tool for the field inspector to evaluate a pitted plate on scene. By recording a few readily identifiable parameters and comparing them to graphs in the report a recommendation as to the acceptability of the plate section may be made. Should that not provide a clear enough criteria a program "PIT" may be used for further evaluation of the data. The report provides some detail as to the development of the program and parameters for it use.

The program "PIT" will be included in a later CD ROM version of this report.

J. C. CARD
Rear Admiral, U.S. Coast Guard
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16. Abstract

Current practices in inspecting, measuring and evaluating ships' panels of plating for pitting corrosion and existing pitting models used in quantifying this phenomenon were reviewed by a literature search and through limited interviews. Actual pitting data were obtained from two oil companies and analyzed for use in this project.

A mathematical model and a FORTRAN computer program (PIT), which can be run on a personal computer, were developed to predict the residual thickness of pitted plate panels. By inputting a set of actual pitting measurements (number of pits, depth and diameter of pits, plate thickness, etc.), the program will output the reduction in thickness for the panel in question.

Utilizing a range of pit depths, diameters and frequencies with the program, a series of graphs were then created reflecting the predicted thickness reductions for varying parameters. These graphs can be used by field inspectors in estimating the residual thickness corresponding to a set of pitting measurements without having to run the PIT program. The field inspectors will thus have a decision making tool for use in assessing the plate panel's residual strength using a separate graph of spacing versus residual thickness.

A simplified approach for using the proposed decision making tool is presented in Appendix D of the report.

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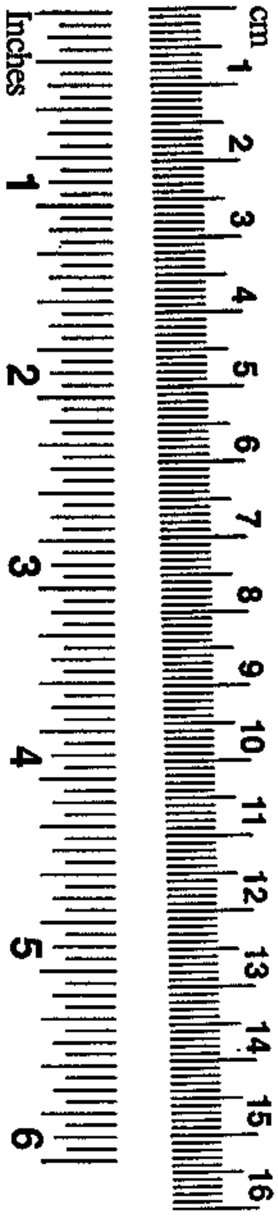
METRIC CONVERSION CARD

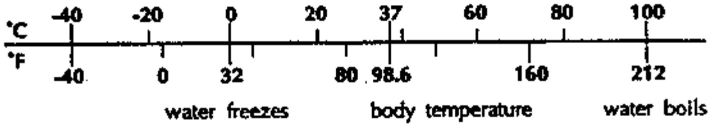
Approximate Conversions to Metric Measures

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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1. INTRODUCTION

Corrosion may be defined as the wastage that occurs in otherwise whole metallic structure or components. It has a large impact on the economic viability and the useful life of a ship.

In a Ship Structure Committee report, Stambauch and Knecht [1][1] identify eight classifications of corrosion with a certain degree of overlap existing among them.:

1. General (Uniform)
2. Galvanic
3. Crevice
4. Pitting/Grooving
5. Intergranular
6. Selective Leaching
7. Velocity Corrosion
8. Stress Corrosion Cracking

As examples, an increase in the general corrosion rate can be due to erosion corrosion caused by high velocity drainage in way of poorly designed cutouts, corrosion due to trapped water, and/or stress corrosion due to flexing of less rigid structure.

The two types of corrosion found to occur most frequently on ships are general corrosion and pitting/grooving corrosion. General corrosion appears in the form of rust over unprotected steel surfaces in the internal spaces of ship's tanks. Pitting corrosion is a localized type of corrosion occurring on bottom plating and other horizontal surfaces taking the form of a cavity and usually growing in the direction of gravity. This report is concerned with pitting and grooving corrosion.

A schedule of steel renewal or other corrective action can be easily established when the wastage is due to general corrosion. However, when deep pitting is present, the schedule is not as readily determined. The strength of steel plating and structural members is dependent not only on the depth and diameter of pits, but equally on the locations and frequencies. The limit to which pitting can occur before corrective action must be taken is often decided upon subjectively and best determined on a case basis.

This report presents a tool to evaluate the residual thickness and strength of a pitted plate and help make a quantitative judgment on whether to repair or replace the plate. The remainder of this Introduction discusses pitting corrosion and those characteristics of vessel construction, maintenance and operation which affect it. Section 2 presents the results of a literature search into guidelines for addressing pitting corrosion in practice, data available on pitting damage, the effect of pitting on vessel strength, and

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[1] Numbers in brackets denote references in Section 8.

mathematical models for predicting pitting. Section 3 develops a new mathematical model for the prediction of pitting. Section 4 considers the effect of pitting on vessel strength using the results of the model. Section 5 presents a decision-making tool for use by inspectors derived from the model presented in Section 3. Conclusions are given in Section 6 as and Recommendations offered in Section 7.

1.1 Pitting Corrosion - An Overview

Pitting is a localized type of corrosion that occurs on a ship's steel structures that are in contact with water (such as the bottom and side shell plating) or subject to wind and water conditions (such as the boot topping area) as well as in the tanks carrying liquid cargoes or ballast. Excessively deep pits can lead to perforation of the plate and possibly to serious pollution. Pitting does not occur in areas of plating that are not immersed in water and/or subject only to spray.

Pitting is self-generating (i.e., autocatalytic), starting from impurities or inhomogeneity in the metal or from scale or other deposits [1]. Pitting corrosion, if left unchecked, can cause severe problems on the horizontal and internal bottom surfaces of tanks in the form of loss of strength and hull integrity resulting in leakage and possible pollution. This type of corrosion is most prevalent in cargo and cargo/ballast tanks of oil carriers and, to a lesser extent, in the ballast spaces of tankers and other types of vessels. In unprotected tanks, most corrosion affects the higher velocity flow paths of the drainage pattern than the stagnant areas. This can cause a specialized form of pitting called groove pitting which generally occurs along welds of seams and stiffeners in the way of flow. It can also occur on the vertical members and flush sides of bulkheads in areas subject to flexing. One other typical finding on bottom plating, and sometimes on other structure, is preferential corrosion of weld seams and butts. Often when this occurs, the welds have corroded up to 3-5 mm more than the surrounding plate. The most likely reason for this attack is galvanic action causing the anodic weld material to corrode in preference of the surrounding plating.

Weber states in [2] that the internal surface of the bottom plating is perhaps the most commonly inspected area on a tanker. The primary concern for the bottom is the determination of the type and extent of wastage in the form of general corrosion and pitting. Even very good ultrasonic readings, taken to show general corrosion wastage, will give no indication of severe pitting problems that can perhaps threaten the oil-tight integrity of the vessel.

An example of pitting corrosion, as viewed during an inspection, has been described by Munger in [3] as follows: "Pitting occurred on all horizontal surfaces... in the cargo/ballast and cargo only tanks. .....The pits increase in size from upper horizontal surfaces to the bottom. ....Corrosion anodes (pits) had a bright red oxide upper surface with a soft black pasty material between the surface and the steel. The steel below the black was bright. The edges of the anode pits were sharp and distinct with the cathode areas being covered with a very tightly adherent black scale 2mm to 3mm in thickness.

There was a light, whitish crystalline deposit over most of the tank surface. ....The deposit might have been mistaken for the white calcareous deposit from cathodic protection; however, in this case there was no cathodic protection present. ....The whitish deposit had very much the appearance of the sulfur deposit which is common on the surfaces of sewer manholes and the crown of tanks. It was evident that sulfur was present in these tanks, as a 10-karat gold ring and silver coin became tarnished on exposure to the tank atmosphere. ....Cathodic protection (presumably cathodic protection only) in the oil-ballast tank did not appear to be of any value.....Permanent ballast tanks do not show the same corrosion pattern. Up to that time (March 1976) the horizontal surfaces in crude oil and crude oil-ballast tanks reacted in a similar way even though coated (although presumably not fitted with cathodic protection). It had been true with inorganic zinc or organic coatings. The number of pits on coated surfaces were reduced; however, wherever there have been both low spots in the tanks which may have accumulated water, or where there have been coating imperfections, such as pinholes, dirt, holidays or over spray, pitting has occurred in the same manner as described above. Pitting observed on coated surfaces was observed to be equivalent to or greater than the pits found on bare steel.

The pitting reactions on the horizontal surfaces in crude oil tankers is very complex. The intensity of the corrosion process is many times that of steel subjected to seawater..."

1.1.1 Pitting Corrosion in Cargo/Ballast, Cargo, and Ballast Tanks

Eleven of the twenty-three vessels surveyed by the Tanker Structure Cooperative Forum, TSCF - 1986, [4] had significant corrosion problems in their cargo/ballast tanks. All eleven of these experienced bottom pitting corrosion and six experienced general corrosion. In crude oil cargo tanks, seven of the twenty-three vessels had significant corrosion problems reported. Of those, six experienced bottom pitting and five experienced general corrosion. One weld related pitting corrosion problem was reported and attributed to the use of incorrect filler metal. The fewest significant corrosion problems were reported in the ballast tanks. General corrosion was the principal type cited requiring extensive steel renewals every 10 years in uncoated ballast tanks. No bottom pitting corrosion was reported in the ballast tanks.

As mentioned above, pitting corrosion in tankers is most notable on the bottom shell and on other horizontal surfaces. Pitting is severe in cargo tanks where coatings can develop small local failures. In this case, the pit depth can be larger than its diameter. In uncoated tanks, as pitting progresses it can form shallow but wide pits resembling general corrosion. This pitting can be very severe in cargo/ballast tanks used to carry, alternately, sour crude oil cargo and dirty or clean ballast. Sour crude oil contains hydrogen sulfide, which can form sulfuric acid (due to the environment in the tank). This acid can penetrate imperfections in coating and cause accelerated corrosion, especially if there is no efficient secondary cathodic protection to slow the process.

Bottom water wedges, caused by a combination of unstrippable ballast water and water settling out from cargo, accumulate normally in the bays of cargo/ballast tanks. Thus, bays of cargo/ballast tanks can experience corrosion almost continuously [2]. Pitting is most prevalent in the aftermost two bays of tankers that trim by the stern in the full load condition [5]. On stringer platforms, pitting is very common; its occurrence may be aided by the effects of fluids dripping from structure higher in the tank [2]. Under bellmouths, pitting may be accelerated by the velocity of discharge, sometimes causing penetration of the shell [1].

1.1.2 Pitting Corrosion and Tank Washing

The effect of pitting in cargo/ballast tanks is apparently increased by the use of salt water wash which is used to prepare the tank for ballast or different cargo. Salt water washing is especially detrimental if heated. Washing tends to remove the oily residue which serves to protect the structure [6]. The residue of washing and the other sources mentioned above combine. This repeating sequence of carrying sour crude, washing, and then carrying salt water ballast creates a corrosion promoting atmosphere. Washing with crude oil can reduce general corrosion by maintaining the oily residue left on the tank [1]. However, high pressure washing of any kind tends to erode coatings and can cause local breakdowns enhancing the chances for pitting corrosion.

1.1.3 Pitting Corrosion and Gasoline or Home Heating Oils

Gasoline cargo is rich in oxygen which promotes general corrosion. Additionally, gasoline does not provide the coating that crude oil provides, leaving surfaces within tanks unprotected from the oxygen. These two factors unfortunately combine to cause accelerated general corrosion in tanks carrying gasoline.

Home heating oils have a coating property similar to that of crude oil which gives protection to the structure until washed. Tanks carrying home heating oil do not experience the accelerated pitting corrosion as tanks carrying sour crude oil.

A respondent to a questionnaire of the TSCF stated that the probes had determined that "corrosion" rates were more severe during the ballast period in a cargo/ballast tank, and more severe during the "empty" period in a cargo only tank. Another opinion was that severe localized pitting occurs immediately following hot washing. General corrosion is also more severe during ballast or empty periods. Generalized pitting occurs in the aftermost two bays of cargo only tanks during or after the phase because of the acidic water which accumulates at this location due to trim [1].

1.1.4 Pitting Corrosion and Gas Inerting

Most agree that inert gas has rust preventive properties only above the normal cargo level but that it does not prevent localized pitting of horizontal surfaces [7]. However, when the inerting gas used is high in sulfur content, gas inerting has also been found to accelerate corrosion. Sulfur compounds in the inert gas combine with the water in the tank atmosphere or residual water in the crude oil to form sulfuric acids which attack the coatings or steel [7].

In non-inerted empty tanks, high humidity can provide a corrosion inducing environment. This effect can be increased if the tank is adjacent to one carrying heated cargo. Also, the level of humidity can be influenced by the navigational route [6].

1.1.5 Pitting Corrosion and Coatings

For coated cargo/ballast tanks, wastage can take the form of localized pitting and grooving in way of coating failure. With inorganic zinc (IZ) coating, the wastage will tend to be in scaly patches with only minimal thickness loss. IZ coating for cargo tanks is only recommended for use with the carriage of sweet oil (low sulfur content). It is not recommended for tanks containing sour oil or those containing sulfur compounds [7]. The main advantage of IZ coating is that it acts as an anode to protect any pinhole failures in the original coating. Thus, the coating will hold up very well over a number of years to protect exposed plating. The main disadvantage is that the zinc is gradually consumed and when failure occurs, corrosion is very rapid. Corrosion in pin holes may then be accelerated. IZ is affected by inert gas and therefore is seldom used for cargo service. In addition, it is not recommended to use IZ for partial coating systems for, in this service, the zinc in the coating will act as an anode and will be rapidly consumed by the unprotected steel.

Due to the above-cited reasons, coal tar epoxy (CTE) is the preferred choice for cargo tanks and partial coating systems. For recoating of ballast tanks, CTE is also the preferred choice simply because it is difficult to achieve the required surface preparation for IZ on the corroded steel [2]. For CTE coated tanks, unchecked wastage will tend to be deep pits of limited area. These pits present a definite risk of bottom penetration at this location if not repaired as their rate of growth can be quite rapid [2]. Unlike IZ, CTE is not consumed through galvanic action and protects by forming a protective barrier. In way of pinholes or other failures in the coating, pitting and grooving will occur, sometimes at a very rapid rate, particularly in horizontal platforms and bottom shell plating. This pitting and grooving also occurs under bellmouths where there are erosion forces on the coating. For this reason, Weber recommends in [2] that a light anode system ($22 mA/m^2$ current density) be used in conjunction with an epoxy coating system. Larger bellmouths may also be utilized to reduce the flow velocity causing erosion. The failure of CTE coatings occurs gradually over time. The expected life of CTE is thought by some to be greater than IZ.

As stated by reference [8] "it is estimated that no more than 2 or 3% of all coatings ever fail because of the paint itself." Coating failures, however, can be linked to steel preparation for coating, application and curing, cargo washing and flexing of structure in a seaway.

1.1.6 Pitting Corrosion and Cathodic Protection

Cathodic protection when installed to obtain the appropriate field strength by choosing the correct current, number of anodes for the tank and by their proper placement, can retard corrosion. The proper field strength is high enough to prevent corrosion but not so high as to damage coatings. Proper anode placement is mandatory when the tank has only residual liquid remaining on the bottom. In such cases, anodes must be submerged in the remaining liquid to be effective. A tank protected only by anodes will likely experience corrosion on unsubmerged surfaces. Thus, the use of a combination of coating/anode protection in the form of epoxy/zinc anode or CTE/zinc anodes is recommended.

Coal tar epxoy, being black, makes inspections difficult. It is no longer used in the U.S. shipbuilding industry due to the fact that it is a known carcinogen [9]. Some lighter color applications of this substance are available. However, it is still being used and specified by the Japanese shipbuilders.

Aluminum anodes are considered more effective than zinc anodes both in field density and cost. However, there are safety problems with aluminum anodes due to sparking when dropped onto steel. In addition, regulations limit the height at which aluminum anodes can be mounted in cargo oil tanks thereby dissuading their use. Proper, specially designed holders need be used with aluminum anodes to prevent them from coming loose. Also they must be protected against the occurrence of items falling from above and striking an exposed aluminum anode, possibly causing sparks.

For short voyage durations, the correct current density may not build up and the cathodic protection system may be rendered almost useless. It can take from four to five days for zinc anodes to stabilize and polarize an area. This is especially possible if they are covered with an oily residue in a cargo/dirty ballast tank on a ballast trip. However, it is considered that aluminum anodes are self-cleaning of this oily residue and may stabilize and polarize more quickly, even on relatively short voyages. On the other hand, there is some thought that this same oil coating helps retard corrosion on the remainder of the tank until zinc anodes become effective. Therefore, in the majority of cases (and for the reasons enumerated above), zinc anodes are used over aluminum anodes. All anodes must be replaced as they waste away or as the system becomes ineffective.

As stated by one owner, "anodes can be inexpensive and relatively effective if the anode system is designed properly. Using our current densities we believe we achieve a 70% reduction in corrosion rates. Limited data indicate this to be a reasonably good assumption. So we use 30% of unprotected corrosion rates" [2].

1.1.7 Impressed Current Systems

Impressed current systems provide cathodic protection by superimposing a direct current from an external power source on the steel surfaces to be protected. In this manner, the need for local sacrifical anodes are eliminated, and the steel surfaces themselves become complete cathodes.

By maintaining the proper amount of electrical potential, corrosion in general and pitting in particular can be prevented. The impressed current systems are also capable of providing additional current to compensate for any coating breakdowns and the consequent increase in the amount of protection needed. However, over-protection should be avoided since it could lead to an acceleration of the pitting rate.

1.2 High Strength Steel and Corrosion

When high strength steel is used in the construction of a vessel, the plating is thinner than in comparable mild steel construction. High strength steel, of resultant thinner thickness, corrodes at the same rate as mild steel. The result is that the higher strength steel has less wastage allowance and will hence have to be renewed sooner than its mild steel counterpart. In addition, a structure constructed of high strength steel, due to its thinner plating, is usually less stiff than a comparable mild steel structure. This lack of stiffness can cause flexing of composite parts, increasing the risk of general stress corrosion. Flexing can jeopardize the surface coating and allow corrosion to initiate. Continued flexing can break the surface of corrosion and allow new steel to be exposed to the corrosion process. This causes corrosion to accelerate above the rate that would have taken place had the member been thicker and been subject to less flexing.

2. LITERATURE REVIEW

Relevant literature was reviewed to enable encapsulation of the existing guidance available on the prediction and treatment of pitting in plate panels. This review was the starting point in arriving at the final objective of this report, i.e., the means of prediction and strength evaluation of pitting effects on the vessel. The materials reviewed are listed in the references and bibliography at the end of this report in Sections 8 and 9. Within the topic "Existing Practices", guidelines; printed pit data; and strength criteria were sought as starting points upon which to improve. Existing pitting models endeavoring to quantify the pitting phenomenon, with regard to determining residual plating, were also evaluated. The results of this review are presented in the following subsections.

2.1 Existing Practices

Regulatory and statutory guidance for determining the residual strength of pitted plates does not exist. Several agencies provide some guidance regarding the replacement of pitted plates based on empirical measures related to the amount of wastage observed. Neither the U.S. Coast Guard nor the classification societies specifically refer to the residual strength that can be expected from a pitted plate panel.

2.1.1 Guidelines

Table 2.1 lists several sources which were surveyed with regard to their treatment of pits. The table should not be considered complete since not all entries were fully available. Where information was lacking or unobtainable, the table entries were left blank. As noted in the table, the American Bureau of Shipping (ABS) allows a maximum 15% area loss due to pitting in the cross section of a plate before replacement is required. The TSCF, ABS, and two oil companies surveyed, were found to give specific information for repair, but did not indicate residual strength expectations. In general repairs are based on the intensity of pitting as shown for example in the TSCF diagram, Figures 2.1 and 2.2.

Treatment for pitting corrosion usually consists of filling the pits with epoxy, as long as the depth of the pit is not greater than 50% of the plate thickness and the cross-sectional area lost is not greater than 15% in any transverse section of the strake. Welding of the pits is allowed as long as there is at least 1/4" of material remaining at the bottom of the pit, at least 3" distance between adjacent pits and the maximum diameter of any pit does not exceed 12 inches (from ABS Surveyor guidelines, [Circular 453 Index 1.2.1, 29 August 1990) [10]]. Similar treatments of pitting corrosion have been found to be practiced by others.

Coating of pitted surfaces after repair is referred to the original coating manufacturer. Suggested specific guidelines for surface preparation, application and curing may be different with different coatings and coating manufacturers.

TABLE 2-1
Current Practices for Corrosion and Pitting Control in the Bottom of Tanks in Tankers

Reference	Allowable Bottom Corrosion Wastage	Buckling*	Pitting wastage	Repairs	Intensity diagrams	Diameters	Thickness	Notes
USCG NVIC 7-68 Bibl. [14]	Average 20% from original in 1/2t Locally 25%				no	no	no	
TSCF [4]	10-20% on Rule "t"	s/t = 55-50 MS s/t = 49-52 H36		Pitting or grooving filled by welding Shallow pits with synthetic materials	yes	Asks for Max & Aver	Asks for Max & Aver	Has specific instruc. for gaugings pp175-183
ABS [10]	Bottom area. wastage 15% for single btm and those built before 1962. 20% all others	Max s/t = 65 MS Max s/t = 60 H32 Max s/t = 55 H36	15% max area loss in plt X-section or replace	15%t wasted just repair coating Sctrd up to 50%t wasted - epoxy filled. Any depth welded if 1/4" remains provided 3" betwn pits and none > 12"	no	no	no	Has reqmts for girth gauging during Special Surveys
Lloyds Reg. Bureau Veritas [20]	25% of original thickness minus constr. margin (actually rule "t") Check residual longl. strength							Has reqmts for girth gauging during Special Surveys
Nippon Kaiji Kyokai [6]	20% + 1mm subject to verification of residual longl. strength.							Has reqmts for girth gauging during Special Surveys
EXXON [6]	SM = 15% below rule min or 18% on area 85% rule t or 75% design less owner extra			Pit & groove < 1/3t recoat Pit & groove > 1/3t weld Pit & groove > 2/3t renew				Replace plate with groove & Buckling., Fract, Perm. Defmtn due thinning or loss of w.t. intergrity
Chevron Bibl. [27]				Pits < 8mm epoxy Pits > 8mm weld				

S/T: Plate Aspect Ratio (Spacing/Thickness).

