ASSESSMENT AND MONITORING OF CORROSION CONDITION OF STEEL SHIP STRUCTURES

A thesis

Submitted by

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Dedicated to my Family, Friends and Teachers

DECLARATION

I hereby declare that the work presented in this thesis entitled "**Assessment and Monitoring of Corrosion Condition of Steel Ship Structures"** is based on the original research work carried out by me under the guidance and supervision of Dr. A. Mathiazhagan, Department of ship Technology, Cochin University of Science and Technology, Kochi-22 and no part of the work reported in this thesis has been presented for the award of any degree from any other institution.

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ABSTRACT

Shipping industry plays a major role for the economic prosperity of maritime countries. Corrosion has been a known factor since metal was first used in the construction of ships and it causes accelerated decline in the material state of structures. Corrosion also causes several concerns on the safety of cargo, crew as well as the environment. Safe operation for almost 25 years is necessary to make the ships economically viable.

Based on a detailed literature review, a definite need was felt to develop an effective method to assess and monitor the corrosion condition of ship structures which can be an indicator of fitness for operations. Accordingly a new concept of “Corrosion Condition Index (C.C.I)” has been developed. The existing knowledge base on marine corrosion have been documented and incorporated in the formulation of C.C.I. The ship structure has been divided into six corrosion zones viz. Submerged zone, Splash zone, Atmospheric zone, Ballast tank zone, Cargo hold zone and Other Internal structures zone. These zones may be further subdivided into subzones depending on the size and complexity of each zone. Six major assessment criteria have been identified which will contribute towards the overall corrosion condition assessment of ship structures. These are Coating Condition (CC), Uniform Corrosion (UC), Localised Corrosion (LC), Cathodic Protection (CP), Fouling Condition (FC) and contribution of Design Factors (DF). A 10 point Assessment Level (A.L) has been developed for each of the above criterion with a lower A.L indicating a deteriorated state of corrosion condition. Each observed corrosion will have an impact on the Structure, Cargo, Environment, Safety of crew, Repair / maintenance cost, and Operational availability of ships. Accordingly, a corrosion consequence matrix has been developed to qualitatively assess the impact of corrosion and to assign a Corrosion Weightage (C.W).

The proposed approach involves conducting corrosion inspections at a subzone level, assigning of C.W and A.L for the relevant corrosion assessment criteria. Condition Indices (C.I) for a given subzone (i,j) for each assessment criterion are estimated as $(A.L)_{i,j}$ x $(C.W)_{i,j}$. The lowest of the C.I values will be the $C.C.I_{i,j}$ of the subzone, being representative of the most critical corrosion condition. This process is repeated for all subzones and the C.C.I of each zone ($C.C.I_i$) has been represented by the lowest of the $C.C.I_{i,j}$ values of its constituent subzones. Similarly the C.C.I of all corrosion zones and overall ship structure are determined. A C.C.I rating scale with recommendations has also been suggested for future operation of ships. Based on the C.C.I, the ship’s structure may be rated as ‘As built condition’, ‘Excellent’, ‘Very good’, ‘Good’, ‘Satisfactory’ or ‘Poor’. Three case studies for a given ship (in three different corrosion conditions) have been carried out to validate the proposed C.C.I rating system.

A user friendly Knowledge Based Decision Support System (KBDSS) has been developed as a web based application for corrosion assessment and monitoring of ship structures integrating the knowledge base compiled and the concept of C.C.I. The DSS has been designed as four functional modules viz. Project setup module, Corrosion observation module, CCI calculation module and Administrative functions module. The DSS will be highly useful for effectively monitoring the overall corrosion condition of ships by all stakeholders.

Recommendations for corrosion control has been suggested for different life cycle phases of ships along with a “Corrosion Control Model” (C.C.M) as a long term strategy to oversee the corrosion prevention and mitigation programme. This model illustrates the flow of information between life cycle phases and stipulates a framework for interaction between various stakeholders in the shipping industry

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ABBREVIATIONS

ABS	American Bureau of Shipping
AL	Assessment Levels
ASP.NET	Active Server Page. Network Enabled Technology
BAL	Business Access Layer
BDI	Baltic Dry Index
BLY	Business Logic Layer
BV	Bureau Veritas
$CC_{i,j}$	Coating Condition for subzone (i,j)
CAS	Condition Assessment Scheme
CAP	Condition Assessment Programme
C.C.B	Corrosion Control Booklet
C.C.I	Corrosion Condition Index
$C.C.I_{Ship}$	Corrosion Condition Index of Overall Ship Structure
$C.C.I_{Ext}$	Corrosion Condition Index of External Ship Structure
$C.C.I_{Int}$	Corrosion Condition Index of Internal Ship Structure
$C.C.I_{Sub}$	Corrosion Condition Index of Submerged Zone
$C.C.I_{Splash}$	Corrosion Condition Index of Splash Zone
$C.C.I_{Atmos}$	Corrosion Condition Index of Atmospheric Zone
$C.C.I_{Ballast}$	Corrosion Condition Index of Ballast Tank Zone
$C.C.I_{Cargo}$	Corrosion Condition Index of Cargo Zone
$C.C.I_{Otherinternal}$	Corrosion Condition Index of Other Internal Structures Zone
CDI	Chemical Distribution Institute
CI	Condition Index
CM	Corrosion Management
CP	Cathodic Protection
$CPC_{i,j}$	Cathodic Protection Condition for Subzone (i,j)
CSI	Clean Shipping Index
CW	Corrosion Weightage
DAL	Data Access Layer
$DF_{i,j}$	Design Factors Condition for Subzone (i,j)
DNV	Det Norske Veritas, Norway
DSS	Decision Support System