FIGURE 2.1

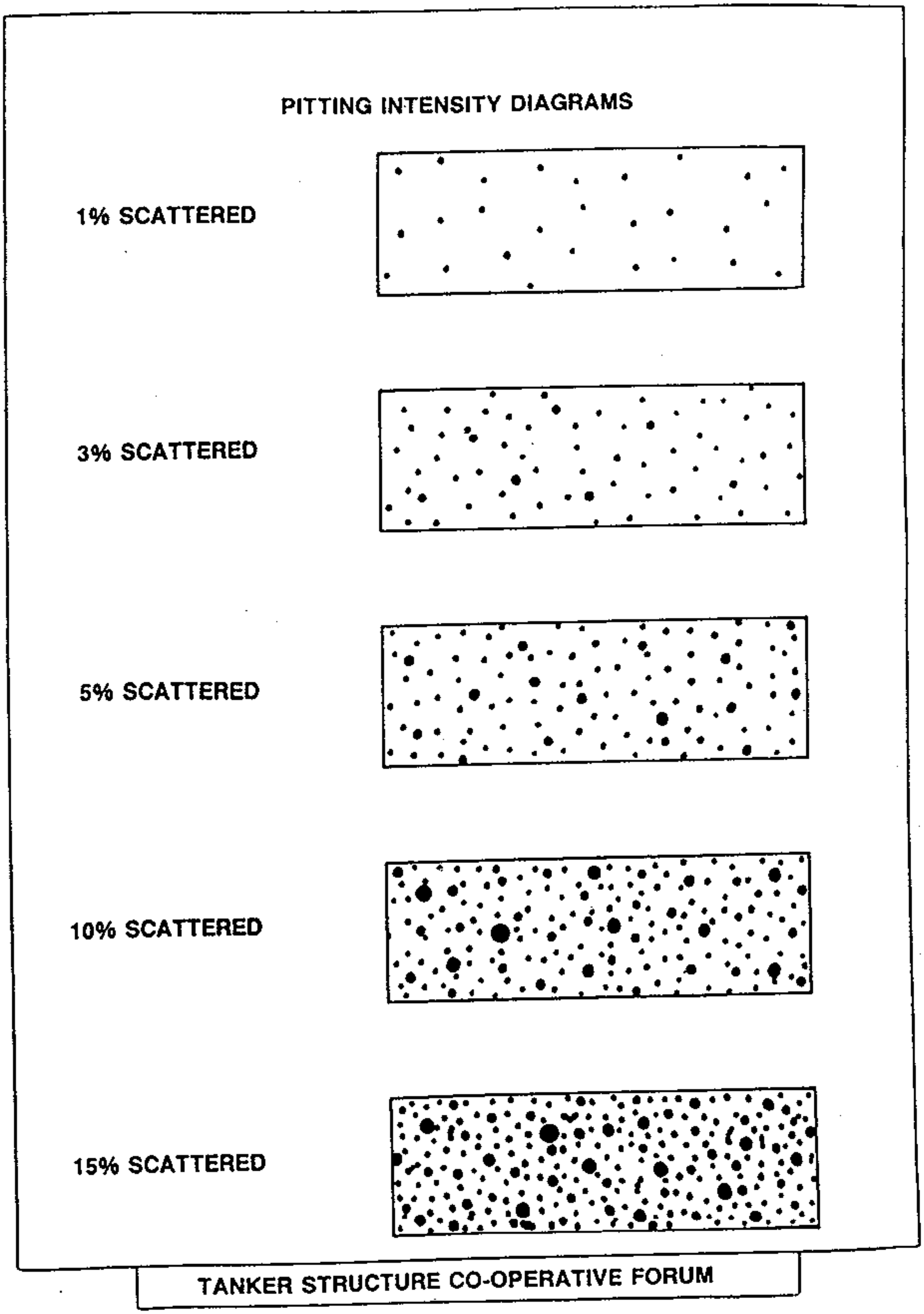
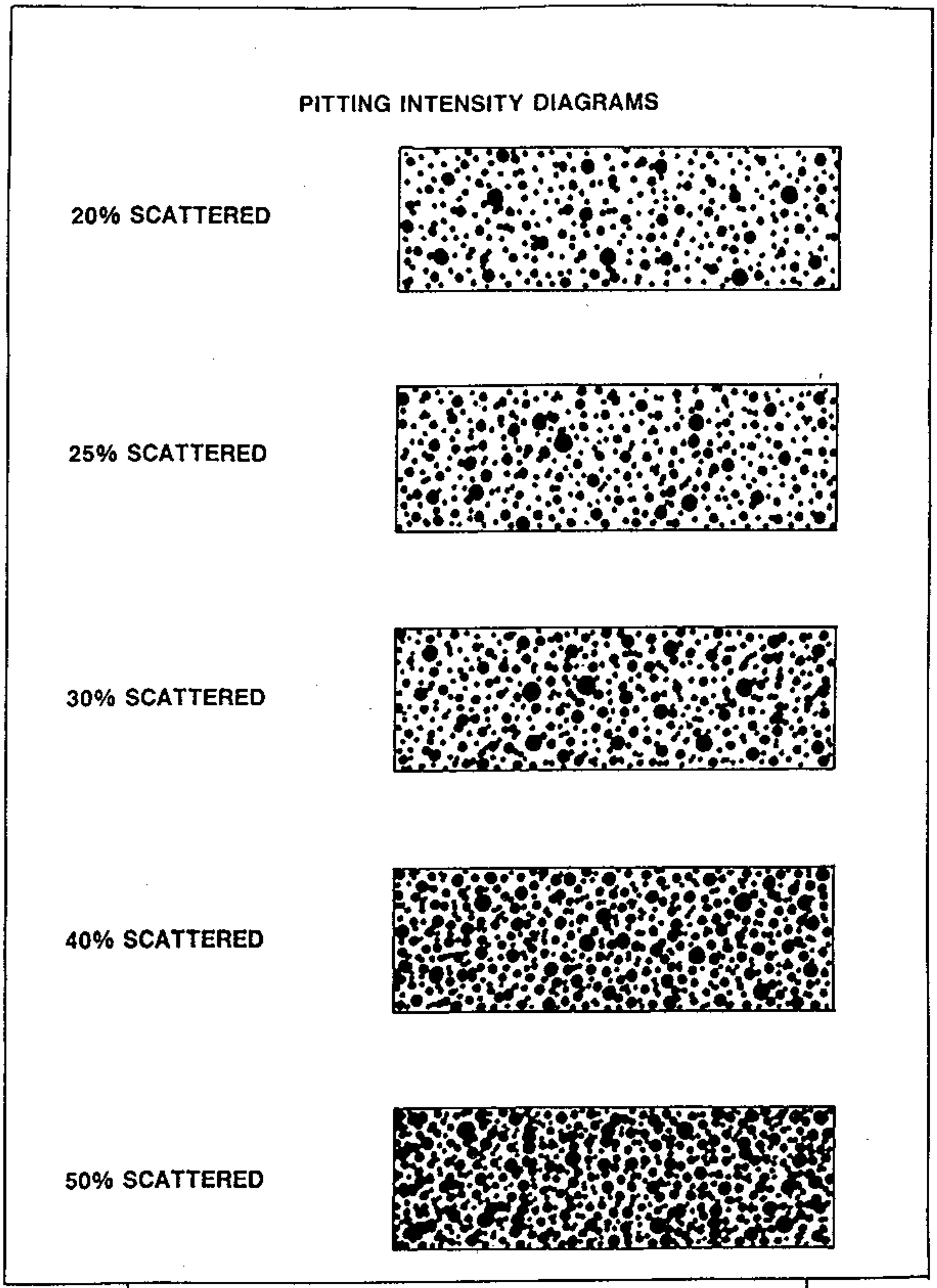

PITTING INTENSITY DIAGRAMS
1% SCATTERED
3% SCATTERED
5% SCATTERED
10% SCATTERED
15% SCATTERED
TANKER STRUCTURE CO-OPERATIVE FORUM

FIGURE 2.2



TANKER STRUCTURE CO-OPERATIVE FORUM

2.1.2 Pitting Data

Existing pitting data in the literature are not generally obtainable in a form that allows determination of the full extent of pitting or residual thickness for individual plates. Some data in the literature do give specific pit dimensions for a representative sample but again do not contain enough information to determine exactly how much residual plate remains.

Actual pitting data, received from two oil companies, were quite detailed. The method of data collection allows these companies to forecast problem areas as well as perform needed repairs. However, again the information presented was not conducive to determining individual residual plate thickness remaining. These records were very helpful in calibrating the prediction method contained in Section 3 of this report "Mathematical Pitting Model".

The existing TSCF guidelines on data collection for pitted plates were adopted, with slight modification, as a means to "seed" the decision making tools discussed in Section 5 of this report.

2.1.3 Residual Strength Determination

TSCF Project 300 on the effects of pitting upon the strength of plates [11] undertook a study to determine the strength of uniformly machined - pitted plate models subjected to bending with uniform pitting intensities of 14, 23.5 and 35.5 percent, and uniform variation of pit depth from 5mm to 15.4mm. The tests determined the residual thicknesses of plate by using the edge deformations of pitted and unpitted plate panels. The results of the tests showed a 25.8% maximum reduction in bending capacity for the plates in the tests.

The major concern with pitting is with regard to bottom plating which is under bending and biaxial loads. The tests of Project 300 were conducted on uniformly pitted plates under bending loads only. There was no simple expression provided to determine the residual thickness of the plate for the uniform distribution of pitting investigated. There was no reference to non uniform pitting. The investigation of Project 300 accomplished an important step in determining the residual strength of pitted plates; however, it was not deemed sufficient for use in developing a method for determining the residual strength of randomly pitted plates considered in this project.

2.2 Existing Pitting Models

SSC-372 [9] depicts a model for predicting the residual thickness of pitted plate based on a homogenous plate of reduced thickness based on the average volume and density of pits. This reduced plate is derived by using the uniform distribution of an average pit from inspection data to create a mesh arrangement of pits. No evaluation of residual strength is provided.

CGCORA, a U.S. Coast Guard computer program [12] developed by White and Ayyub, uses "Kriging" and "Semi-variogram Analysis" with the input of plate dimension. "Kriging" is a technique often used for the optimal interpolation of spatial phenomena or data. "Semi-varigoram Analysis" essentially describes the statistical relationship or correlations between values of physical parameters at various locations in a spatial domain. In this program the actual, accurate pit locations and depths of a number of pits must be used to predict the remaining plate thickness available; no evaluation is made of the residual strength of plate.

3. MATHEMATICAL MODEL FOR RESIDUAL STRENGTH ASSESSMENT

3.1. Typical Inspection Data

During ship structural surveys, pitting is one of the damage modes to be inspected. Inspections are conducted using ultrasonic instruments or pit gauges. Pitting data and other structural damages are recorded on forms for data analysis at a later time. However, until now, no standard procedures for pitting data analysis have been established or has much research been done regarding the strength degradation due to pitting. This section presents mathematical models to estimate the effective thickness of a pitted plate that have been developed in this report.

When using the TSCF method, the inspectors usually physically climb into tank bottoms to inspect the extent of pitting. To perform this pitting analysis, seven numbers must be recorded for each area inspected that is usually confined by longitudinal stiffeners and transverse structure. A visual assessment of the pitting intensity for the entire area is made using the Pitting Intensity Diagrams as a guide. The **intensity percentage** is recorded as the first entry. The **depth of the deepest pit** within all adjacent areas is measured and recorded as the second entry. Then a 300 mm x 300 mm (12" x 12") sample square which is regarded to be most representative of the pitting in the area being inspected is selected. The following five measurements from this representative square are recorded: [4]:

- **Frequency** - The number of pits in the square.
- **Average Depth** - The depth in millimeters of the pit regarded as having the average depth for the square.
- **Maximum Depth** - The depth in millimeters of the deepest pit in the square.
- **Average Diameter** - The diameter in millimeters of the pit regarded as having the average diameter for the square.
- **Maximum Diameter** - The diameter in millimeters of the largest pit within the square.

Because of the large number of pits that could exist in a vessel's tanks (see Table 3.1 for example), it is almost impossible to measure and record every single pit. Following the data collecting procedures described above, there will be only seven pieces of data required for a large plate panel section that can be many meters in length and width. One of the purposes of pitting surveys is to check if the residual strength of a pitted panel is still within the design criteria or rules. If a pitted plate is proved to have enough strength to continue its service, the plate may not need any repair. On the other hand, a heavily pitted plate that is a potential hazard to the safety of the ship will need repair before the ship can go in service again. To make a judgment on whether or not a pitted plate has sufficient residual strength, a criterion needs to be developed. In the criterion, a variable such as an effective or equivalent thickness of the pitted plate needs to be defined. In the following section, a mathematical model is developed to interpret the above data into an effective thickness (or a thickness reduction) for the panel.

3.2. Problem Definition

The ultimate goal of this work is to assess the strength of a pitted plate. The scope of the problem is first limited to the small **300x300 mm sample square** identified by inspectors. The sample square is chosen to characterize the most representative of the pitting on the entire adjacent plate panel area that is under consideration. A pitted plate inevitably has less strength than its original condition simply because of the reduced thickness due to pits. Historically thickness has been considered as the variable affected by pitting. As pitting affects the geometry of a panel and translates directly to mateial wastage, the use of thickness has a physical significance. It is also relevant to an inspector when measuring depth of pits and considering their suitability as compared to plating affected by general corrosion. Other candidate variables may not exhibit this same significance as, for example, elastic modulus, which is an instrinsic material property and is not dependent on geometry. As a result, thickness has been adopted as the variable to be considered within a criterion for pitting.

An effective thickness can be defined as the thickness of a non-corroded plate that has the same strength as the pitted plate. If the strength considered here is yielding in tension (see Figure 3.1), then the effective thickness is the smallest cross sectional area divided by the plate width.

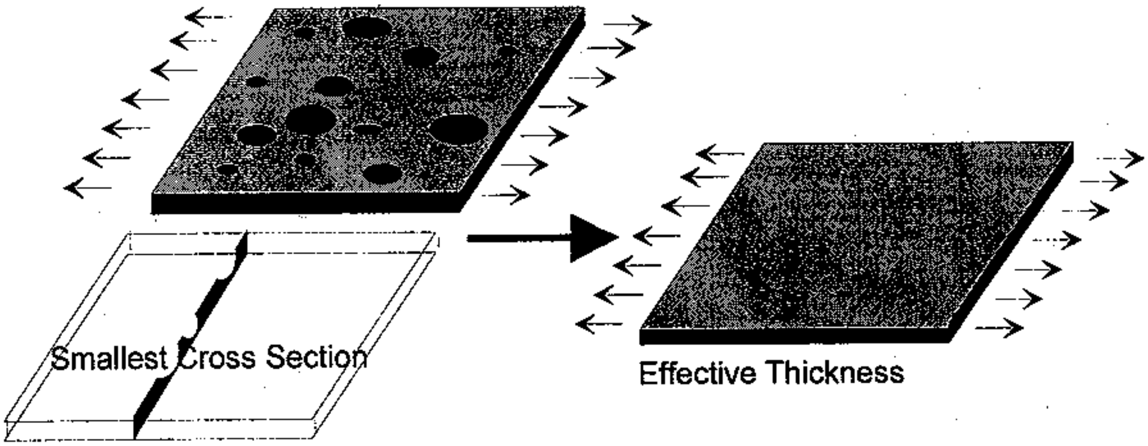


Figure 3.1: Definition of the effective thickness by equivalent cross section area.

When considering another type of strength, a different definition of the effective thickness may be needed for the same pitted plate, and the definition has to be verified by experimental results. Any variation of the definition of thickness will depend on the variation of the strength with thickness and volume. For example, in the case of buckling, the thicknesses could be determined by a reduction of the effective radius of gyration of an average strip of the plate. In this case, the assumption of an effective thickness based on volume reduction is conservative. However, in order to make the problem easier, a universal definition of effective thickness is now developed, that can be used conservatively (since thickness is reduced linearly with volume) to yield approximate results for all kinds of failure modes. One can consider a thickness reduction Δt that is formulated by spreading the lost steel volume evenly over the area of the plate as:

$$\Delta t = \frac{V}{A} \tag{3.1}$$

where A = the area of the square. By the assumption above, this is 300 mm x 300 mm, according to the previous definition of the square, and V = the total lost steel volume due to pitting.

Then the effective thickness can be defined as:

$$t_{eff} = t_o - \Delta t \tag{3.2}$$

The ultimate goal is to find the thickness reduction due to pitting (or the effective thickness, if the original thickness is given). Two approaches have been developed to achieve this goal; one approach uses the average and maximum values of pitting data (Section 3.3) and the other uses the number of deepest pits (Section 3.4). Both approaches are described in the following subsections.

3.3. Mathematical Model Using Average and Maximum Pit Data

To determine the effective thickness of a pitted plate, it is necessary to obtain the volume loss of steel due to pitting, V. Ideally the volume loss can be calculated by taking measurements on each pit and summing up all the pit volumes. The volume loss can be expressed as:

$$V = \sum_{i=1}^{N} c_i a_i d_i \tag{3.3}$$

where a_i and d_i are the area and depth of pit 'i', respectively. The quantity c_i is the cylinder coefficient defined as the actual pit volume divided by the corresponding cylinder of depth d_i and top area a_i. The parameter c_i has the range: $0 < c_i \leq 1.0$, in which a value of c_i = 1.0 corresponds to a pit whose shape is actually (perfectly) cylindrical. Finally, *N* is the number of pits in the 300x300 mm sample square.

However, due to the large number of pits, it is very impractical to measure all pits in a ship. In one example of a structural survey on an old tanker, there were as many as seven thousand pits (see Table 3.1); the number of pits can be as high as one thousand or more for a single tank. As for a plate panel that is surrounded by two transverse webs and two longitudinal stiffeners, the number of pits may be up to a hundred. Consequently, general time constraints encountered during a typical structural survey limit data taking to only a few representative pits for one area of adjacent plate panels. As previously described, the method developed limits the data to only seven inputs for a representative area. A mathematical model has been developed to estimate the steel volume loss due to pitting by using this limited data. The mathematical model is based on a probabilistic approach and was developed to process the limited input data.

The model assumes the pit depth *d* and the pit width (diameter) *w* to be random variables following lognormal distributions. The reason for choosing lognormal distributions to model pit depths and widths is its non-negative property. Other probability distributions that deal with only positive values include Chi-square, Gamma, Gumbel, Rayleigh, Extreme Type II. Any of these distributions can be a candidate to be applied to the developed mathematical model. The only restriction on the method is that only two parameter distributions can be used. The approach has difficulty solving for the extra parameter when three parameter distributions are used.

It is not known which probability distribution produces the best fit for pitting data. Selecting lognormal for this model does not imply that it produces a better fit than any other distribution candidate. To determine which distribution fits pit depth or width data the best, a sufficient number of pitting measurements on the depth and width of each pit in a field has to be supplied. Unfortunately, such data are generally not available as they are expensive to gather. Most of the existing survey reports record only the number of pits and the deepest pits. Some more detailed survey reports list the size of pits deeper than a certain limit (for example, 12 mm) in order to monitor and track pit growth. For the shallower pits, no measurements were collected. This is due mainly to the large number of shallower pits and their apparent insignificance. If a complete set of pitting measurements are available, the corresponding distribution can be determined by classical statistical inference procedures. Two common methods in this connection are the method of moments and the method of maximum likelihood [Ang & Tang, 1975] [13]. It is recommended that future work be commissioned to take measurements from different types of ship tanks and determine the probabilistic characteristics of pits directly from these data.

With due consideration of the above, the current work was accomplished by solely using lognormal distribution. An evaluation of the process is presented in Section 5.3.

The probability density function of lognormal distribution is expressed as:

$$f_X(x) = \frac{1}{\sqrt{2\pi}\zeta x}\exp\left[-\frac{1}{2}\left(\frac{\ln x - \lambda}{\zeta}\right)^2\right] \qquad 0 \le x < \infty \tag{3.4}$$

where $\lambda = \mathrm{E}(\ln X)$ and $\zeta = \sqrt{Var(\ln X)}$ are, respectively, the mean and standard deviation of ln X, and are the parameters of the distribution.

The two parameters, mean and standard deviation of lognormal distribution, are now to be determined. Once these two parameters have been determined, a simulation can be performed on both pit depths and widths. Then an estimate of the steel volume loss can be computed.

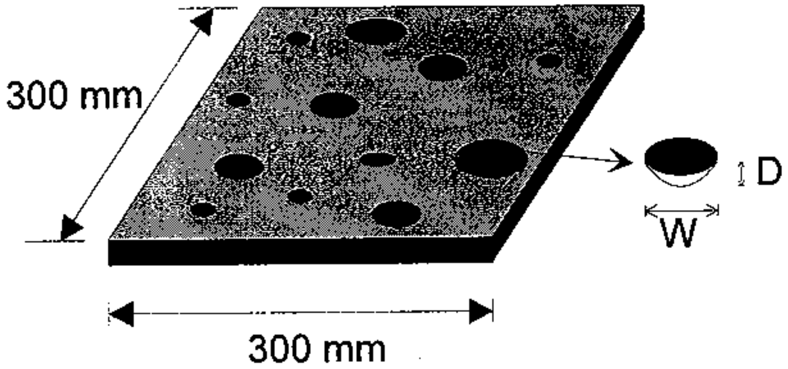


Figure 3.2: A representative sample square of the inspected pitted panel.

Consider the random variable *d* first. The mean and standard deviation of *d* in a sample square is determined, which is assumed to have a lognormal probability distribution. The averaged depth in a 300 mm x 300 mm (12" x 12") square is one of the seven known data items that are collected during inspection. Its value should be close to the mean of *d*. Therefore, it is simply assumed that the **averaged depth** is to be the mean, μ_D, of *d*. Then the only parameter left to be determined here is the standard deviation, σ_D. It should be noted that this assumption for the mean may not be accurate because the average depth comes from a pit measurement that is considered most representative of the average based on an inspector's human judgment. Later in this presentation another mathematical model is explored, which avoids this assumption but requires changes in the current pitting inspection practice.

Next, the second unknown parameter is considered, which is the standard deviation of the depth of the pits. The ideal way of calculating standard deviation is to measure all the pit depths in the sample square and input them into the following equations:

$$Var(D) = \frac{1}{N}\sum_{i=1}^{N}(d_i - \mu_D)^2 \tag{3.5}$$

$$\sigma_D = \sqrt{Var(D)} \tag{3.6}$$

Since the depths of all pits in the sample square are not available, σ_D cannot be calculated in this ideal way. A different method of calculating σ_D has been developed by utilizing the extreme value theory.

The total number of pits in the square is available as **Frequency** N. The pit depths in the sample square can be considered as a sample of N lognormal random variates. The **maximum depth** is therefore the extreme (largest) value of the N lognormal random variates. These two data together with the assumed mean depth can be used to predict the unknown standard deviation. Normally when the mean, the standard deviation and the total number of the random variates are known, the extreme value can be predicted. In our case, the extreme value is known already. Instead, the standard deviation σ_D is unknown. σ_D is then determined by trial and error as indicated below.

With a starting trial value of σ_D, a set of N lognormal random variates can be generated. The averaged extreme value of the set can be calculated. The trial-and-error iterations on σ_D are continued until an averaged extreme value matches the maximum depth. The estimate of the standard deviation σ_D is then determined.

With both the mean and standard deviation obtained, the exact distribution function of d is determined. The distribution of the other random variable W can be determined in the same manner.

Since the distribution parameters have been determined above, simulations on the pit depths and widths can now be performed. It is done by generating N lognormal random vectors as $\{(d_1, w_1), (d_2, w_2), \ldots, (d_N, w_N)\}$ where (d_i, w_i) represents the depth and width of the i_th pit in the sample square. To generate lognormal random vectors, one can first generate independent standard normal random variates [Press, 1989] [14]. Then transform the independent standard normal variates to correlated standard normal variates [Chang, 1994] [15]. There are several methods of transformations. Among those, Rosenblatt transformation [16] and orthogonal transformation are very popular. However, another method which is developed by Rubenstein [Rubenstein, 1981] [17] [Melchers, 1987] [18] is used in this study. Correlated lognormal random variates can be obtained by transforming the correlated standard normal variates.

It should be noted that the correlation coefficient, ρ_{DW}, between the depth and width is high (close to one), since a deeper pit tends to have a wider diameter. The parameter ρ_{DW} is a measure of the statistical dependence between two random variables d and w. It is defined as:

$$\rho_{D,W} = \frac{Cov(D,W)}{\sigma_D \sigma_W} \qquad -1 \leq \rho_{DW} \leq 1 \tag{3.7}$$

where $Cov(D,W) = E[(D-\mu_D)(W-\mu_W)]$,
E[ ]: expected value,
μ_D, σ_D: the mean and the standard deviation of D,
μ_W, σ_W: the mean and the standard deviation of W.

It would be valuable to gather actual measurements on pit depths and widths and calculate the correlation coefficient between them. However, upon searching existing survey reports in the industry for actual pit measurements, only an incomplete set of data from a survey report was found. The report was used to monitor and record the size growth of deeper pits, so only the sizes of pits deeper than 12 mm were measured. The report summarizes pit numbers in different tanks and depth categories. A summary of this report is reproduced in Table 3.1. The corresponding ship has a total of 7595 pits. The size of pits deeper than 12 mm (90 pits) are listed in Appendix A.

The correlation between the mean widths and depths of the 90 deep pits was analyzed. The correlation coefficient, ρ_{DW}, was found out to be about 0.4 which is lower than expected. The reason for this low correlation is due to the incompleteness of the data set. In order to find out the correlation coefficient for a complete set of data, the data for pits shallower than 12 mm were reproduced by re-scaling the sizes of the available 90 deep pits and distributing them uniformly to the range from 0 mm to 12 mm. The result turned out to be a correlation coefficient of 0.9. This number was used in this study. It is also recommended to be used in the pitting program developed in the study. It is a rough estimate and, however, the only currently available information on ρ_{DW}.

Table 3.1: Summary of pit number in a ship.

Tank No.	0-7.9mm	8-11.9mm	12-14.9mm	15-17.9mm	18-Above	Total
1 STBD	47	0	0	0	0	47
1 PORT	63	3	0	0	0	66
2 STBD	87	0	0	0	0	113
2 PORT	141	2	1	0	0	144
3 STBD	1366	167	9	4	1	1547
3 PORT	1255	127	8	1	0	1691
4 STBD	166	12	2	1	1	182
4 PORT	140	2	0	0	0	142
5 STBD (Ballast Tank)						
5 PORT (Ballast Tank)						
6 STBD	152	20	0	0	0	172
6 PORT	124	1	0	0	0	125
7 STBD	1247	306	21	4	1	297
7 PORT	1075	251	15	14	0	1355
8 STBD	333	13	7	0	0	353
8 PORT	359	46	0	0	0	1708
	6555	950	63	24	3	7595

To simplify Equation 3.3, assume a constant cylinder coefficient and round shapes for all pits. Applying the random vectors from the simulation, the wasted steel volume, V, can be computed by the following equation:

$$V = c \cdot \sum_{i=1}^{N} \left(\frac{\pi}{4} w_i^2 \cdot d_i \right) \tag{3.8}$$

By further assuming that all pits have a semi-spherical shape, the value of the cylinder coefficient can be obtained as:

$$c = \frac{V_{semisphere}}{V_{cylinder}} = \frac{\frac{1}{2}\left(\frac{1}{3}\pi w^2 d\right)}{\frac{1}{4}\pi w^2 d} = 0.667$$

Note that since d and w are random variables, V is also a random variable. Each simulation may produce different values of V. Therefore, sufficient simulation runs should be performed in order to determine the mean of V.

Once V is obtained the thickness reduction Δt can be calculated using equation 3.1 and the effective thickness that will be used in the strength assessment can be readily obtained by subtracting the thickness reduction from the original thickness as: $t_{eff} = t_o - \Delta t$. The advantage of this approach is that it utilizes all the pertinent information collected/recorded by surveyors under current practice. On the other hand, there are some disadvantages. The approach contains a number of assumptions that could cause uncertainties in the result. The assumption that may have the largest impact on possible results is that which considers the average depth and width recorded by inspectors to be the true mean of the pits in the sample square. The measurement of the average depth and width are taken on a pit and the pit is selected by inspectors based solely on their human judgment. The variation in selectively estimating the average depth and width by different inspectors may be large. The thickness reduction is very sensitive to these two data inputs. This and other sources of uncertainties, of which the inspectors should be aware when estimating thickness reductions, are listed below:

NATURE OF PITTING RANDOMNESS

Natural variation of pit depth & width

Coating and anodes: variation of protection over the entire plate making estimating difficult

Types of tanks (i.e. nature of corrosive environment)

DATA COLLECTION (Perhaps the most important source)

Human judgment on choosing the average and maximum pits to be measured

Selecting the most representative sample square

Errors in measuring equipment

Insufficient number of data

MATHEMATICAL MODEL

Predefined shape of pits

Assumption on probability distribution

Assumption on uniform distribution of pit locations

Numerical error in simulation

In summary, care should be taken while using this approach to adhere to as many of the assumptions as possible. The accuracy of this approach is dependent on how closely the assumptions compare with reality.

A FORTRAN computer program (PIT) which can be run on a personal computer, has been developed from the mathematical model to demonstrate the approach. A description of the program is given in Section 5.2 of this report and a listing of the FORTRAN code is provided in Appendix B. Using the PIT program, a series of graphs reflecting predicted thickness reductions were created. These charts are included in Section 5.1. The charts were designed for practical use in accordance with the findings and assumptions of this report. One of them is shown in below as Figure 3.3. In order to keep the number of graphs to a reasonable limit, considering that there are seven input parameters of the developed math model and program PIT, the following additional assumptions were made:

- Lognormal distribution of w and d
- Mean pit width is a function of mean depth as '$\mu_W \cong 2.5\mu_D$'
- COV of d & w are both 20%
- Correlation between d & w is 0.9
- Pits have semi-spherical shape

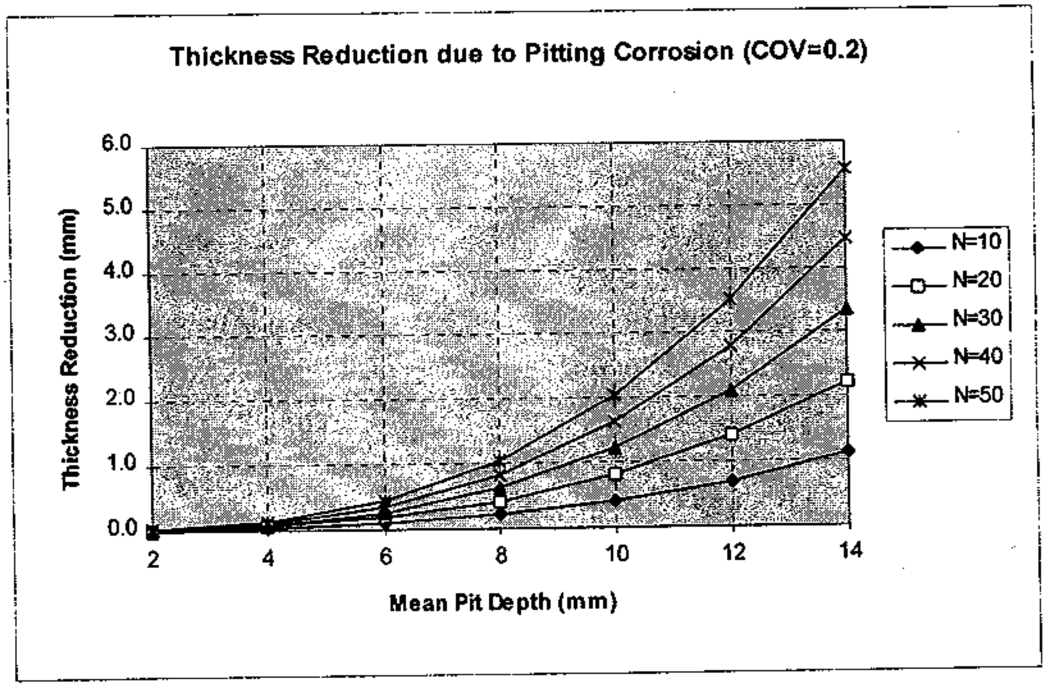


Figure 3.3: Thickness reduction as a function of mean pit depth and pit number (N = number of pits in a sample square of 300 mm x 300 mm)

3.4 Alternative Proposed Mathematical Model Using the "r" Deepest Pits

In order to overcome the difficulty associated with the potentially large variations in the inspector selected average depth and width of pits, as described in the above method, an alternative approach has been explored. This second approach uses the number of pits and the depths of their deepest pits as inputs to predict the average depth and width of pits of the raw sample data. For this method, inspectors would not need to define the most representative sample square or the average pit depth/width. Instead, the pit depths of the r deepest pits in the adjacent plate panels will be measured and recorded. This way, less human judgment will be involved in the collection of pitting data.

Consider a plate with M number of pits. The plate could be either a 300 mm x 300 mm (12" x 12") sample square or the associated adjacent plate panels in question. The first approach was demonstrated on a sample square, because the current suggested practice collects most data there. In this second approach, an entire plate panel will be used for demonstration. This approach can be used in any size of plate panels. Since the considered area is larger than the one in the first approach, the value of M will be bigger than the value of N.

The depths and widths of the M pits can be denoted as a set of lognormal random vectors $\{d_1, d_2, ..., d_M\}$ and $\{w_1, w_2, ..., w_M\}$, assuming both to be lognormally distributed. The goal, again, is to find out the total wasted steel volume as:

$$V = c \cdot \sum_{i=1}^{M} \left(\frac{\pi}{4} w_i^2 \cdot d_i \right) \tag{3.9}$$

The set of lognormal random vectors can be sorted in an ascending order so that (d_1, w_1) and (d_M, w_M) are the smallest and the largest respectively. The r largest pit depths and widths that will be recorded during inspections are known as $\{d_{M-r+1}, d_{M-r+2}, ..., d_M\}$ and $\{w_{M-r+1}, w_{M-r+2}, ..., w_M\}$. Assume that the values of COVs of d and w in any plate panels are almost the same, and equal to a fixed value. With the above information, the means of the pit depth and width can be estimated.

By using trial and error on the mean of d, a mean extreme (largest) value of the M pit depth can be found to be x_M. Continue trial and error on μ_D until x_M matches d_M. This μ_D obtained is one estimate of the true mean pit depth. To better explain this approach, one can consider an extreme value as a function of the mean, the standard deviation (or COV) and the total sample number:

$$x_M = f_M(\mu_D, \sigma_D, M) \tag{3.10}$$

Rearrange it to make x_M as an input and μ_D as an output, and replace x_M by d_M:

$$\mu_D = g_M(d_M, \sigma_D, M) \tag{3.11}$$

Equation 3.11 can be solved by trial and error.

The obtained estimate of μ_D together with the assumed COV have decidedly defined the lognormal distribution. A simulation can be performed on *d* (as well as *w* by following the similar trial-and-error procedures). Then the wasted steel volume can be computed by using Equation 3.9. Upon reaching this point, the problem can be considered solved.

However, the estimate of μ_D may deviate from the true mean when the input, d_M, is inaccurate. This is often the case. Thus more extreme data should be used to reduce the variation of the estimate of μ_D. The second extreme data can be used to predict the second estimate on μ_D. The function can be expressed as:

$$\mu_D = g_{M-1}(d_{M-1}, \sigma_D, M) \tag{3.12}$$

By continuing to use the above procedures on the r extreme input data, r estimates of μ_D can be calculated. An overall better estimate can be obtained by averaging them.

In order to demonstrate the approach and to see the accuracy improvement from using more inputs, five tests were performed. Test #1 used only the deepest pit depth as input data. The test was done by generating twenty correlated lognormal-distributed random vectors to represent the depths and widths of twenty pits in a plate. The actual volume loss in the plate was calculated as V_{actual} using Equation 3.9. Then the approach was used to make predictions on V_{actual}. The largest depth and width were sorted out and used as inputs to determine the values of μ_D and μ_W.

Based on μ_D and μ_W and their corresponding assumed standard deviations, a simulation on lognormal random variates can be performed. Twenty pits were generated to simulate the actual pits in the plate. The predicted volume loss was calculated as $V_{predicted}$. To see the goodness of the prediction, a prediction error, *R*, is defined as:

$$R = \frac{V_{predicted} - V_{actual}}{V_{actual}} \tag{3.13}$$

R is also a random variable and should have a mean value of zero. Each run of the test produced a different error. Some of the errors can be higher than 100%. In each test, one-thousand runs were performed. The prediction errors *R* in Test #1 are summarized in the histogram of Figure 3.4.

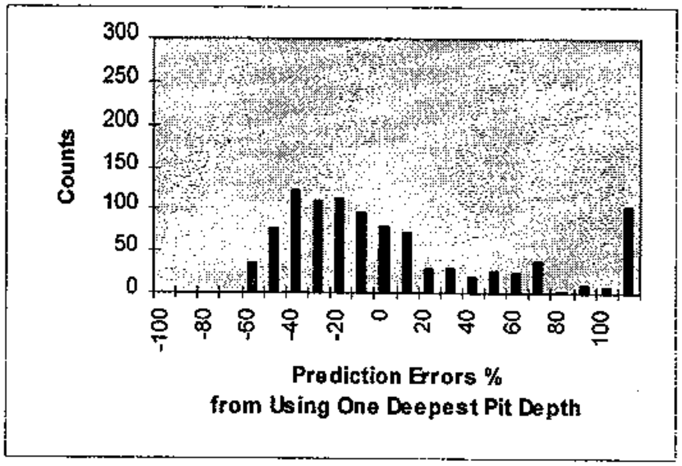


Figure 3.4: Histogram of prediction errors in percentage using one pit depth/width.

It can be seen that *R* varies in range from -60% to 100%. The errors are very large. More than a hundred of the 1000 runs have errors greater than 100%. This indicates that the prediction based on one extreme pit depth and width may not produce an accurate steel volume loss.

Four other tests were performed by using the 2, 3, 4 and 5 deepest pit depths and widths. The intention was to see that if more input data are provided, can better prediction can be made. Each test consisted of 1000 trials. The prediction errors of the 1000 trials were again plotted into histograms (Figures 3.5 through 3.8). The raw data of the five tests are listed in Table 3.2.

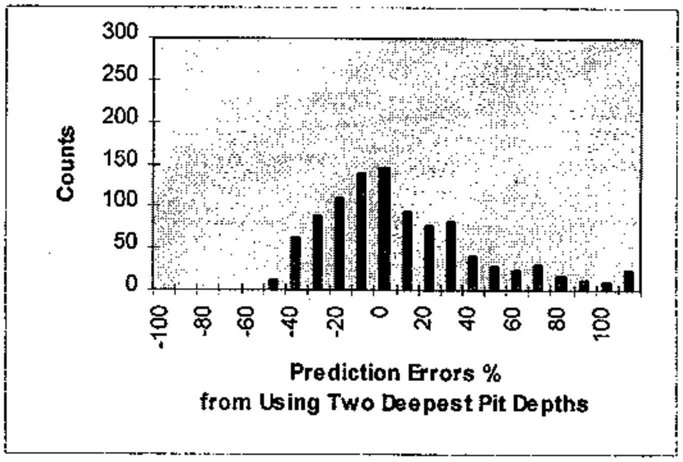


Figure 3.5: Histogram of prediction errors using two largest pits.

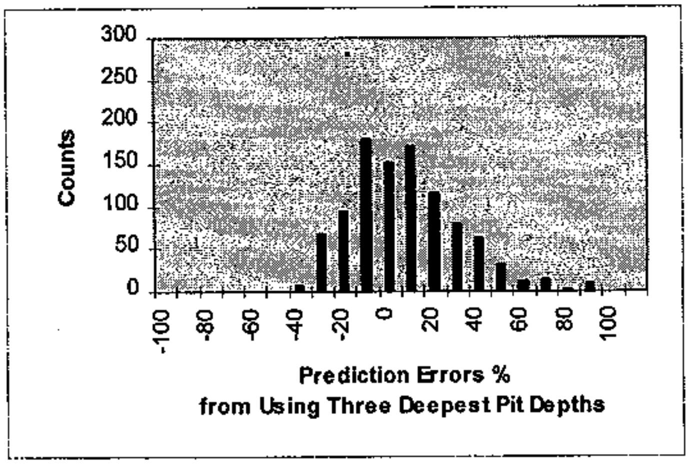


Figure 3.6: Histogram of prediction errors using three largest pits.

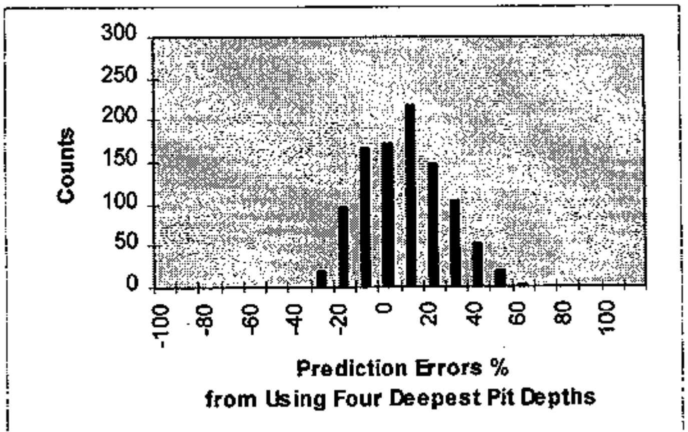


Figure 3.7: Histogram of prediction errors using four largest pits.

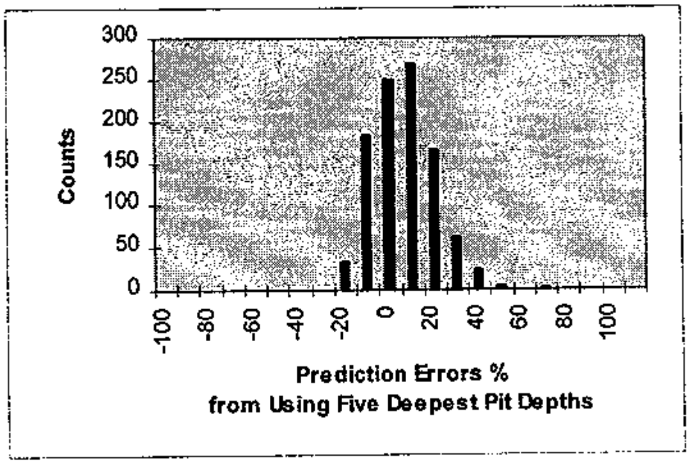


Figure 3.8: Histogram of prediction errors using five largest pits.

Table 3.2: Counts of Prediction Error Percentages for the five analyses.

				Counts of Prediction Error Percentages for Five Analyses														
Err %	-70%	-60%	-50%	-40%	-30%	-20%	-10%	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	
1 Extr	0	37	77	122	111	114	96	79	73	29	28	20	27	24	39	3	10	8	103
2 Extr	0	0	11	62	90	110	139	146	94	78	81	41	30	24	31	16	13	10	24
3 Extr	0	0	0	8	67	94	179	153	171	116	79	64	31	12	14	2	9	1	0
4 Extr	0	0	0	0	20	96	166	171	218	148	103	53	20	3	1	1	0	0	0
5 Extr	0	0	0	0	1	34	183	250	270	165	63	25	6	0	3	0	0	0	0

From these histograms, it can be seen that the prediction error *R* decreases when more extreme data are used as inputs. Test #5 which used five extreme pit depth/width gave a very good prediction on steel volume loss. The errors that lay in the range from -25% to +25% consist of 902 trials. In other words, 90.2% of the trials give reasonable predictions. The tests show a reducing trend on errors while using more extreme pit depths/widths as inputs. This indicates that this alternative approach could be a promising method for a practical application of pitting data collection strategy in the future.

To further analyze the prediction errors in the five tests, a mean and a standard deviation of prediction error *R* can be calculated. The mean should have a value of zero, or it is biased. The means of the five tests are all slightly above zero. However, it approaches zero when more extreme pit depths/widths are used as inputs (Figure 3.9). The standard deviation also shows a decreasing trend (Figure 3.10). The two figures indicate that better prediction on steel volume loss will be made when more inputs are provided.

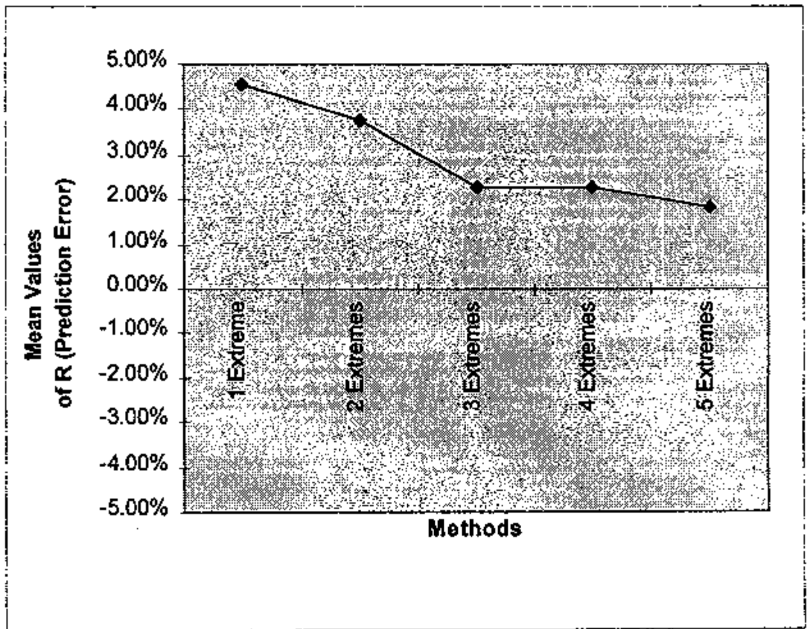


Figure 3.9: The mean of *R* approaches zero while using more inputs.

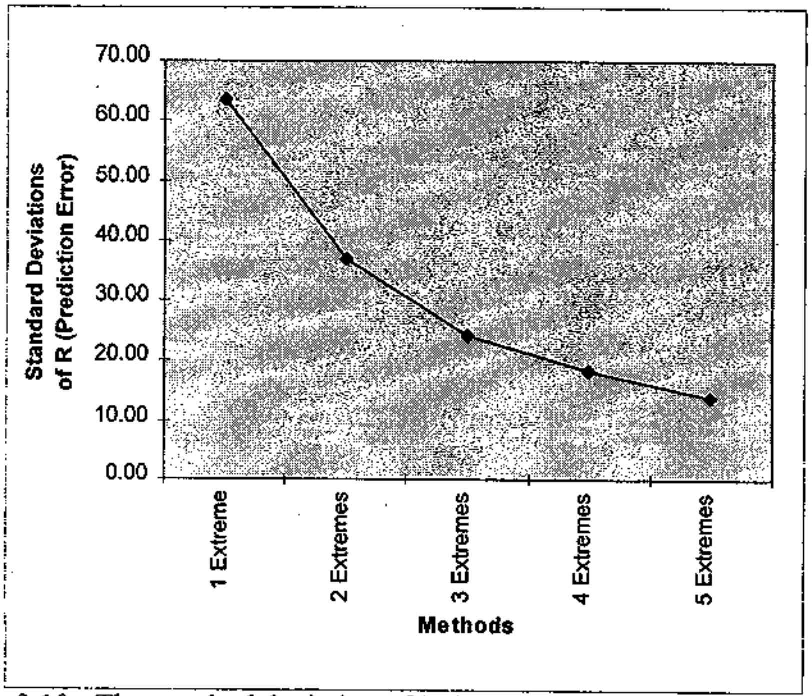


Figure 3.10: The standard deviation of *R* decreases while using more inputs.

In summary, a proposed alternative physical and mathematical approach, to the one presented earlier in this report, has been developed to predict the residual thickness of pitted plates. This approach eliminates the uncertainty, in the form of human judgment, present in the first method presented in Section 3.3. The latter method requires selective estimation by the inspector of the most average pit depth, which is one of the parameters normally gathered in present day inspections. Although the first approach is a true advancement using the present day inspection techniques, the alternative approach can prove to be more progressive than the first method. However, one of the weaknesses associated with this second method, as with the first, is that it still requires a computing facility to calculate accurately, the steel volume reduction (and thus the thickness reduction). Another disadvantage, as shown above, is that it may require five or more input data sets to produce a reliable prediction. It is however, offered for future development. To demonstrate this alternative approach, another FORTRAN program, PITA, has been developed. Its flow chart is included in Section 5 and its code listing is included in Appendix B.

4. STRENGTH ASSESSMENT

The local strength assessment of a pitted plate panel is presented in this section. The rationale for the major decision to base the residual strength of a pitted plate on residual thickness is discussed. Also presented are the guidelines for assessing the global residual strength of a vessel with pitted plates based on deterministic parameters. Finally, a proposed method is presented to assess the effect of thickness reduction due to pitting on the global hull structure based on probabilistic approach.

4.1 Local Residual Strength Assessment

It is understood that, under load, a pitted plate may behave differently than a generally corroded plate. However, the literature search has not uncovered a suitable, consistent, and all encompassing method with which to evaluate the residual strength of pitted plates. In order to arrive at the residual strength assessment of pitted plating, within the scope of this report, the following approach has been used:

1) Firstly, the residual thickness of the pitted plate is determined based on the method set forth in Section 3 of this report, utilizing the graphs developed in Section 5. This method of determining the residual thickness of pitted plates by estimating pit intensities and average values is considered more comprehensive than the methods cited in Section 2.2.

2) After arriving at this relatively accurate residual thickness, accepted procedures and criteria of the classification societies or the TSCF are used to determine the allowable wastage for the area under investigation. These criteria are given in Table 2.1. In so doing, it is assumed that the plate with residual thickness behaves similarly to a plate with general corrosion. The acceptance criteria of the TSCF are excerpted in Section 5 of this report for use as guidance; included are buckling requirements based on the residual thickness due to pitting.

3) The subject plating can be accepted or rejected on the above basis.

This procedure enables the inspector, while conducting inspections on the vessel, to determine the acceptability of a pitted plate.

4.2 Global Deterministic Evaluation of Residual Strength

Corrosion of ship's structures leads not only to a decrease in the hull girder section modulus but also to a resultant increase in the primary hull stresses and a decrease in resitance to fatigue.

Following the procedures in Sections 4.1 and 5 of this report, during inspection, or more precisely afterward, the inspector can make a global evaluation of residual strength with the use of the residual thicknesses of the remaining plates. The evaluation of the global strength will be based on experience and the extent of present wastage. Typically, at any cross section, the thickness of the unaffected plates, and the residual thicknesses of acceptable corroded plates, acceptable pitted plates (from 4.1 above), and renewed plates will be included. To determine the reduction in strength, a hull girder section modulus calculation will then be accomplished using the values of thicknesses for the subject section as determined above. The allowable reduction in hull girder section modulus of the "corroded" section from the "as built" section, at the cross section under consideration, is regulated for each ship by the classification society concerned. Their advice should be sought in each case. This process is repeated at cross sections where significant wastage has occurred.

The mid-ship section modulus decreases due to reduced thickness in bottom plates and other pitted longitudinal members.

Consider the hull girder limit state function:

$$g(x) = M_U - M_{SW} - M_{WV} \tag{4.1}$$

Where:

M_u = Ultimate bending moment
M_{sw} = Stillwater bending moment
M_{wv} = Wave bending moment

and $M_u = \sigma_u S_m$; (4.2)
σ_u = Ultimate strength
S_m = Ship Section Modulus

4.3 Probabilistic Residual Strength

4.3.1 Local Yielding:

The resultant stress increases due to reduced thickness are as shown for example in Figure 4.1.

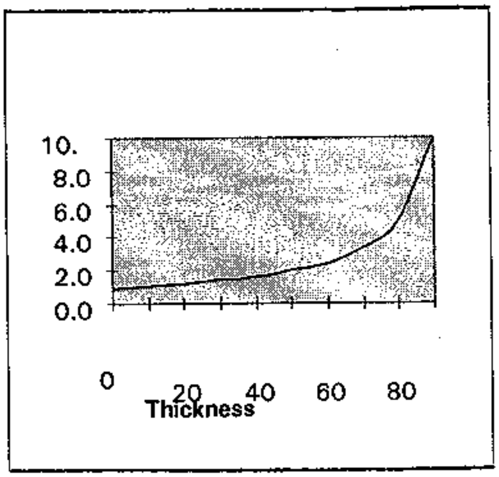


Figure 4.1: Resultant stress increases due to a reduced cross section area.

Consequently, that is a reduction in safety factor or residual strength with reduced thickness:

$$SF = \frac{\sigma_Y}{\sigma_A} \tag{4.3}$$

$$\beta_Y = \Pr ob\{(\sigma_Y - \sigma_A) \leq 0\} \tag{4.4}$$

Where:

SF = Factor of Safety
σ_Y = Rational Yield Street
σ_A = Actual Stress
β_Y = Safety Index

4.3.2 Plate Buckling:

Critical buckling stress decreases due to reduced effective thickness are as shown for example in Figure 4.2.

$$\sigma_{CR} = \frac{\pi^2 E}{12(1-\nu^2)}\left(\frac{t}{a}\right)^2 (1+\alpha^2)^2 \tag{4.5}$$

$$SF = \frac{\sigma_A}{\sigma_{CR}} \tag{4.6}$$

$$\beta_B \cong \Pr ob\{(\sigma_{CR} - \sigma_A) \leq 0\} \tag{4.7}$$

Where:

E = Young's Modulus
ν = Poisson's Ratio
t = Thickness
a = Plate Breadth Between Supports
α = End Fixity Coefficient of Supports
σ_A = actual stress
σ_{CR} = Critical Buckling Stress

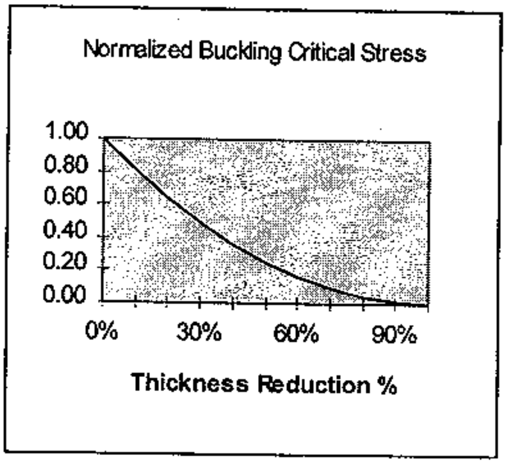


Figure 4.2: Buckling Strength Decreases Due to Effective Thickness Reduction.

4.4 Perforation (allowable wastage):

$\beta_U \cong \text{Prob}\{(\sigma_U - \sigma_A) \leq 0\}$

Where:

σ_A = actual stress (including accounting for orthogonal hydrostatic normal load)

β_U = safety index

It has been noted from literature that the problem of bottom penetration is important. This can be considered by establishing appropriate values of allowable remaining plate thickness:

$$t_0 - t_{pit} \leq \alpha t_0 \tag{4.8}$$

Where:

t_0 = required thickness
t_{pit} = thickness of pitting reduction
α = allowable % plate remaining/100

4.5 Fatigue

Fatigue problems can be addressed by adequate assessment of design details and selection of notch tough steel. Also, attention to structural discontinuities, as well as notches, will lessen the chance of coating breakdown due to structure working or having sharp corners. Minimization of weld residual stress is as important. With these precautions in construction, and adequate inspection procedures to preclude crack initiation, the largest problem with pitting remains to be possible tank envelope penetration. According to [8], pitting corrosion "seldom leads to fatigue problems".

5 DECISION MAKING TOOLS

A principal output of this report is a simple deterministic set of graphs to enable an inspector, on board ship, to make the decision to replace, repair in place or accept as is, a plate in a tank of a ship that has pitting corrosion. Additional tools are provided to further investigate marginal plates by portable computer or in the office environment. Up to the present, the means of assessing residual strength of pitted plates was either too time consuming, inaccurate, or left to past experience to determine which plates to replace or repair. These procedures can be modified with the assimilation of the tools presented in this report.

5.1 Decision making Graphs

The graphs are divided into two basic groups: The estimated equivalent thickness loss graphs (Figures 5.1 through 5.6), and the residual strength graph (Figure 4.2).

5.1.1 Graphs of Estimated Equivalent Thickness Loss

To use the residual thickness graphs to evaluate a plate under consideration, use the following proposed procedure may be utilized:

1. Visually mark the perimeter of the extent of pitting.

2. Within this area, locate a sample square 300mm x 300 mm (12" x 12") that is representative of pitting of the full plate in terms of intensity, depths, and diameters of pits.

3. Within the 300mm x 300mm square record the following:

i) The FREQUENCY (N) of pits in the square - Count the number of pits in the sample square.

ii) The AVERAGE DEPTH (μ_D)- Record the depth (in millimeters) of the pit regarded as having the average depth for the square.

iii) The MAXIMUM DEPTH (χ_D) - Record the depth (in millimeters) of the deepest pit in the square.

iv) The AVERAGE DIAMETER (μ_W) - Record the average diameter (in millimeters) of the pit regarded as being the average of all pits in the sample square.

v) MAXIMUM DIAMETER (χ_W) - Record the Maximum Diameter (in millimeters) of the largest pit within the sample square.

vi) ORIGINAL THICKNESS (t) of plate under consideration - This will be needed to evaluate the percentage wastage of the plate.

The program PIT, developed in this research project, was used to calculate thickness reductions as a function of mean pit depth and pit numbers. Using the results of these calculations, a series of charts indicating thickness reductions were created. Each chart corresponds to a specific COV (coefficient of variation) for both pit depth and width (from 0.1 to 0.6). The graphs are designed for practical use in the future. They are generated by using the method given in Section 3.3 and by adopting a number of additional assumptions to eliminate some of the less sensitive parameters:

- Lognormal distribution of w and d
- Mean pit width is a function of mean depth as ' $\mu_W \cong 2.5\mu_D$ '
- Correlation between d & w is 0.9
- Pits have semi-spherical shape

These assumptions are deemed reasonable on the basis of data available on pitting from both marine and non-marine sources:

With the above parameters, enter the residual thickness graph for the correct coefficient of variation (COV) of pit depth and diameter. A 0.1 COV indicates a generally poor correlation between the dimensions of depth and diameter, while a 0.6 indicates generally a much better correlation between these dimensions. The appropriate graph will provide a relatively accurate estimated equivalent thickness loss.

A comparison should be made of the pitting parameters gathered by inspection as described in Section 5.1 with the assumptions used above to generate the thickness reduction graphs. If there is good correspondence between the two, then the graphs should yield satisfactory results of equivalent thickness reduction for the set of analytical data. If the correspondence is poor, the subject set of data should be subjected to the program "PIT" (Section 5.2), to more accurately determine the equivalent thickness loss.

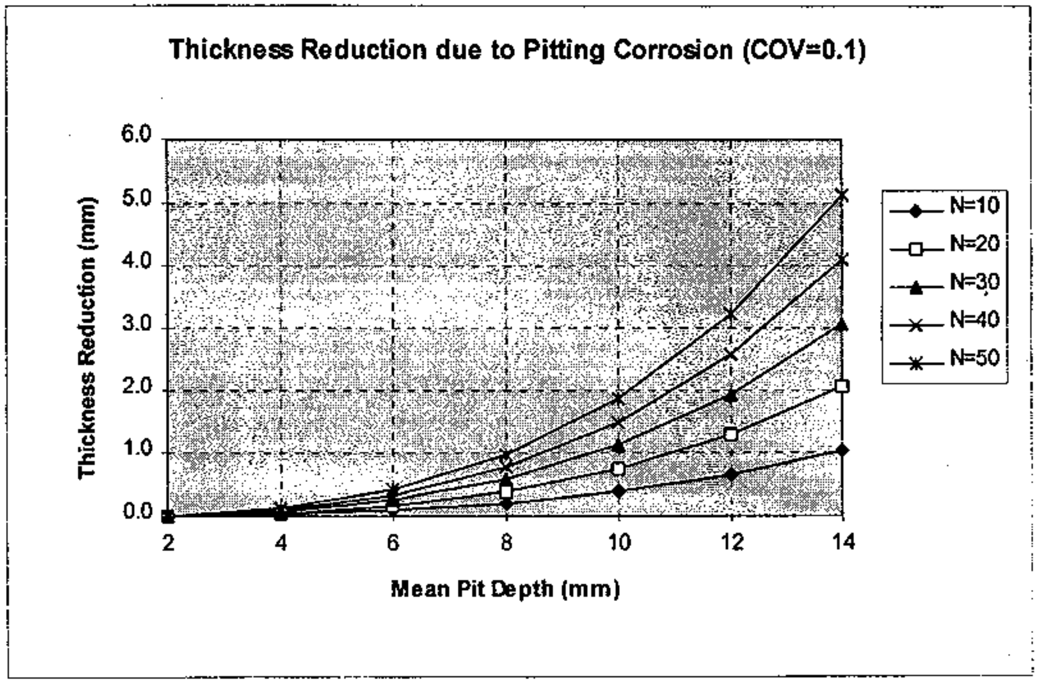


Figure 5.1: Thickness reduction while assuming the COV of pit depth and width to be 0.1.

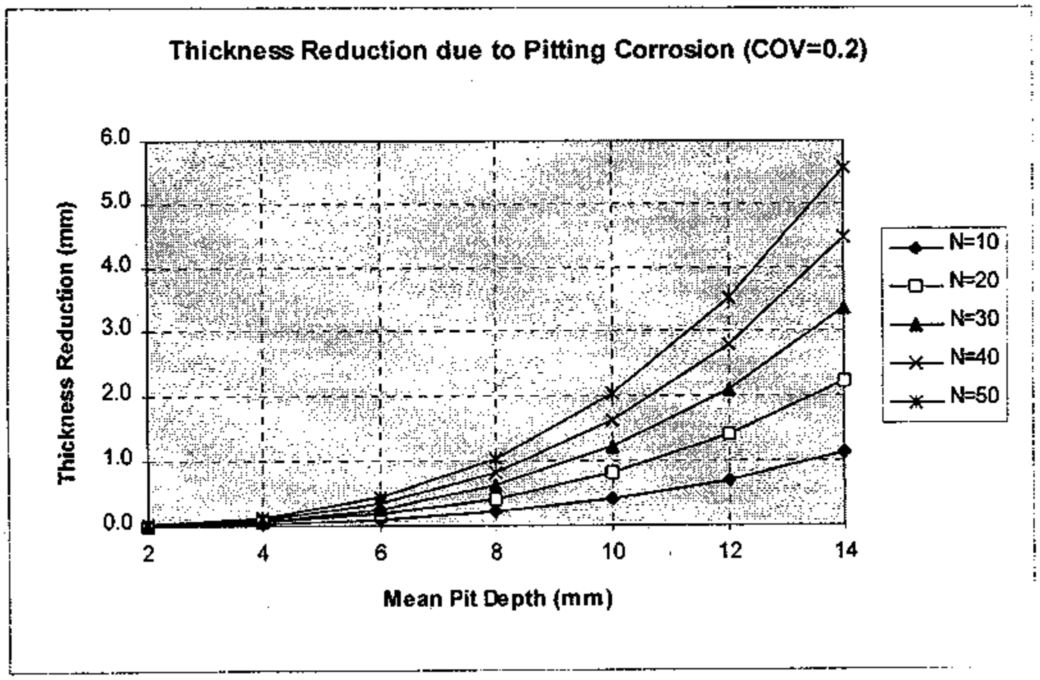


Figure 5.2: Thickness reduction while assuming the COV of pit depth and width to be 0.2.

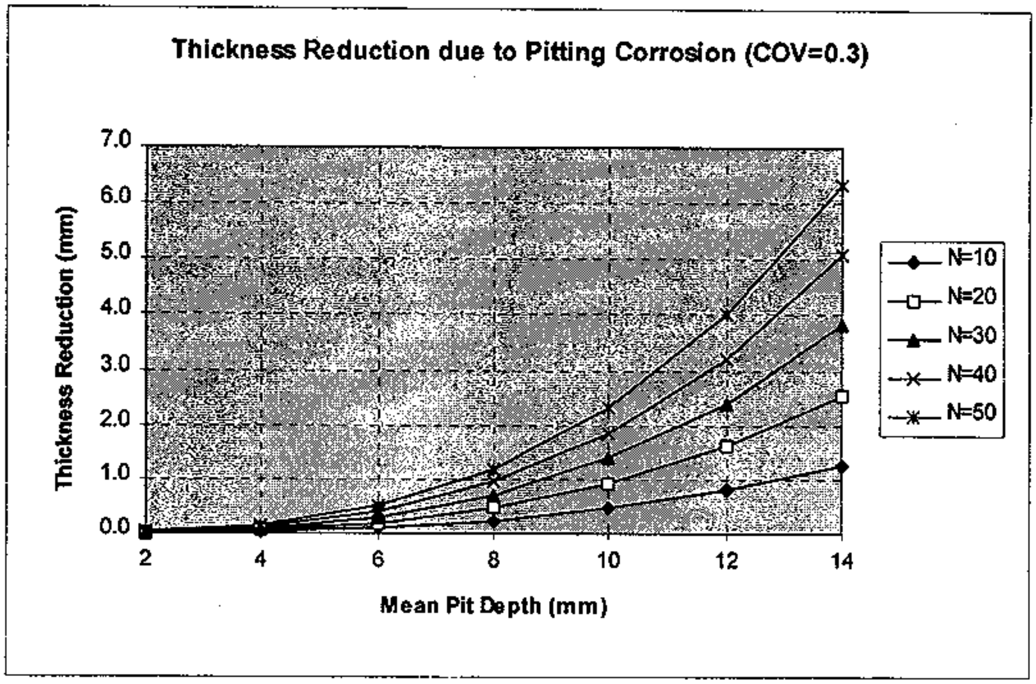


Figure 5.3: Thickness reduction while assuming the COV of pit depth and width to be 0.3.

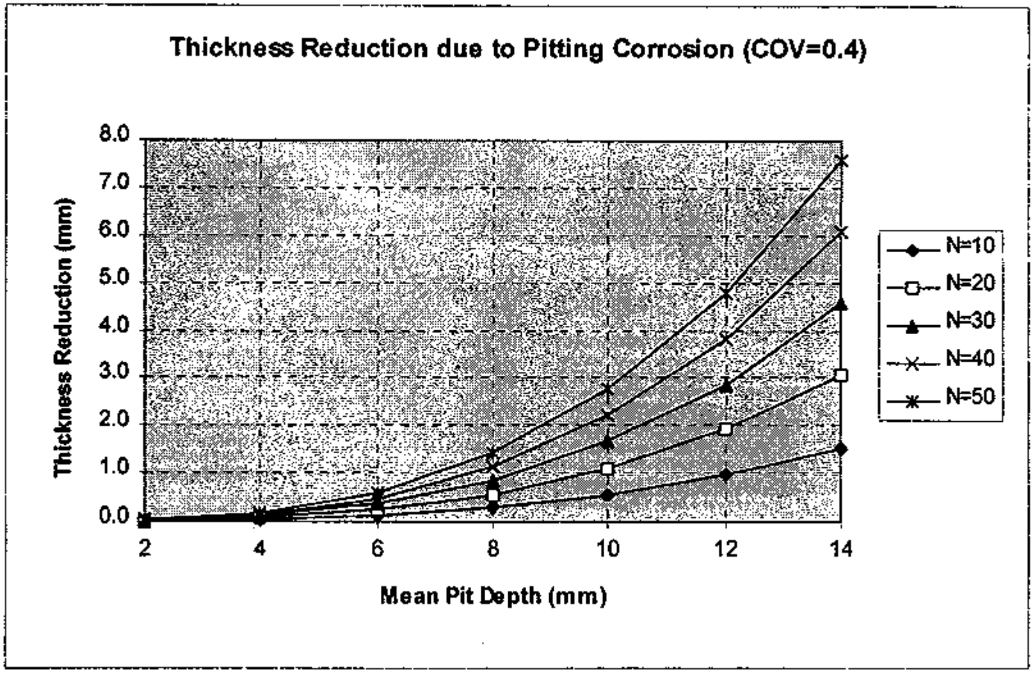


Figure 5.4: Thickness reduction while assuming the COV of pit depth and width to be 0.4.

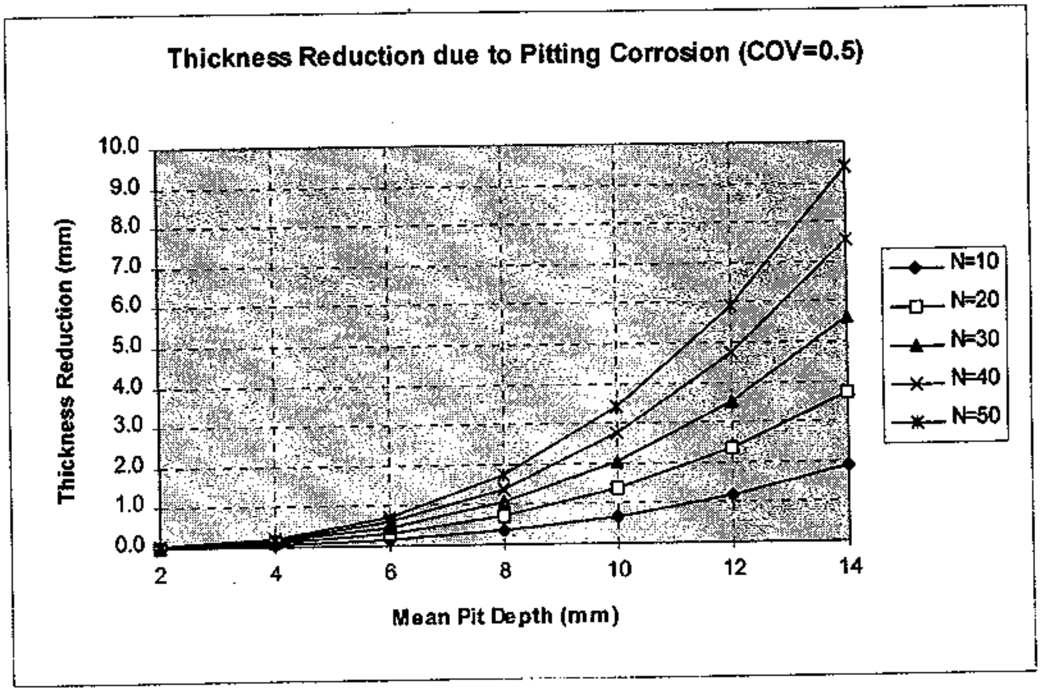


Figure 5.5: Thickness reduction while assuming the COV of pit depth and width to be 0.5.

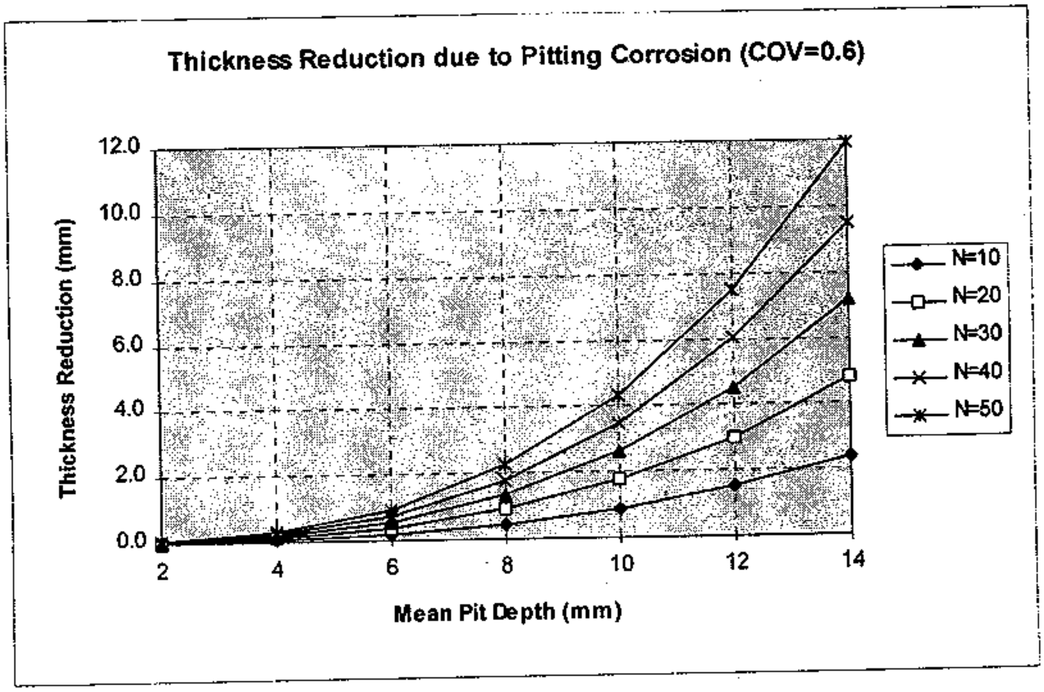


Figure 5.6: Thickness reduction while assuming the COV of pit depth and width to be 0.6.

5.1.2 Graph of Residual Strength Based on Buckling

To use the residual strength graphs to evaluate the plate under consideration, after determining its residual thickness, proceed with the following:

1. STIFFENER SPACING - Record the stiffener spacing (s) in millimeters for the plate under consideration.

2. Using the graph for residual strength (Figure 5-7), stiffener spacing and residual plate thickness, find the residual s/t of the plate and determine if it is acceptable from a strength standpoint. Compare this thickness to the guidelines of Table 2.1 or similar data.

The above guidelines for allowable residual thickness and residual strength (s/t) were derived from values of the TSCF. The procedures and limits of treating acceptable thickness pitted plate were adopted from the guidelines of ABS. It is suggested that the guidelines and procedures be modified to satisfy the approving authority for the vessel being inspected. This modification is relatively simple in that it only involves reassigning allowable residual thicknesses and s/t ratios. The procedure for treating pitted plate may be customized to the satisfaction of the approving authority. The use of these residual thicknesses can help plan for future inspections or economic "what if" scenarios for the vessel.

5.1.3 Repair Alternatives for the Above Findings:

The alternatives available for repairing the pitted areas are:

- No repair
- Epoxy compound filling (Figure 5.8)
- Clad weld
- Clad weld plus coating
- Cropping out and Renewing
- Installing zinc anode
- If the plate is to be retained, determine the following and record for further action during drydocking.
- Pits with depths not greater than 50% of the residual thickness are to be properly prepared to coating manufacturer's specifications and epoxied, to prevent further pitting corrosion.

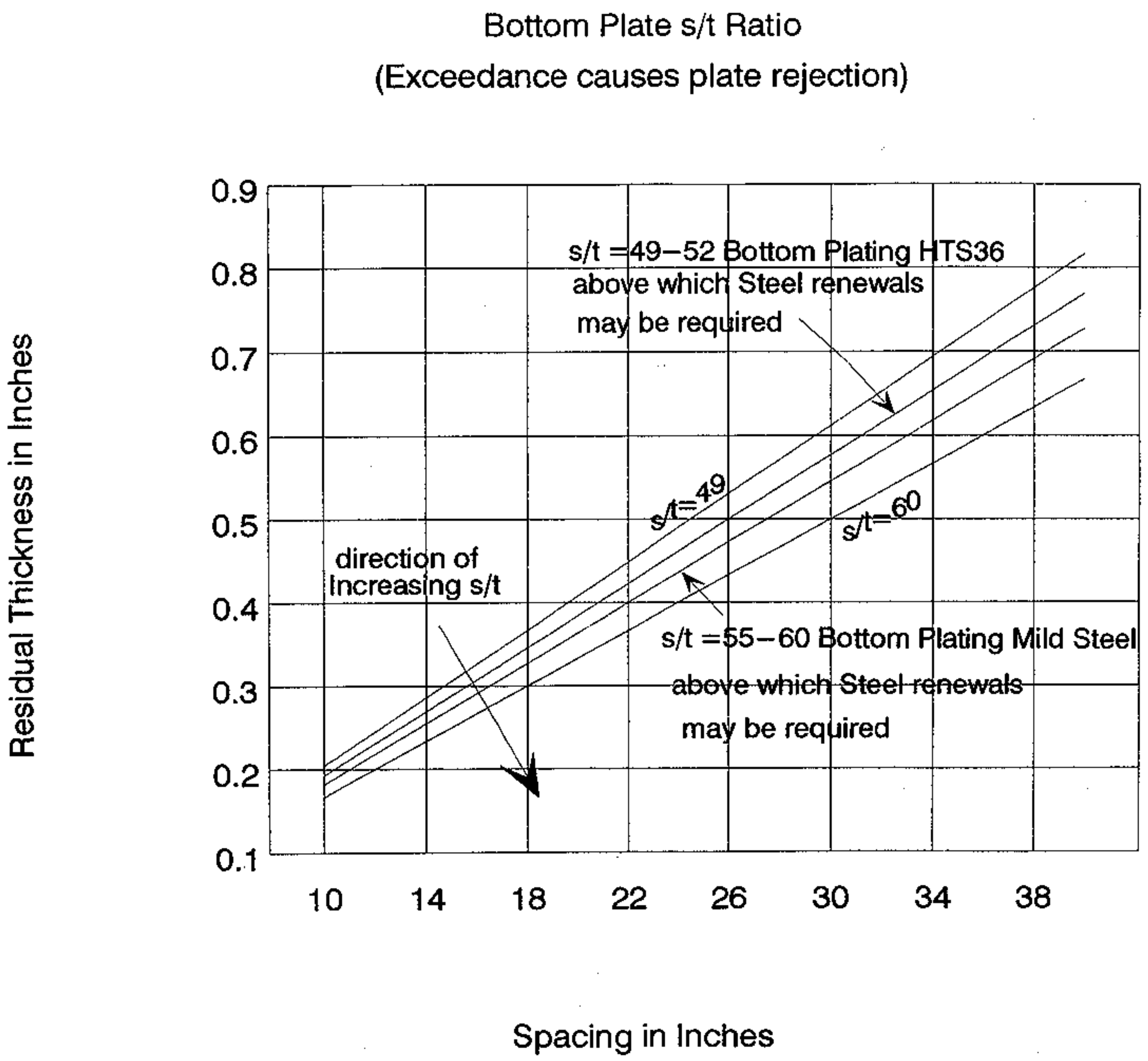

Bottom Plate s/t Ratio
(Exceedance causes plate rejection)
Residual Thickness in Inches
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
10
14
18
22
26
30
34
38
Spacing in Inches
s/t =49−52 Bottom Plating HTS36
above which Steel renewals
may be required
s/t=49
s/t=60
direction of
Increasing s/t
s/t =55−60 Bottom Plating Mild Steel
above which Steel renewals
may be required

Figure 5.7

- Pits with depths greater than 50% of the residual thickness may be welded provided there is at least 6.5mm (1/4 inch) of material remaining at the bottom of the pit and at least 76mm (3 inches) between adjacent pits and the maximum diameter of any welded pit does not exceed 305mm (12 inches).
- The cross sectional area lost in any section of the pitted plate should not be more than 15%.

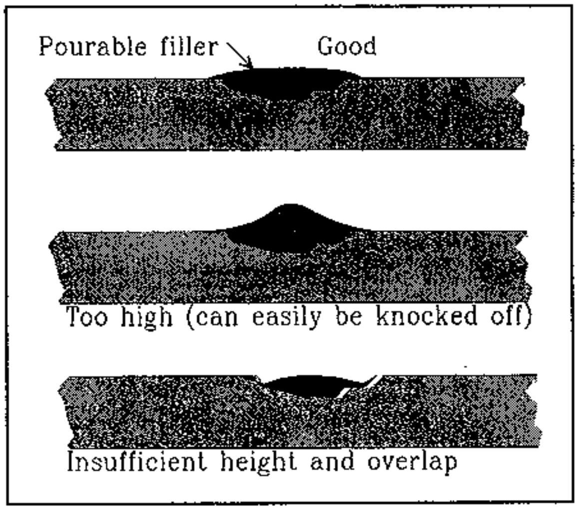


Figure 5.8: Pitting Repair by Pourable Filler, Ma & Bea, [19]

5.2 Computer Based Tool - FORTRAN Program 'PIT' & Alternatively 'PITA'

Two FORTRAN programs have been developed to illustrate the two mathematical models presented in 3.3 and 3.4 above. "PIT" has been used to develop the graphs presents in Section 5.1.1 for prediction of reduction in plate thickness due to pitting. PITA is a program that determines similar information but requires specific input not customarily collected during inspections at this time. Both programs used Lahey FORTRAN 77 version 4.0 as their compilers. The two programs are listed in Appendix B and C. The programs require an IBM compatible PC with a minimum of four megabytes of RAM and a math co-processor installed. The Lahey compiler uses the additional memory and it is not compatible with other memory manager programs. Therefore a computer should not be configured with any memory manager such as the DOS provided EMM386.EXE, or the program will not run. If a memory manager program is listed in the config.sys file, it should be remarked out by typing 'REM' in the beginning of the line. Input data can be entered on-screen or into an input file, PITDATA.TXT or PITADATA.TXT, in both programs. The following figures show the flow charts of the programs 'PIT' (Figure 5.9 & Figure 5.10) and 'PITA' (Figure 5.11).

5.3 Testing of Proposed Mathematical Method and Program 'PIT'

Twenty-three randomly generated PIT data sets were analyzed with the program 'PIT' to ascertain thickness reduction. The plate assumed was the typical 300 x 300mm (12" x 12") plate. The tests simulated plates that were severely pitted (93% of the surface) as well as plate slightly pitted (0.5% of surface). The plate was assumed to be 25mm (1") thick. The diameter ranges as well as their associated pit depth ranges were assumed. The diameter and pit depth, within each range chosen for the samples, was randomly chosen for trials 1-18 and 21-23. As this was the case the correlation coefficient between them was zero. This is an important feature of the test as one of the features of the PIT program was therefore rendered useless. In trials 19 and 20 sample pits were distributed with correlation coefficients of 0.781 for trial 19 and 0.970 for trial 20. This assumes that the pit depth and diameter are almost equal. The cylinder coefficient for all trials was assumed to be 1.0.The results obtained from the testing are listed in Table 5-1.

The resultant percent error in thickness reduction estimation from actual varied from 22.8% for trial 10 down to 0.7% error for trial 6. However, the reduced thicknesses from original was 10.4% actual and 8.03% calculated for trial 6.

For each case the actual volume loss was calculated by assuming the volume of the randomly or discretely modeled pits. The program PIT was then used to calculate the volume of the pits using only the parameters set forth in Section 3.3. The test generally shows the maximum error that can be expected when using the program PIT. When looking at the other results of the test, indications are that there may be a 5% difference (trial 21) in thickness reduction for plate wasted heavily in the order of 30%.

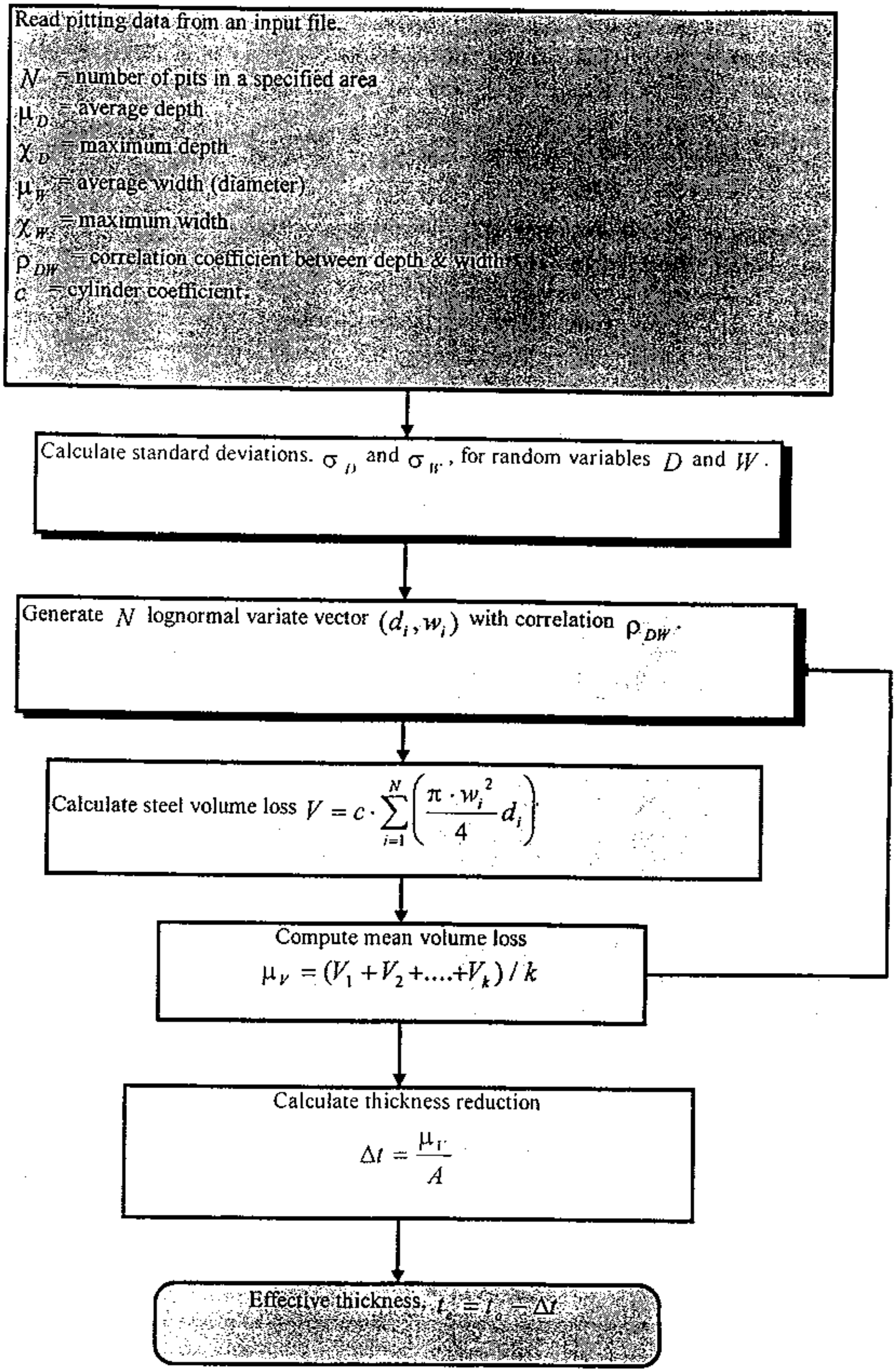


Figure 5.9 Flowchart of program PIT.

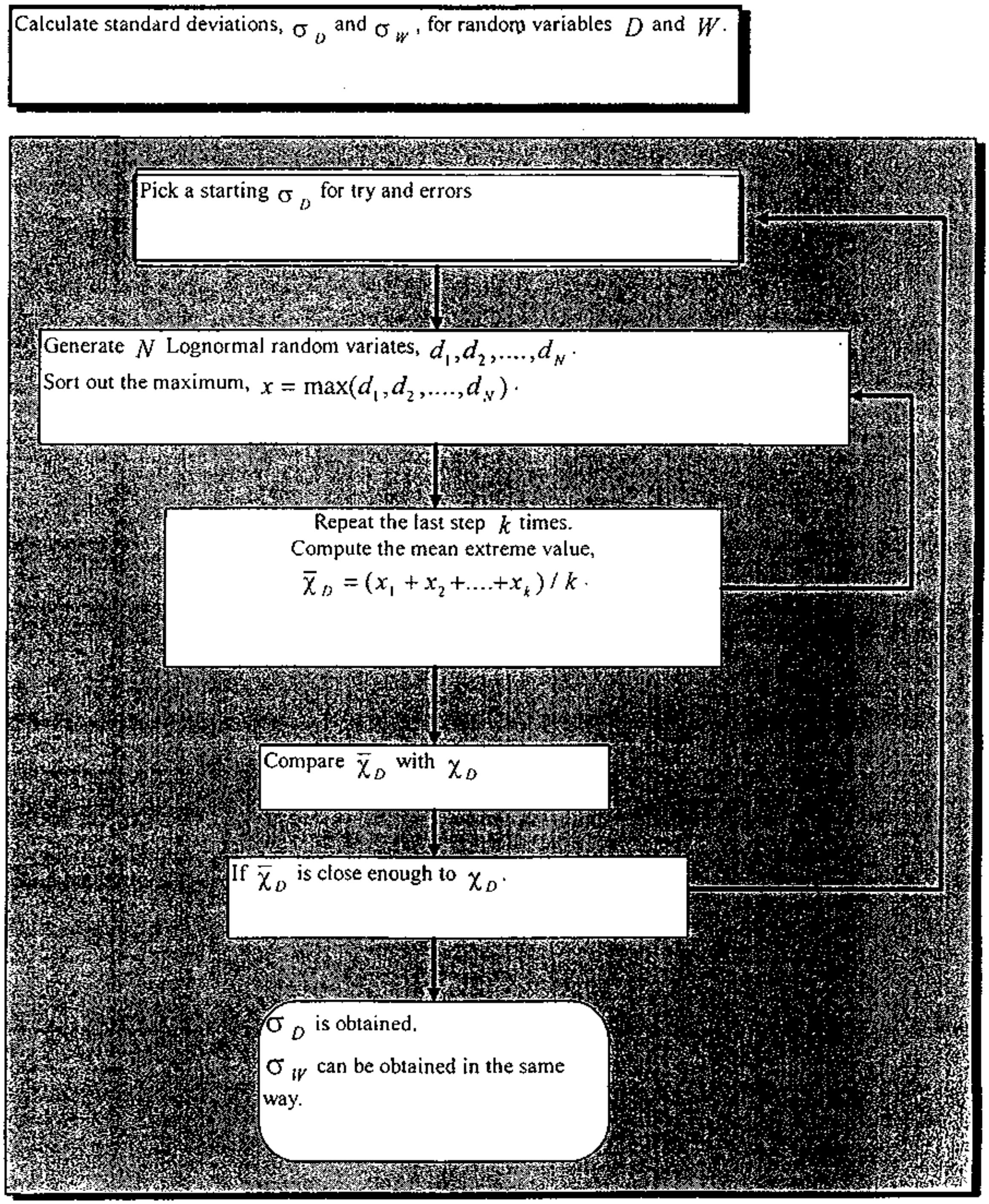


Figure 10 Part of the flowchart of program PIT.

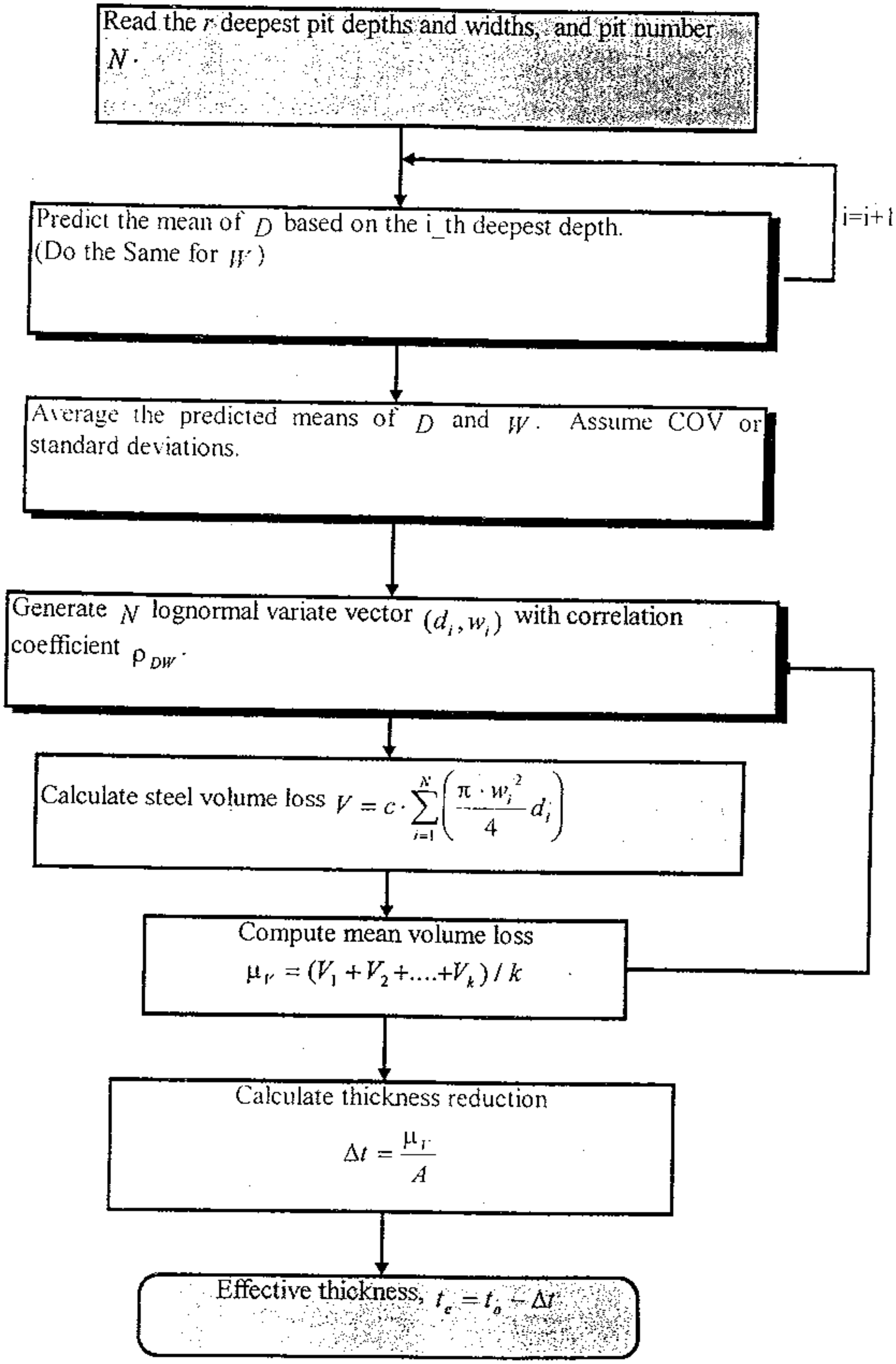


Figure 11 Flowchart of program PITA.

Table 5.1
Results of Preliminary Testing of Pit Thickness Reduction Program

Trial	Percent	Pit Diameter (mm)		Pit Depth (mm)		Volume Loss (mm^3)		Thickness Reduction (mm, %)				Error in
	Surf. Pitted	max	avg	max	avg	actual	program	actual	program	actual	program	% thk reduction
1	0.6%	7.79	4.98	14.93	11.06	5888	5709	0.065	0.063	0.26%	0.25%	-3.1%
2	0.6%	7.93	5.03	14.76	11.94	6728	6292	0.075	0.070	0.30%	0.28%	-6.5%
3	0.7%	7.74	5.13	14.19	11.08	6385	5994	0.071	0.067	0.28%	0.27%	-6.1%
4	0.5%	7.25	4.66	14.76	11.62	5582	5242	0.062	0.058	0.25%	0.23%	-6.2%
5	6.6%	24.31	16.25	11.73	6.51	39478	35257	0.439	0.392	1.75%	1.57%	-10.6%
6	6.2%	24.80	15.96	11.65	6.82	36430	36220	0.405	0.402	1.62%	1.61%	-0.7%
7	5.6%	24.03	14.73	11.78	5.91	27321	27024	0.304	0.300	1.21%	1.20%	-1.2%
8	5.1%	24.72	14.14	11.39	4.55	18758	19577	0.208	0.218	0.83%	0.87%	4.6%
9	42.6%	74.56	37.73	11.72	6.98	260551	226175	2.895	2.513	11.58%	10.05%	-13.2%
10	48.8%	73.92	42.34	11.75	4.69	234011	180715	2.600	2.008	10.40%	8.03%	-22.8%
11	31.3%	68.66	32.25	10.13	5.52	127999	133950	1.422	1.488	5.69%	5.95%	4.6%
12	57.9%	73.29	47.60	11.02	6.46	303707	302657	3.375	3.363	13.50%	13.45%	-0.3%
13	52.0%	73.09	44.64	11.63	7.12	333318	299169	3.704	3.324	14.81%	13.30%	-10.2%
14	23.1%	48.27	30.28	11.76	6.67	144575	127823	1.606	1.420	6.43%	5.68%	-11.6%
15	16.5%	49.96	6.05	11.20	6.05	91399	83045	1.016	0.923	4.06%	3.69%	-9.1%
16	12.9%	47.59	20.75	10.62	5.09	60352	53667	0.671	0.596	2.68%	2.38%	-11.1%
17	27.7%	49.86	32.83	11.02	5.19	121197	115999	1.347	1.289	5.39%	5.16%	-4.3%
18	19.8%	49.64	27.42	11.82	5.72	99692	93892	1.108	1.043	4.43%	4.17%	-5.8%
19	57.3%	101.60	60.11	7.62	4.03	204069	234635	2.267	2.607	9.07%	10.43%	15.0%
20	14.6%	75.90	42.04	0.75	0.46	8097	9013	0.090	0.100	0.36%	0.40%	11.2%
21	93.0%	74.67	42.77	11.86	7.94	678809	565940	7.542	6.288	30.17%	25.15%	-16.6%
22	78.6%	73.56	37.80	11.98	7.44	513147	425816	5.702	4.731	22.81%	18.92%	-17.0%
23	69.5%	74.97	36.15	11.85	7.05	423544	376944	4.706	4.188	18.82%	16.75%	-11.0%

Notes:

1) Plate size used in calculations was 300mm x 300mm x 25mm thick.

2) Because the pit dimensions (i.e., diameter and depth) were generated randomly in trials 1-18 and 21-23, the correlation coefficient between them was zero. In trials 19 & 20, the correlation coefficients were 0.781 and 0.970, respectively.

3) The cylinder coefficient (c) was assumed to be 1.0 for all trials.

4) Ranges used for random generation of pit dimensions in trials 1-18 and 21-23:

Trials	Diameter Range (mm)	Depth Range (mm)
1-4	2-8	8-15
5-8	3-25	0.1-12
9-13	3-75	0.1-12
14-18	3-50	0.1-12
21-23	3-75	3-12

6. CONCLUSIONS

A relatively simple set of tools has been developed which can be used to accurately assess the residual strength of pitted plates. These tools, mainly in the form of graphs, can be used during inspection of pitted plates to determine their local condition and help make the decision to replace, repair or leave in place, easy and consistent. The computer program method utilized accurately predicts, based on random probabilistic and Monte Carlo methods, the residual thickness of a randomly pitted plate, with relatively few input parameters. These input parameters are the suggested values of the TSCF, and should routinely be gathered during inspection. A program is provided to calculate the thickness loss due to pitting.

The program results, incorporated into graphs, provide the basis for a method of evaluating the residual strength of pitted plates that can be used in the field. Included is guidance to determine global residual strength of a cross section by both deterministic and probabilistic methods. Results of this method of determining residual thickness of pitted plate can be used to plan vessel inspection and economic decisions.

7. RECOMMENDATIONS

- Conduct experiments to determine how a pitted plate behaves differently than a corroded plate while under load. Test various plates that have near equal calculated residual equivalent thickness for tensile and buckling strengths.

- Conduct experiments to evaluate the accuracy of using residual equivalent thickness to model the strength of a pitted plate both in the tensile and buckling modes.

- The Strength models, particularly the hull girder probabilistic, should be further developed for future use.

- Take extensive measurements from different types of ship tanks and determine the probability distribution type and its characteristics of pits directly from these data.

- Data on pitting and grooving and the reults of application of the objection making tools developed herein should be tracked for further verification of procedures as necessary.

- Determine a more accurate and easy to use method to correlate depth and width of pits to strengthen the ability to predict residual equivalent thickness with this method.

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Appendix A: Pitting Data

Table 4-1 on the following pages lists the findings of a pitting survey report. The source of the report and the ship's name are not disclosed due to the confidentiality requests. The aim of the cited survey was to track and monitor the pit depth and its growth. Only pits deeper than 12 mm were measured and recorded, so the table gives only a partial listing of the pits; some of the ship tanks are more than a thousand pits; most of them are under 8 mm deep. The ship has a total pit number of 7595.

The pit size is recorded by its two surface dimensions as width 1 and width 2, and by its depth. The data are grouped according to their tank number. The location of each pit is plotted on a ship crossing in the survey report; but these are not reproduced here.

Table A-1

Sizes and Depth of Deep Pits

Tank No.	Pit No.	Width1 (mm)		Width2 (mm)		Depth (mm)
2 PORT	1	40.0	x	30.0	x	12.9
3 PORT	1	30.0	x	30.0	x	12.0
	2	30.0	x	30.0	x	12.0
	3	40.0	x	30.0	x	13.0
	4	30.0	x	30.0	x	12.0
	5	30.0	x	30.0	x	12.0
	6	30.0	x	30.0	x	13.0
	7	40.0	x	30.0	x	13.0
	8	40.0	x	30.0	x	15.0
	9	30.0	x	30.0	x	12.0
	10	30.0	x	30.0	x	12.0
3 STBD	1	30.0	x	30.0	x	12.0
	2	40.0	x	30.0	x	15.0
	3	40.0	x	30.0	x	15.0
	4	30.0	x	30.0	x	13.0
	5	30.0	x	30.0	x	13.0
	6	30.0	x	30.0	x	13.0
	7	40.0	x	30.0	x	16.0
	8	30.0	x	30.0	x	13.0
	9	50.0	x	40.0	x	19.0
	10	30.0	x	30.0	x	14.0
	11	40.0	x	40.0	x	15.0
	12	30.0	x	30.0	x	13.0
	13	40.0	x	30.0	x	14.0
4 STBD	1	70.0	x	70.0	x	15.0
	2	50.0	x	50.0	x	18.0
	3	30.0	x	50.0	x	13.0
	4	30.0	x	30.0	x	13.0

Table A-1 Cont'd.

Sizes and Depth of Deep Pits						
Tank No.	Pit No.	Width1 (mm)		Width2 (mm)		Depth (mm)
7 PORT	1	60.0	x	40.0	x	14.0
	2	30.0	x	30.0	x	12.0
	3	40.0	x	30.0	x	15.0
	4	40.0	x	30.0	x	15.0
	5	30.0	x	30.0	x	15.0
	6	30.0	x	30.0	x	14.0
	7	30.0	x	30.0	x	14.0
	8	30.0	x	30.0	x	14.0
	9	40.0	x	30.0	x	15.0
	10	30.0	x	30.0	x	13.0
	11	30.0	x	30.0	x	12.0
	12	30.0	x	30.0	x	12.0
	13	70.0	x	30.0	x	12.0
	14	30.0	x	30.0	x	12.0
	15	30.0	x	30.0	x	16.0
	16	30.0	x	30.0	x	15.0
	17	30.0	x	30.0	x	15.0
	18	30.0	x	30.0	x	12.0
	19	30.0	x	30.0	x	12.0
	20	40.0	x	30.0	x	15.0
	21	40.0	x	30.0	x	16.0
	22	30.0	x	30.0	x	15.0
	23	30.0	x	30.0	x	15.0
	24	30.0	x	30.0	x	13.0
	25	30.0	x	30.0	x	13.0
	26	40.0	x	30.0	x	15.0
	27	30.0	x	30.0	x	16.0
	28	30.0	x	30.0	x	13.0
	29	40.0	x	30.0	x	15.0

Table A-1 Cont'd.

Sizes and Depth of Deep Pits						
Tank No.	Pit No.	Width1 (mm)		Width2 (mm)		Depth (mm)
7 STBD	1	30.0	x	30.0	x	12.0
	2	30.0	x	30.0	x	12.0
	3	30.0	x	30.0	x	12.0
	4	30.0	x	30.0	x	12.0
	5	30.0	x	30.0	x	12.0
	6	30.0	x	30.0	x	12.0
	7	30.0	x	30.0	x	12.0
	8	60.0	x	60.0	x	15.0
	9	30.0	x	30.0	x	12.0
	10	30.0	x	30.0	x	12.0
	11	40.0	x	30.0	x	13.0
	12	30.0	x	30.0	x	12.0
	13	40.0	x	30.0	x	14.0
	14	40.0	x	40.0	x	15.0
	15	60.0	x	50.0	x	15.0
	16	65.0	x	65.0	x	15.0
	17	60.0	x	50.0	x	14.0
	18	60.0	x	60.0	x	13.0
	19	10.0	x	10.0	x	13.0
	20	50.0	x	40.0	x	14.0
	21	40.0	x	40.0	x	12.0
	22	50.0	x	50.0	x	18.0
	23	80.0	x	40.0	x	16.0
	24	30.0	x	30.0	x	12.0
	25	30.0	x	30.0	x	12.0
	26	40.0	x	30.0	x	14.0
8 PORT	1	80.0	x	50.0	x	13.0
	2	30.0	x	30.0	x	12.0
	3	30.0	x	30.0	x	12.0
	4	30.0	x	30.0	x	12.0
	5	40.0	x	30.0	x	12.0
	6	40.0	x	40.0	x	12.0
	7	30.0	x	30.0	x	12.0

Appendix B: Source Code of Program PIT

```
C*********************************************************************
C
C   THIS IS A PROGRAM TO INPUT PITTING DATA AND CALCULATE
C   THE THICKNESS REDUCTION FOR A PITTED PLATE.
C
C   WRITTEN BY DR. KAI-TUNG MA AND DR. ORISAMOLU, MAY 1995
C
C   INPUT:
C     NFQ   = NUMBER OF (FREQUENCY) PITS IN A 30X30CM PLATE
C     VMN(1) = AVERAGED DEPTH OF THE PITS
C     XTRM(1)= MAX DEPTH
C     VMN(2) = AVERAGED WIDTH (DIAMETER) OF THE PITS
C     XTRM(2)= MAX WIDTH
C     CC    = CORRELATION COEFFICIENT
C     CLNDR  = CYLINDER COEFFICIENT
C     IDUM   = -1 = SEED FOR RANDOM NUMBER GENERATION
C
C   OUTPUT:
C     THKRD  = THICKNESS REDUCTION
C
C*********************************************************************
      PROGRAM PITTING
      INCLUDE   'RELFNCT.V20'
      PARAMETER  (NVBL=2)
      IMPLICIT   REAL*8 (A-H,O-Z)
      DIMENSION  VMN(NVBL),ST(NVBL),XTRM(NVBL)
      WRITE(6, *) '--------------------------------------------------'
      WRITE(6, *) 'THIS IS A PROGRAM TO INPUT PITTING DATA AND'
      WRITE(6, *) 'CALCULATE THICKNESS REDUCTION FOR A PITTED PLATE.'
      WRITE(6, *)
      WRITE(6, *) 'BY DR. KAI-TUNG MA AND DR. ORISAMOLU, MAY 1995.'
      WRITE(6, *) '--------------------------------------------------'
      WRITE(6, *)
C
C   READ NUMBER OF PITS, AVERAGE DEPTH, MAX DEPTH, AVERAGE WIDTH,
C   MAX WIDTH (DIAMETER) FROM AN INPUT FILE.
C
      OPEN(UNIT=10,FILE='PITDATA.TXT',FORM='FORMATTED',
     &                  STATUS='OLD',ERR=100)
      GO TO 110
 100    CONTINUE
        WRITE(6, *)
        WRITE(6, *) '*** WARNING: INPUT FILE DOES NOT EXIST.'
        WRITE(6, *)
 110  CONTINUE
      WRITE(6, *) 'READING DATA FROM INPUT FILE - PITDATA.TXT'
      WRITE(6, *)
      READ(10, *) NFQ,VMN(1),XTRM(1),VMN(2),XTRM(2)
      WRITE(6, *) 'Frequency:       ',NFQ
      WRITE(6, *) 'Average Depth:       ',VMN(1)
```

```
      WRITE(6, *) 'Maximum Depth:      ',XTRM(1)
      WRITE(6, *) 'Average Width:      ',VMN(2)
      WRITE(6, *) 'Maximum Width:      ',XTRM(2)
C
C   READ CORRELATION COEFFICIENT
C
      READ (10,*)  CC
      IF (CC.LT.0.OR.CC.GT.1) THEN
        WRITE(6,*)
        WRITE(6,*) 'ERROR: INVALID INPUT OF CORRELATION COEFFICIENT.
        WRITE(6,*) '       CHECK INPUT FILE.'
        STOP
      ENDIF
      WRITE(6, *) 'Correlation Coefficient:', cc
C
C   READ CYLINDER COEFFICIENT
C
      READ (10,*)  CLNDR
      IF (CLNDR.LT.0.3.OR.CLNDR.GT.1.0) THEN
        WRITE(6,*)
        WRITE(6,*) 'ERROR: INVALID INPUT OF CYLINDER COEFFICIENT.'
        WRITE(6,*) '       CHECK INPUT FILE.'
        STOP
      ENDIF
      WRITE(6, *) 'Cylinder Coefficient:  ', CLNDR
      WRITE(6, *)
      CLOSE(10)
      IDUM=-1
C
C   CALCULATE STANDARD DEVIATIONS OF DEPTH & WIDTH, ST(1) & ST(2).
C   THIS WILL TAKE A FEW MINUTES.
C
      WRITE(6,*) 'PROGRAM RUNNING, PLEASE WAIT.'
      ST(1)=STDD(IDUM, NFQ, VMN(1), XTRM(1))
      ST(2)=STDD(IDUM, NFQ, VMN(2), XTRM(2))
      WRITE(6,*)
C     WRITE(6,*) 'ST(1), ST(2)',ST
C     PAUSE
C     CALL LNVARI(IDUM, NFQ, DAVG, D_ST, VLN)
C     CALL LNVARI(IDUM, NFQ, WAVG, W_ST, VLN)

C
C   CALCULATE STEEL VOLUME LOSS & THICKNESS REDUCTION
C
      TMPMN =0.0
      VOLMN =0.0
      N    =0
      DO 400 I=1,10000000
        VLOSS=0.0
        DO 390 J=1,NFQ
          CALL CRPAIR(ST,VMN,CC,IDUM,D,W)
          VLOSS=VLOSS+CLNDR*D*(3.14159*W*W/4)
```

```
  390 CONTINUE
      TMPMN=(TMPMN*(I-1)+VLOSS)/I
      IF(ABS(TMPMN-VOLMN).LT.TMPMN/10000) THEN
        N=N+1
C         WRITE(6,*) 'I, TMPMN, VOLMN, N',I,TMPMN.VOLMN,N
        IF(N.GT.100) THEN
          GOTO 410
        ENDIF
      ELSE
        N=0
      ENDIF
      VOLMN=TMPMN
  400 CONTINUE
      WRITE(6,*) '*** WARNING: VOLUME LOSS DOES NOT CONVERGE
     &                         WITHIN TOLERANCE.'
  410 CONTINUE
      THKRD=TMPMN/300/300
      WRITE(6,*)
      WRITE(6,*) 'VOLUME LOSS IN CUBIC MM:  ', TMPMN
      WRITE(6,*) 'THICKNESS REDUCTION IN MM: ', THKRD
      WRITE(6,*)
      WRITE(6,*) 'PROGRAM IS COMPLETED SUCCESSFULLY.'
      END
C*******************************************************************
C
C   THIS SUBROUTINE GENERATES CORRELATED LOGNORMAL
C   RANDOM VARIATES PAIR.
C
C   LOGNORMAL DISTRIBUTION
C   PAR1 = LOWER-BOUND
C   PAR2 = EPSILON
C   PAR3 = KSI
C
C*******************************************************************
      SUBROUTINE CRPAIR(ST,VMN,CC,IDUM,D,W)
      PARAMETER  (NVBL=2)
      INCLUDE    'RELFNCT.V20'
      IMPLICIT   REAL*8 (A-H,O-Z)
      REAL*4     GASDEV
      DIMENSION  VMN(NVBL),ST(NVBL),PAR(NVBL,5),S(NVBL,NVBL)
      DIMENSION  CRNM(NVBL),RNDM(NVBL)
      DO 200 I=1,NVBL
        PAR(I,1)=0.0
        PAR(I,2) = 1.D0 + (ST(I)/(VMN(I)-PAR(I,1)))**2
        PAR(I,2) = SQRT(LOG(PAR(I,2)))
        PAR(I,3) = LOG(VMN(I)-PAR(I,1))-0.5D0*PAR(I,2)**2
  200 CONTINUE
C
C   GENERATE INDEPENDENT STANDARD NORMAL RANDOM PAIR RNDM(I)
C
      DO 310 I = 1,2
```

```
      RNDM(I) = DBLE(GASDEV(IDUM))
  310 CONTINUE
C     WRITE(6,*) 'UNCORRELATED STD. NORMAL PAIR', RNDM(1), RNDM(2)

C
C    GENERATE CORRELATED STD NORMAL VARIATE PAIR, CRNM(I)
C    BASED ON ALGORITHM IN 'SIMULATION AND THE MONTE CARLO METHOD'
C    BY RUBINSTEIN, PAGE 65-67, 1981
C
      S(1,1)=1.0
      S(1,2)=0.0
      S(2,1)=CC
      S(2,2)=1.0
      CRNM(1)= SQRT(S(1,1)) * RNDM(1)
      CRNM(2)= S(2,1)/SQRT(S(1,1))*RNDM(1) + SQRT(S(2,2)-S(2,1)*S(2,1)
     &      /S(1,1))*RNDM(2)
C     WRITE(6,*) 'CORRELATED STD. NORMAL PAIR',CRNM(1),CRNM(2)
C
C    GENERATE CORRELATED LOGNORMAL PAIR, RNDM(I)
C
      DO 380 I=1.2
        RNDM(I) = PAR(I,1) + EXP(CRNM(I)*PAR(I,2)+PAR(I,3))
C       WRITE(6,*) 'CORRELATED LOGNORMAL PAIR', RNDM(I)
  380 CONTINUE
      D = RNDM(1)
      W = RNDM(2)
      END
C*********************************************************************
C
C    THIS FUNCTION 'MEAN_VALUE_EXTREME()' ESTIMATES THE
C    MEAN EXTREME VALUE OF 'nfq' LOGNORMAL VARIATES.
C
C*********************************************************************
      FUNCTION VMEXTR(IDUM, NFQ, AVG, ST)
      IMPLICIT  REAL*8 (A-H,O-Z)
      TOTL=0.0
      TMP=0.0
C     WRITE(6,*) 'CALL ESEXTR: IDUM, NFQ, AVG, ST'
C     WRITE(6,*) IDUM, NFQ, AVG, ST
      DO 130 I=1,1000000
        EXTR=ESEXTR(IDUM, NFQ, AVG, ST)
        TOTL=TOTL+EXTR
        VMXTR=TOTL/I
        ERR=ABS(VMXTR-TMP)
C
C    IF THIS FUNCTION TAKES TOO MUCH TIME, CONSIDER REDUCE
C    THE '1000' IN THE FOLLOWING LINE TO A SMALLER NUMBER.
C    HOWEVER, ACCURACY OF ESTIMATED MEAN EXTREME WILL REDUCE, TOO.
C
        VLMT=VMXTR/1000
        IF(ERR.LT.VLMT) THEN
          N=N+1
```

```
C        WRITE(6,*) 'I, EXTR, VMXTR, ERR, VLMT, N in vmextr'
C        WRITE(6,*) I,EXTR,VMXTR,ERR,VLMT,N
        IF(N.GT.8) THEN
C          WRITE(6,*) I,VM
          GOTO 140
        ENDIF
      ELSE
        N=0
      ENDIF
      TMP=VMXTR
 130  CONTINUE
 140  CONTINUE
      VMEXTR=VMXTR
C     WRITE(6,*) 'MEAN EXTREME FOUND:', VMEXTR
      END
C*******************************************************************
C
C   THIS SUBROUTINE 'LNVARI()' GENERATES LOGNORMAL
C   RANDOM VARIATES 'VLN'.
C
C*******************************************************************
      SUBROUTINE LNVARI(IDUM, NFQ, AVG, ST, VLN)
      REAL VLN(NFQ)
      DO 120 I=1,NFQ
      VLN(I)=RANLGN(IDUM, AVG, ST)
 120  CONTINUE
      WRITE(6,*) VLN
      END
C*******************************************************************
C
C   THIS FUNCTION 'ESTIMATED_EXTREME()' GENERATES LOGNORMAL
C   RANDOM VARIATES AND OUTPUT AN EXTREME (MAX) VALUE.
C
C*******************************************************************
      FUNCTION ESEXTR(IDUM, NFQ, AVG, ST)
      IMPLICIT  REAL*8 (A-H,O-Z)
C     WRITE(6,*) 'ESEXTR OK'
      ESDMAX=0.0
      DO 120 I=1,NFQ
        VLGN=RANLGN(IDUM, AVG, ST)
        IF(VLGN.GT.ESDMAX) THEN
          ESDMAX=VLGN
        ENDIF
 120  CONTINUE
      ESEXTR=ESDMAX
      END
C*******************************************************************
C
C   THIS FUNCTION GENERATES A LOGNORMAL RANDOM VARIATE.
C
C*******************************************************************
```

```
      FUNCTION RANLGN(IDUM, VM, ST)
      IMPLICIT  REAL*8 (A-H,O-Z)
      REAL*4    GASDEV
      INCLUDE   'RELFNCT.V20'
      RR     = DBLE(GASDEV(IDUM))
      A      = LOG(1.D0+ST*ST/VM/VM)
      B      = LOG(VM)-0.5D0*A
      C      = SQRT(A)
      RR     = B + C*RR
      RANLGN = EXP(RR)
      END
C*********************************************************************
C
C   THIS FUNCTION ESTIMATES THE STANDARD DEVIATION BASED ON THE
C   PITTING NUMBER 'NFQ', THE MEAN 'DAVG' AND THE EXTREME 'DMAX'.
C
C*********************************************************************
      FUNCTION STDD(IDUM,NFQ,DAVG,DMAX)
      IMPLICIT  REAL*8 (A-H,O-Z)
      VLWB=0.00000001*DAVG
      UPPB=1.00000000*DAVG
      VLWXTR=VMEXTR(IDUM, NFQ, DAVG, VLWB)
      UPPXTR=VMEXTR(IDUM, NFQ, DAVG, UPPB)
C     WRITE(6,*) 'LOWER AND UPPER BOUNDS OF THE EXTREME INPUT'
C     WRITE(6,*) VLWXTR,UPPXTR
      IF((DMAX.GT.UPPXTR).OR.(DMAX.LT.VLWXTR)) THEN
        WRITE(6, *) '*** WARNING: INPUT EXTREME VALUE IS UNREASONABLE.'
      ENDIF
      DO 150 I=1,100000
        ST=(VLWB+UPPB)/2
C         WRITE(6,*) 'TRY ST =', ST
        EXTRM=VMEXTR(IDUM, NFQ, DAVG, ST)
        DIFF=ABS(EXTRM-DMAX)
C         WRITE(6,*) 'I, GOAL, ESTM, ERR', I,DMAX,EXTRM,DIFF
C     USE 10000 INSTEAD OF 1000 IN THE FINAL CODE IN THE NEXT LINE.
        IF(DIFF.LT.DMAX/1000) THEN
          GOTO 160
        ENDIF
        IF(EXTRM.LT.DMAX) THEN
          VLWB=ST
        ELSE
          UPPB=ST
        ENDIF
 150  CONTINUE
      WRITE(6,*) '*** WARNING: EXTREME DOES NOT APPROACH CLOSE TO DMAX.'
 160  CONTINUE
C     WRITE(6,*) 'STD. DEVIATION & COV FOUND', ST, ST/DAVG
C     PAUSE
      STDD=ST
      END
```

Appendix C: Source Code of Program PITA

```
C*******************************************************************
C
C   THIS IS A PROGRAM TO INPUT EXTREME PITTING DATA AND CALCULATE
C   THE THICKNESS REDUCTION FOR A PITTED PLATE.
C
C   WRITTEN BY DR. KAI-TUNG MA AND DR. ORISAMOLU, JUNE 1995
C
C   INPUT:
C     NFQ  = NUMBER OF (FREQUENCY) PITS IN A 30X30CM PLATE
C     VMD   = AVERAGED DEPTH OF THE PITS
C     VMW   = AVERAGED WIDTH (DIAMETER) OF THE PITS
C     DX(1)= MAX DEPTH
C     DX(2)= SECOND MAX DEPTH
C     ..... UP TO FIVE MAX
C     WX(1)= MAX WIDTH
C     WX(2)= SECOND MAX WIDTH
C     ..... UP TO FIVE MAX
C     CC    = CORRELATION COEFFICIENT
C     CLNDR  = CYLINDER COEFFICIENT
C     IDUM   = -1 = SEED FOR RANDOM NUMBER GENERATION
C
C   OUTPUT:
C     THKRD  = THICKNESS REDUCTION
C
C*******************************************************************
      PROGRAM PITA
      INCLUDE   'RELFNCT.V20'
      IMPLICIT   REAL*8 (A-H,O-Z)
      DIMENSION  DX(5),WX(5)
      CHARACTER  FILEOUT*12

      WRITE(6, *) '----------------------------------------------'
      WRITE(6, *) 'THIS IS A PROGRAM TO INPUT EXTREME PITTING DATA'
      WRITE(6, *) 'AND COMPUTE THICKNESS REDUCTION FOR A PITTED'
      WRITE(6, *) 'PLATE.'
      WRITE(6, *) 'BY DR. KAI-TUNG MA AND DR. ORISAMOLU, JUNE 1995.'
      WRITE(6, *) '----------------------------------------------'
      WRITE(6, *)

      WRITE(6,*)'HOW MANY TRIALS (DEFAULT= 1000): '
      READ (5,'(I8)') NTRY
      IF(NTRY.EQ.0) THEN
        NTRY = 1000
      ENDIF
      WRITE(6,*) NTRY

      WRITE(6, *) 'HOW MANY PITS ON THE PLATE (DEFAULT= 20): '
      READ (5, '(I8)') NFQ
```

```
      IF(NFQ.EQ.0) THEN
        NFQ = 20
      ENDIF
      WRITE(6,*) NFQ

      WRITE(6,*)'HOW MANY EXTREMES FOR ESTIMATION (1-5) (DEFAULT=5):
      READ (5, '(I1)') NXT
      IF(NXT.EQ.0) THEN
        NXT = 5
      ENDIF
      WRITE(6,*) NXT

      WRITE(6, *) 'OUTPUT FILE NAME (DEFAULT= PIT.OUT):
      READ (5, '(A12)') FILEOUT
      IF(FILEOUT.EQ.' ') THEN
        FILEOUT = 'PIT.OUT'
      ENDIF
      WRITE(6,*) FILEOUT

      WRITE(6,*)'ENTER MEAN PIT DEPTH FOR SIMULATION (DEFAULT= 5.0):
      READ (5,'(F12.3)') VMD
      IF(VMD.EQ.0) THEN
        VMD = 5.0
      ENDIF
      WRITE(6,*) VMD

      WRITE(6,*)'ENTER MEAN PIT WIDTH FOR SIMULATION (DEFAULT= 10.0): '
      READ (5,'(F12.3)') VMW
      IF(VMW.EQ.0) THEN
        VMW = 10.0
      ENDIF
      WRITE(6,*) VMW

      WRITE(6,*)'ENTER STANDARD DEVIATION OF DEPTH (DEFAULT= 1.5): '
      READ (5,'(F12.3)') STD
      IF(STD.EQ.0) THEN
        STD = 1.5
      ENDIF
      WRITE(6,*) STD

      WRITE(6,*)'ENTER STANDARD DEVIATION OF WIDTH (DEFAULT= 3.0): '
      READ (5,'(F12.3)') STW
      IF(STW.EQ.0) THEN
        STW = 3.0
      ENDIF
      WRITE(6,*) STW

      WRITE(6,*)'CORRELATION COEFF. BETWEEN DEPTH & WIDTH (DEF.=0.9): '
      READ (5,'(F6.4)') CC
      IF(CC.EQ.0) THEN
        CC = 0.9
```

```
      ENDIF
      WRITE(6,*) CC

      WRITE(6,*)'ENTER CYLINDER COEFFICIENT (DEFAULT= 0.6667): '
      READ (5,'(F6.4)') CLNDR
      IF(CLNDR.EQ.0) THEN
        CLNDR = 4.0/6.0
      ENDIF
      WRITE(6,*) CLNDR

      IDUM=-1

      OPEN(UNIT=11,FILE=FILEOUT,FORM='FORMATTED',
     &                 STATUS='UNKNOWN',ERR=111)
      GO TO 110
 111    CONTINUE
        WRITE(6, *)
        WRITE(6, *) '*** WARNING: FILE OPENNING ERROR.'
        WRITE(6, *)
 110  CONTINUE
      PAUSE
C
C   TEST RANDOMNESS
C
      DO 1002 II= 1, NTRY
      WRITE(6,*) 'TRIAL NUMBER ', II
C
C   CREATE A SAMPLE OF SIZE NFQ IN A SQUARE PLATE.
C   THEN COMPUTE THE ACTUAL VOLUME LOSS.
C
      D_MN   = 0.0
      W_MN   = 0.0
      V_LOSS = 0.0
      DO 20 I=1,5
        DX(I) = 0.0
        WX(I) = 0.0
 20   CONTINUE

      DO 1001 I=1,NFQ
        CALL CRPAIR(STD,STW,VMD,VMW,CC,IDUM,D,W)
        D_MN = D_MN + D
        W_MN = W_MN + W
        V_LOSS = V_LOSS + CLNDR*3.14159*W*W*D/4
        CALL ORDER(D, DX)
        CALL ORDER(W, WX)
 1001 CONTINUE
      D_MN = D_MN / NFQ
      W_MN = W_MN / NFQ
C     WRITE(6, *) 'V_LOSS =', V_LOSS
C     WRITE(6, *) 'Maximum 5 Depths:        ',DX
C     WRITE(6, *) 'Maximum 5 Widths:        ',WX
```

```
C***********************************************************
C***********************************************************
C
C   CALCULATE THE MEANS OF DEPTH & WIDTH, EDM & EWM.
C   THIS WILL TAKE A FEW MINUTES.
C
      EDM = ESMN(IDUM, NFQ, STD, DX, NXT)
      EWM = ESMN(IDUM, NFQ, STW, WX, NXT)
      WRITE(6,*) 'EDM, EWM         ', EDM, EWM

C
C   CALCULATE STEEL VOLUME LOSS & THICKNESS REDUCTION
C
      EV_LOSS =0.0
      VOLMN =0.0
      N    =0
      DO 400 I=1,10000000
        VLOSS=0.0
        DO 390 J=1,NFQ
          CALL CRPAIR(STD,STW,EDM,EWM,CC,IDUM,D,W)
          VLOSS=VLOSS+CLNDR*D*(3.14159*W*W/4)
 390    CONTINUE
        EV_LOSS=(EV_LOSS*(I-1)+VLOSS)/I
        IF(ABS(EV_LOSS-VOLMN).LT.EV_LOSS/10000) THEN
          N=N+1
          IF(N.GT.100) THEN
            GOTO 410
          ENDIF
        ELSE
          N=0
        ENDIF
        VOLMN=EV_LOSS
 400  CONTINUE
      WRITE(6,*) '*** WARNING: VOLUME LOSS DOES NOT CONVERGE
     &                      WITHIN TOLERANCE.'
 410  CONTINUE
      THKRD=EV_LOSS/300/300
C     WRITE(6,*)
C     WRITE(6,*) 'VOLUME LOSS IN SIMULATED FIELD (ACTURAL):',V_LOSS
C     WRITE(6,*) 'VOLUME LOSS IN MATH MODEL (ESTIMATED):   ', EV_LOSS
C     WRITE(6,*) '                  -- IN CUBIC MM --'
C     WRITE(6,*) 'ERROR PERCENTAGE (%):', 100.0*(EV_LOSS-V_LOSS)/V_LOSS
C     WRITE(11,*) 100.0*(EV_LOSS-V_LOSS)/V_LOSS
      WRITE(6,*) 'THICKNESS REDUCTION IN MM: ', THKRD
      WRITE(6,*)
1002  CONTINUE
      CLOSE(11)
      WRITE(6,*) 'PROGRAM IS COMPLETED SUCCESSFULLY.'
      END
```

```
C******************************************************************
C
C   THIS SUBROUTINE INPUT X(1)...X(5), AND OUTPUT Y(1)...Y(5)
C   IN DESCENDING ORDER.
C
C******************************************************************
      SUBROUTINE ORDER(X,Y)
      IMPLICIT  REAL*8 (A-H,O-Z)
      DIMENSION  Y(5)

      IF(Y(1).LT.X) THEN
        Y(5) = Y(4)
        Y(4) = Y(3)
        Y(3) = Y(2)
        Y(2) = Y(1)
        Y(1) = X
      ELSE IF(Y(2).LT.X) THEN
        Y(5) = Y(4)
        Y(4) = Y(3)
        Y(3) = Y(2)
        Y(2) = X
      ELSE IF(Y(3).LT.X) THEN
        Y(5) = Y(4)
        Y(4) = Y(3)
        Y(3) = X
      ELSE IF(Y(4).LT.X) THEN
        Y(5) = Y(4)
        Y(4) = X
      ELSE IF(Y(5).LT.X) THEN
        Y(5) = X
      ENDIF
      END
C******************************************************************
C
C   THIS SUBROUTINE GENERATES CORRELATED LOGNORMAL
C   RANDOM VARIATES PAIR (D. W).
C
C   LOGNORMAL DISTRIBUTION
C   PAR1 = LOWER-BOUND
C   PAR2 = EPSILON
C   PAR3 = KSI
C
C   OUTPUT: D, W
C
C******************************************************************
      SUBROUTINE CRPAIR(STD,STW,VMD,VMW,CC,IDUM,D,W)
      INCLUDE   'RELFNCT.V20'
      IMPLICIT  REAL*8 (A-H,O-Z)
      REAL*4    GASDEV
      DIMENSION  PAR(2,5),S(2,2)
      DIMENSION  CRNM(2),RNDM(2)
```

```
      PAR(1,1)=0.0
      PAR(1,2) = 1.D0 + (STD/(VMD-PAR(1,1)))**2
      PAR(1,2) = SQRT(LOG(PAR(1,2)))
      PAR(1,3) = LOG(VMD-PAR(1,1))-0.5D0*PAR(1,2)**2

      PAR(2,1)=0.0
      PAR(2,2) = 1.D0 + (STW/(VMW-PAR(2,1)))**2
      PAR(2,2) = SQRT(LOG(PAR(2,2)))
      PAR(2,3) = LOG(VMW-PAR(2,1))-0.5D0*PAR(2,2)**2
C
C   GENERATE INDEPENDENT STANDARD NORMAL RANDOM PAIR RNDM(I)
C
      RNDM(1)  = DBLE(GASDEV(IDUM))
      RNDM(2)  = DBLE(GASDEV(IDUM))

C
C   GENERATE CORRELATED STD NORMAL VARIATE PAIR, CRNM(I)
C   BASED ON ALGORITHM IN 'SIMULATION AND THE MONTE CARLO METHOD'
C   BY RUBINSTEIN, PAGE 65-67, 1981
C
      S(1,1)=1.0
      S(1,2)=0.0
      S(2,1)=CC
      S(2,2)=1.0
      CRNM(1)= SQRT(S(1,1)) * RNDM(1)
      CRNM(2)= S(2,1)/SQRT(S(1,1))*RNDM(1) + SQRT(S(2,2)-S(2,1)*S(2,1)
     &      /S(1,1))*RNDM(2)
C
C   GENERATE CORRELATED LOGNORMAL PAIR, RNDM(I)
C
      RNDM(1)  = PAR(1,1) + EXP(CRNM(1)*PAR(1,2)+PAR(1,3))
      RNDM(2)  = PAR(2,1) + EXP(CRNM(2)*PAR(2,2)+PAR(2,3))
      D = RNDM(1)
      W = RNDM(2)
      END
C*******************************************************************
C
C   THIS FUNCTION 'MEAN_VALUE_EXTREME()' ESTIMATES THE
C   MEAN EXTREME VALUE OF 'nfq' LOGNORMAL VARIATES.
C
C*******************************************************************
      FUNCTION VMEXTR(IDUM, NFQ, AVG, ST, NN)
      IMPLICIT  REAL*8 (A-H,O-Z)
      TOTL=0.0
      TMP=0.0

      DO 130 I=1,1000000
        TOTL=TOTL+EXTR(IDUM, NFQ, AVG, ST, NN)
        VMXT=TOTL/I
        ERR=ABS(VMXT-TMP)
```

```
C
C    IF THIS TAKES TOO MUCH TIME, REDUCE '1000' IN NEXT LINE.
C
      VLMT=VMXT/1000
      IF(ERR.LT.VLMT) THEN
        NCOUNT=NCOUNT+1
        IF(NCOUNT.GT.8) THEN
          GOTO 140
        ENDIF
      ELSE
        NCOUNT=0
      ENDIF
      TMP=VMXT
 130  CONTINUE
 140  CONTINUE
    VMEXTR=VMXT
C     WRITE(6,*) 'MEAN EXTREME FOUND:', VMEXTR
    END

C*****************************************************************
C
C    THIS SUBROUTINE 'LNVARI()' GENERATES LOGNORMAL
C    RANDOM VARIATES 'VLN'.
C
C*****************************************************************
    SUBROUTINE LNVARI(IDUM, NFQ, AVG, ST, VLN)
    REAL VLN(NFQ)
    DO 120 I=1,NFQ
    VLN(I)=RANLGN(IDUM, AVG, ST)
 120  CONTINUE
    WRITE(6,*) VLN
    END
C*****************************************************************
C
C    THIS FUNCTION 'EXTR()' GENERATES LOGNORMAL
C    RANDOM VARIATES AND OUTPUT EXTREME (MAX) VALUES.
C
C*****************************************************************
    FUNCTION EXTR(IDUM, NFQ, AVG, ST, NN)
    IMPLICIT  REAL*8 (A-H,O-Z)
    DIMENSION XT(5)
    DO 119 I=1,NN
      XT(I) = 0.0
 119  CONTINUE
    DO 120 I=1,NFQ
      VLGN=RANLGN(IDUM, AVG, ST)
      CALL ORDER(VLGN, XT)
 120  CONTINUE
    EXTR=XT(NN)
    END
```

```
C*****************************************************************
C
C   THIS FUNCTION GENERATES A LOGNORMAL RANDOM VARIATE.
C
C*****************************************************************
     FUNCTION RANLGN(IDUM, VM, ST)
     IMPLICIT  REAL*8 (A-H,O-Z)
     REAL*4    GASDEV
     INCLUDE   'RELFNCT.V20'
     RR    = DBLE(GASDEV(IDUM))
     A     = LOG(1.D0+ST*ST/VM/VM)
     B     = LOG(VM)-0.5D0*A
     C     = SQRT(A)
     RR    = B + C*RR
     RANLGN = EXP(RR)
     END
C*****************************************************************
C
C   THIS FUNCTION ESTIMATES THE MEAN 'ESMN' BASED ON THE
C   PITTING NUMBER 'NFQ'. THE STANDARD DEVIATION 'SD' AND THE
C   EXTREMES 'VX(NX)'.
C
C*****************************************************************
     FUNCTION ESMN(IDUM,NFQ,SD,VX,NX)
     IMPLICIT  REAL*8 (A-H,O-Z)
     DIMENSION VX(5), EVX(5)
     TMPMN = 0.0
C    LOWER AND UPPER BOUNDS OF THE STANDARD DEVIATION
     DO 149 N=1,NX
     VLWB=0.00000000001*VX(N)
     UPPB=1.00000000000*VX(N)
     DO 150 I=1,100000
       VM=(VLWB+UPPB)/2
       EVX(N)=VMEXTR(IDUM, NFQ, VM, SD, N)
       DIFF=ABS(EVX(N)-VX(N))
       IF(DIFF.LT.VX(N)/1000) THEN
         GOTO 160
       ENDIF
       IF(EVX(N).LT.VX(N)) THEN
         VLWB=VM
       ELSE
         UPPB=VM
       ENDIF
 150 CONTINUE
     WRITE(6,*) '*** WARNING: EXTREME NOT APPROACH CLOSE TO VX.'
 160 CONTINUE
C    WRITE(6,*) 'ONE OF THE ESTIMATED MEANS FOUND:', VM, N
C    PAUSE
     TMPMN=TMPMN+VM
 149 CONTINUE
     ESMN=TMPMN/NX
     END
```

Appendix D: Determining the Acceptability of a Pitted Plate Panel

The following procedure may be used during the structural inspection of a ship to gather information for evaluation of the residual thickness and to determine the acceptability of a pitted plate panel in view of its residual strength:

- Pick the panel of plating to be inspected and measured.
- Observe the pitting occurrences within the panel.
- Locate a sample square 300 mm by 300 mm (12 in by 12 in) within the pitted panel that is visually judged to be representative of the full panel in terms of intensity, depth, and diameters of pits.
- Measure and record the following <u>within the sample square</u>:
    - The number of pits (N): Count the number of pits occurring in the sample square.
    - The average depth (μ_D): Measure and record the depth in millimeters of the pit visually regarded as having the average depth for the sample square.
    - The maximum depth (X_D): Measure and record the depth in millimeters of the deepest pit in the sample square.
    - The average diameter (μ_W): Measure and record the average diameter in millimeters of the pit visually regarded as having the average diameter of all the pits in the sample square. This may not necessarily be the same pit that has the average depth.
    - The maximum diameter (X_W): Measure and record the maximum diameter in millimeters of the pit visually regarded as having the maximum diameter of all the pits in the sample square. This may not necessarily be the same pit that has the maximum depth.

- The original thickness of the plate under consideration (t): Record the original plate thickness which is needed for an evaluation of wastage.

We now have the parameters needed to evaluate the residual thickness and strength of each plate panel for which a sample area has been chosen and measured as above:

N = Number of pits
μ_D = Average depth
μ_W = Average diameter
X_W = Maximum diameter
t = Original thickness

We first have to determine the thickness reduction due to pittings. This can be done in the field by using the various COV (Coefficient of Variation) plots given in Figures 5.1 through 5.6 of the report (also reproduced in the following pages) or in the office by using the PIT program.

A. Estimating the Thickness Reduction in the Field

1. To select the correct plot, calculate the COV for each sample square with the parameters recorded as follows:

$$COV = Variance / Mean$$

For the sample, pit depth $COV = (X_D - \mu_D) / \mu_D$

or COV = (Maximum depth-Average depth)/ Average depth

2. Next, determine if the Average diameter (μ_W) is close to 2.5 times the Average depth (μ_D) of the square under consideration. If this is true, then the graphs can be used to dermine the thickness reduction.

3. Enter the appropriate graph (Figures 5.1 to 5.6) with:

   - The COV from above
   - The number of pits (N) in the sample square for the plate panel under consideration
   - The average pit depth (μ_D) of the sample square.

4. Read the thickness reduction in millimeters for each entire plate panel under consideration.

B. Estimating Thickness Reduction in the Office:

Determination of thickness reduction in the office may be accomplished with the program PIT. PIT is a PC based FORTRAN program. The same five measured values as above are the input information for the PIT program for each sample square of a plate panel.

Two additional input features are needed for the PIT program: the correlation coefficient and the cylinder coefficient:

(1) Correlation Coefficient - This is a measure of the statistical dependence between the two random variables of mean pit depth and diameter in the sample square. The findings of the report indicate that this number should be 0.9 for the samples investigated (0.9 is the default of the program PIT) but can be modified for specific samples. When this value is close to one, deeper pits will have wider diameter and shallower pits will have smaller diameters. When this value is close to zero, the depth and width have no influence on each other.

(2) Cylinder Coefficient - This indicates how rounded the floor and vertical sides of the pit are in the sample square. A perfectly cylindrical pit would have a cylindrical coefficient of 1.0. Most pits have somewhat rounded bottoms and sides. The PIT program defaults to an elliptically shaped rounded bottom and vertical sides with a cylinder coefficient of 0.667. A different cylinder coefficient may be used depending on the actual sample squares, raising or lowering this coefficient to suit if necessary.

C. Determining the Acceptability of a Plate Panel with Pitting

(Note: This procedure can be used in association with A or B above).

An initial determination of the acceptability of a plate panel with pitting can be made on the basis of the pit depths.

- Individual Pits with depths less than 50% of the residual thickness can be repaired by epoxy as described in Section 5.1.3 of the report.
- Individual Pits with depth greater than 50% of the residual thickness may be welded if:
  - At least 6.5 mm (1/4 inch) of material remains at bottom of pit,
  - The distance between adjacent pits is at least 76 mm (3 inches), and
  - The maximum diameter of any welded pit does not exceed 305 mm (12 inches).

The total cross sectional area lost in any section of the pitted plate should not be more than 15%.

D. Determining the Residual Strength of a Plate Panel With Pitting

After calculating the residual thickness of the plate panel in question by deducting the thickness reduction from the original thickness, enter Figure 5.7 of the report (reproduced in the following pages) with this residual thickness and stiffener spacing of the panel. If the point of intersection of these two numbers falls to the left and above the governing s/t curve, then the plate can be retained, and will not present a buckling problem. If the intersection of these two numbers falls to the right and below the governing s/t curve, then the plate should be replaced as the residual thickness is such that buckling may be a problem and can compromise the structure.

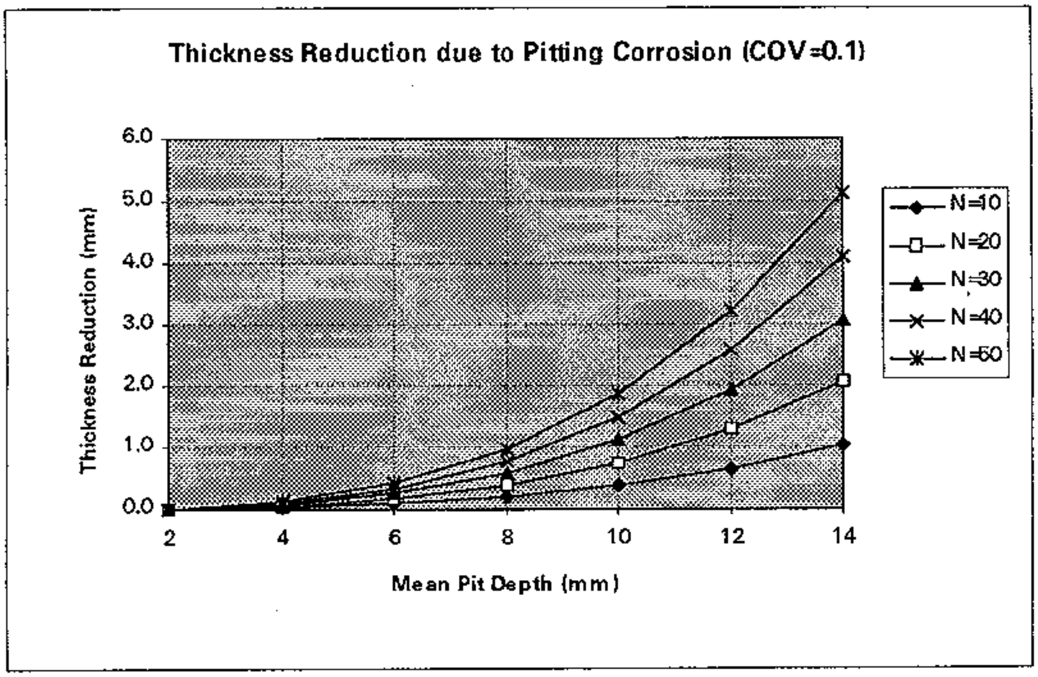


Figure 5.1: Thickness reduction while assuming the COV of pit depth and width to be 0.1.

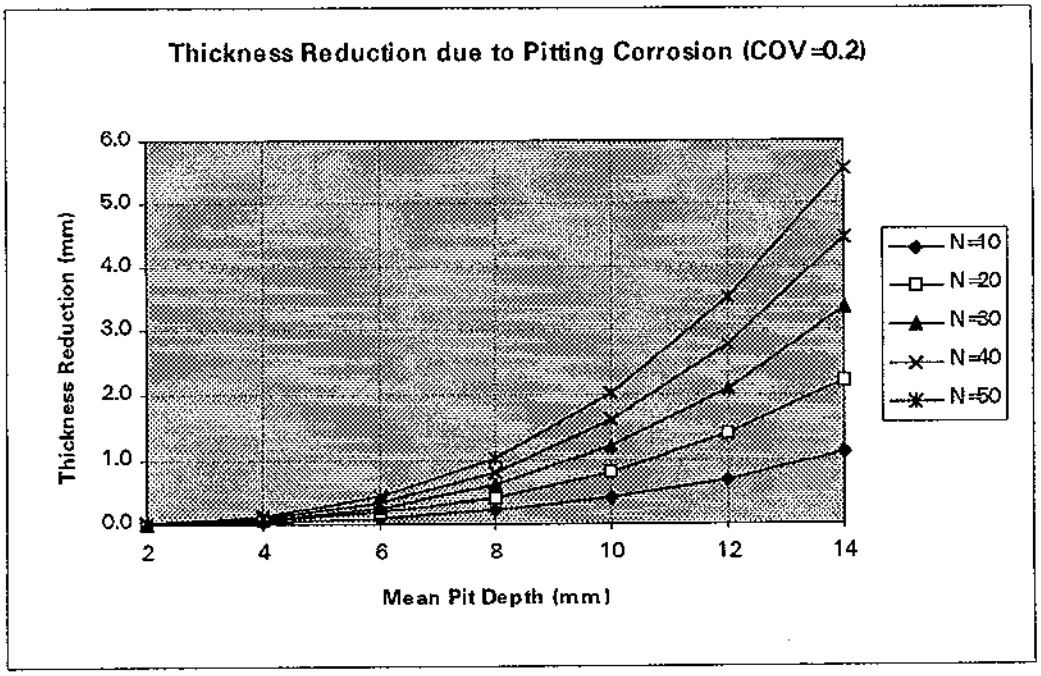


Figure 5.2: Thickness reduction while assuming the COV of pit depth and width to be 0.2.

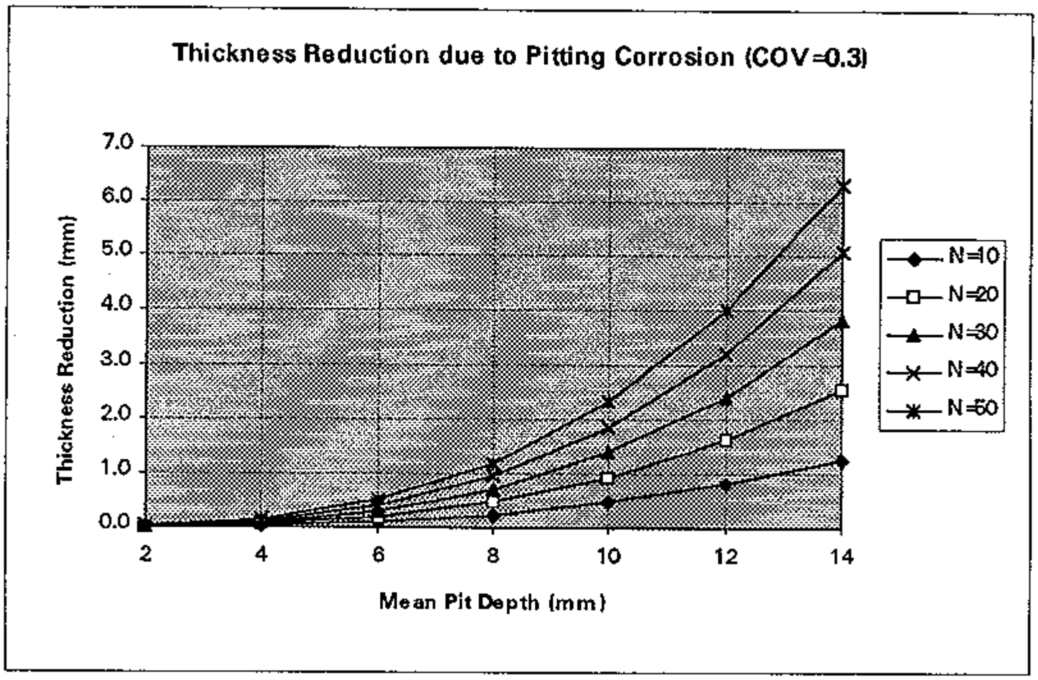


Figure 5.3: Thickness reduction while assuming the COV of pit depth and width to be 0.3.

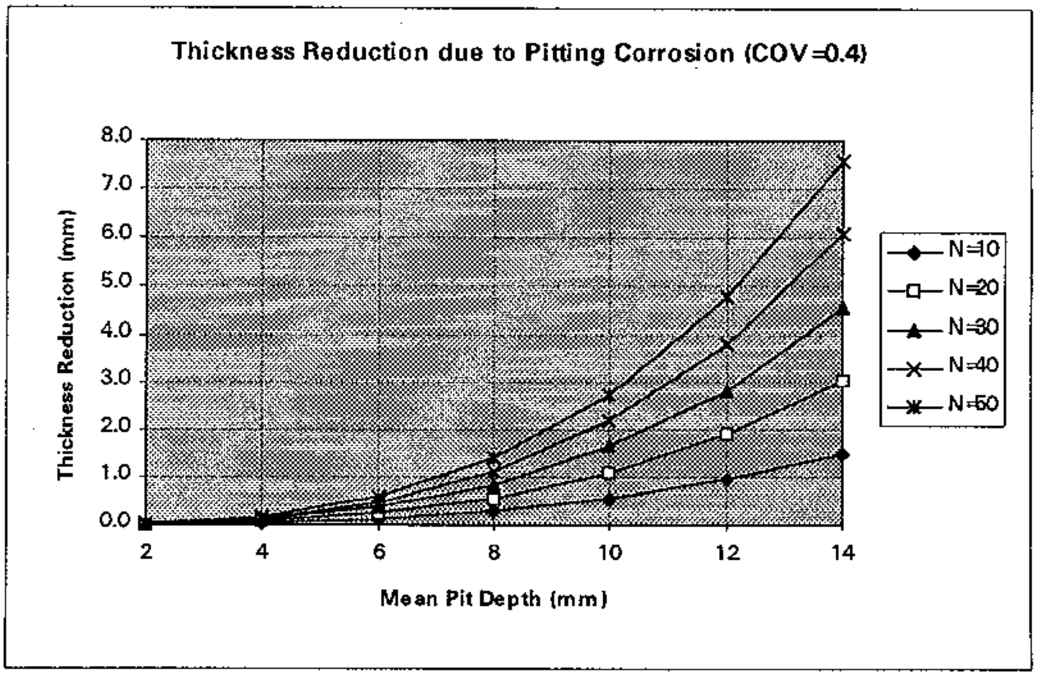


Figure 5.4: Thickness reduction while assuming the COV of pit depth and width to be 0.4.

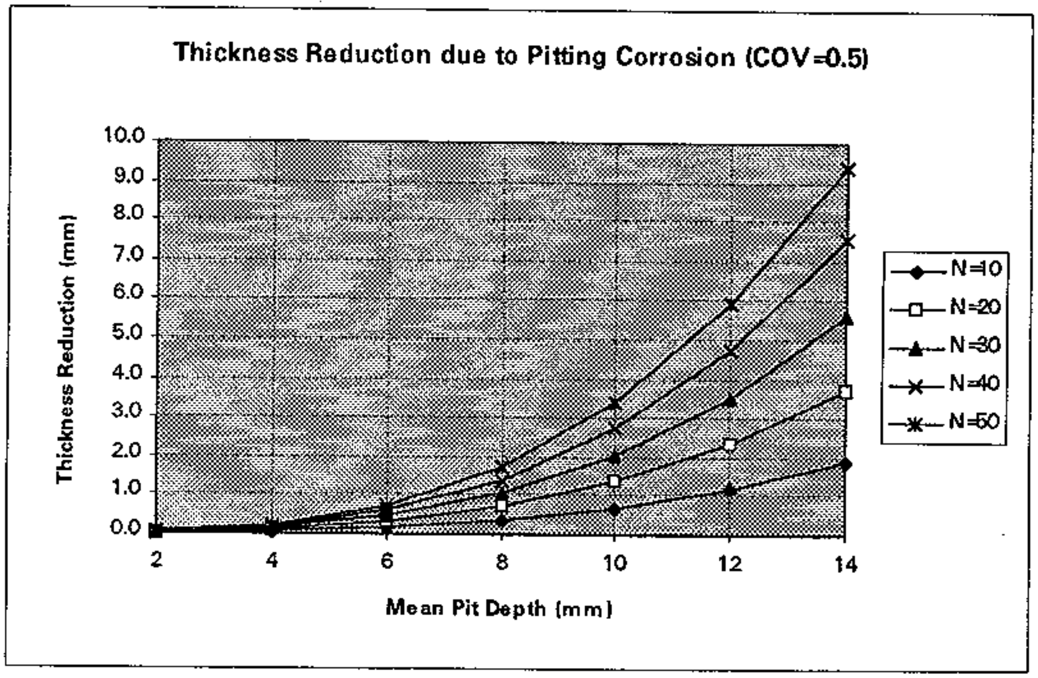


Figure 5.5: Thickness reduction while assuming the COV of pit depth and width to be 0.5.

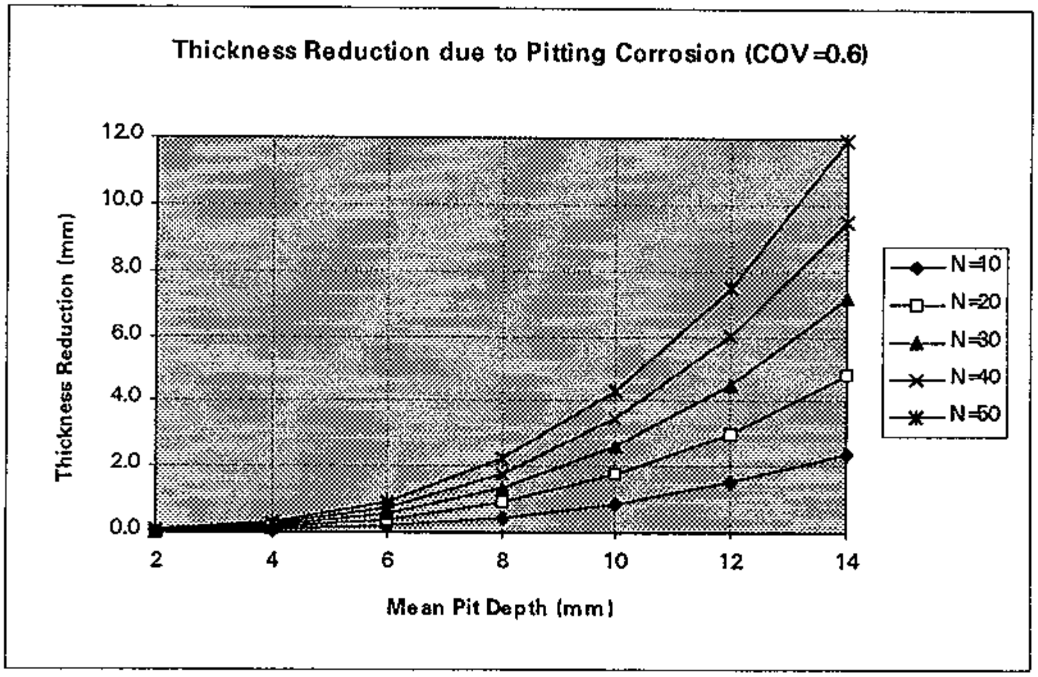
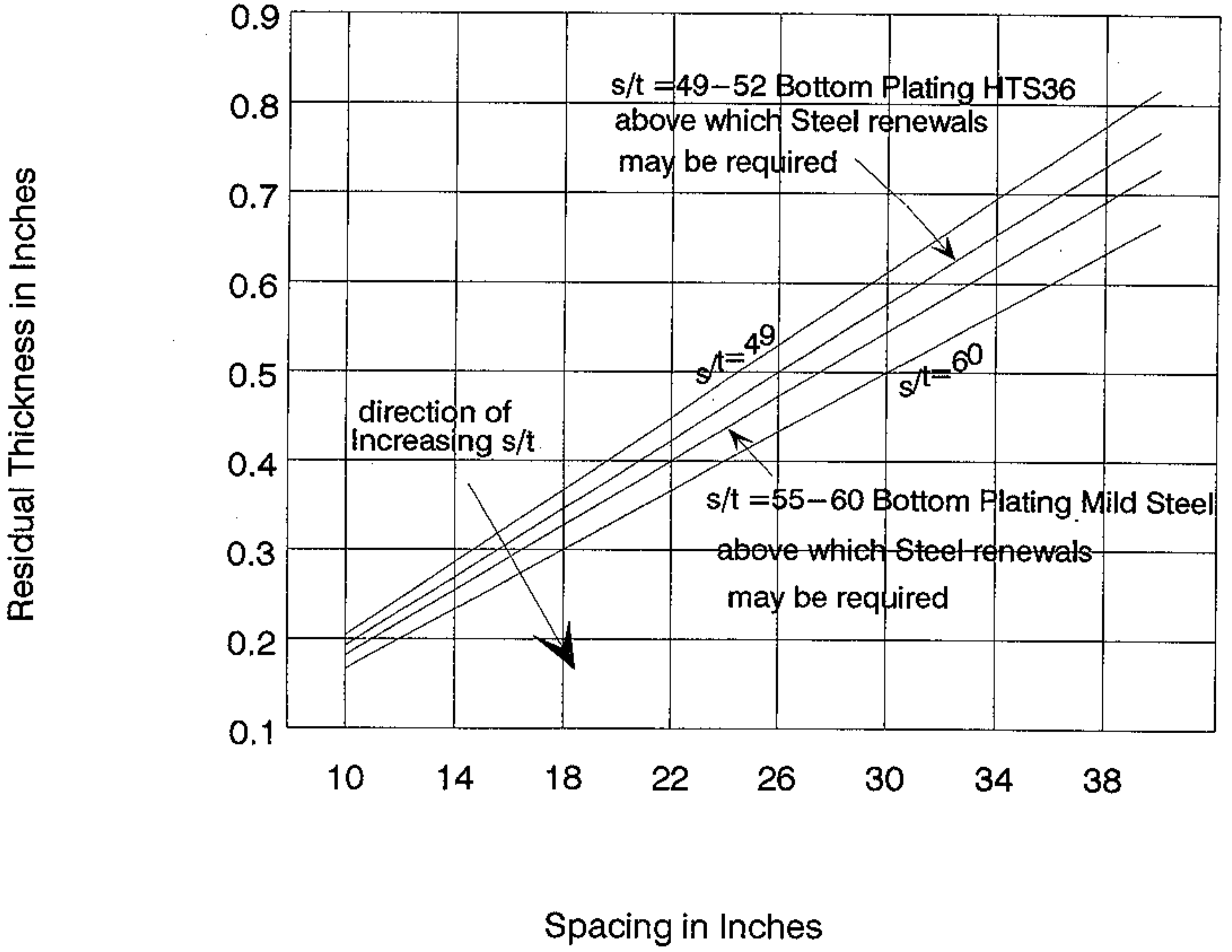


Figure 5.6: Thickness reduction while assuming the COV of pit depth and width to be 0.6.

Bottom Plate s/t Ratio

(Exceedance causes plate rejection)



Project Technical Committee Members

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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Mr. William Siekierka	Naval Sea Systems Command, Contracting Officer's Technical Representative
Dr. Robert Sielski	National Academy of Science, Marine Board Liaison
CDR Steve Sharpe	U.S. Coast Guard, Executive Director Ship Structure Committee

COMMITTEE ON MARINE STRUCTURES

Commission on Engineering and Technical Systems

National Academy of Sciences - National Research Council

The **COMMITTEE ON MARINE STRUCTURES** has technical cognizance over the interagency Ship Structure Committee's research program.

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