EEDI	Energy Efficiency Design Index
ESI	Environmental Ship Index
ESP	Enhanced Survey Programme
$FC_{i,j}$	Fouling Condition for Subzone (i,j)
GL	Germanischer Lloyd
GNP	Gross National Product
GRP	Glass Reinforced Plastic
HARPEX	Harper Petersen Index
HTML	Hyper Text Markup Language
HTTP	Hypertext Transfer Protocol
IACS	International Association of Classification Societies
ISM	International Safety Management
ISPS	International Ship and Port Facility Security
ICCP	Impressed Current Cathodic Protection System
KB DSS	Knowledge Based Decision Support Systems
KR	Korean Register of Shipping
$LC_{i,j}$	Local Corrosion Condition for subzone (i,j)
LBP	Length Between Perpendiculars
LOA	Length Overall
LRS	Lloyd’s Register of Ships
MEPC	Marine Environment Protection Committee
NKK	Nippon Kaiji Kyokai
OCIMF	Oil Companies International Marine Forum
PDR	Paint Deterioration Rating
PSC	Port State Control
QC	Quality Control
RAD	Rapid Application Development
SCCI	Ship’s Corrosion Condition Index
SDLC	System Development Life Cycle
SIRE	Ship Inspection Report Programme
SQL	Structured Query Language
$UC_{i,j}$	Uniform Corrosion Condition for subzone (i,j)
UI	User Interface
VLCC	Very Large Crude Carrier

Chapter 1

INTRODUCTION

1.1 General

Corrosion is a form of damage that has accompanied mankind since the introduction of metals thousands of years ago. Corrosion is the deterioration of a metal that results from an electrochemical or chemical reaction to its surrounding environment (Van Delinder and Brasunas, 1984). Corrosion of steel can be defined as an electrochemical process in which steel reacts with its environment to form an oxide similar to the ore from which it was originally obtained. Around 90% of world trade is carried by the international shipping industry and this industry plays a major role for the economic prosperity of maritime countries. Marine environment is one of the most naturally occurring corrosive environments due to the combined effect of saline seawater, salt laden air, dew, rain, localised high temperature, condensation and combustion gases. Ocean going ships travel across the world and experience these extreme marine environment and therefore corrosion of the steel hull is inevitable.

Merchant shipping is one of the most heavily regulated industries in the world and was amongst the first to adopt international safety standards. The shipping industry is subjected to uniform regulations on matters such as construction standards, navigational rules and standards of crew competence. This industry is principally regulated by the International Maritime Organization (IMO), for the safety of life at sea and the protection of the marine environment. There are over 50,000 merchant ships trading internationally, transporting every kind of cargo. The world fleet is registered in over 150 nations, and manned by over a million seafarers of virtually every nationality (International Chamber of Shipping, 2017).

Statistics for ship hulls show that 90 % of ship failures are attributed to corrosion (Melchers, 1999). Almost all metallic components of the ship including outer hull, superstructure, cargo holds and tanks, ballast tanks, fuel tanks, fresh, grey and black water tanks, bilges, pipe work, rudders, propellers, bearings, flanges, valves, pumps, void spaces, sea chests, stabilizers etc. undergo corrosion. Structural components susceptible to corrosion are highlighted on a ship's profile in Fig 1.1 and a few illustrative pictures are shown in Fig 1.2.

Corrosion is therefore prevalent throughout a ship's structure and it tends to manifest itself in a variety of commonly recognized degradation forms. The common types of corrosion that are observed on the ship structures can be classified as uniform corrosion, crevice corrosion, galvanic corrosion, pitting corrosion, erosion corrosion, microbial corrosion, stress corrosion cracking, high temperature corrosion, waterline corrosion, weld corrosion, corrosion under lagging and heat exchanger corrosion. Corrosion causes loss of cross-sectional area of the structural members and excessive loss of material may lead to failure. Deterioration of ship structures reduces global and local strength and can finally lead to disastrous casualties in rough seas. Literature on the influence of corrosion wastage on hull girder strength, local strength and fatigue strength has been reviewed by Wang et al. (2009).

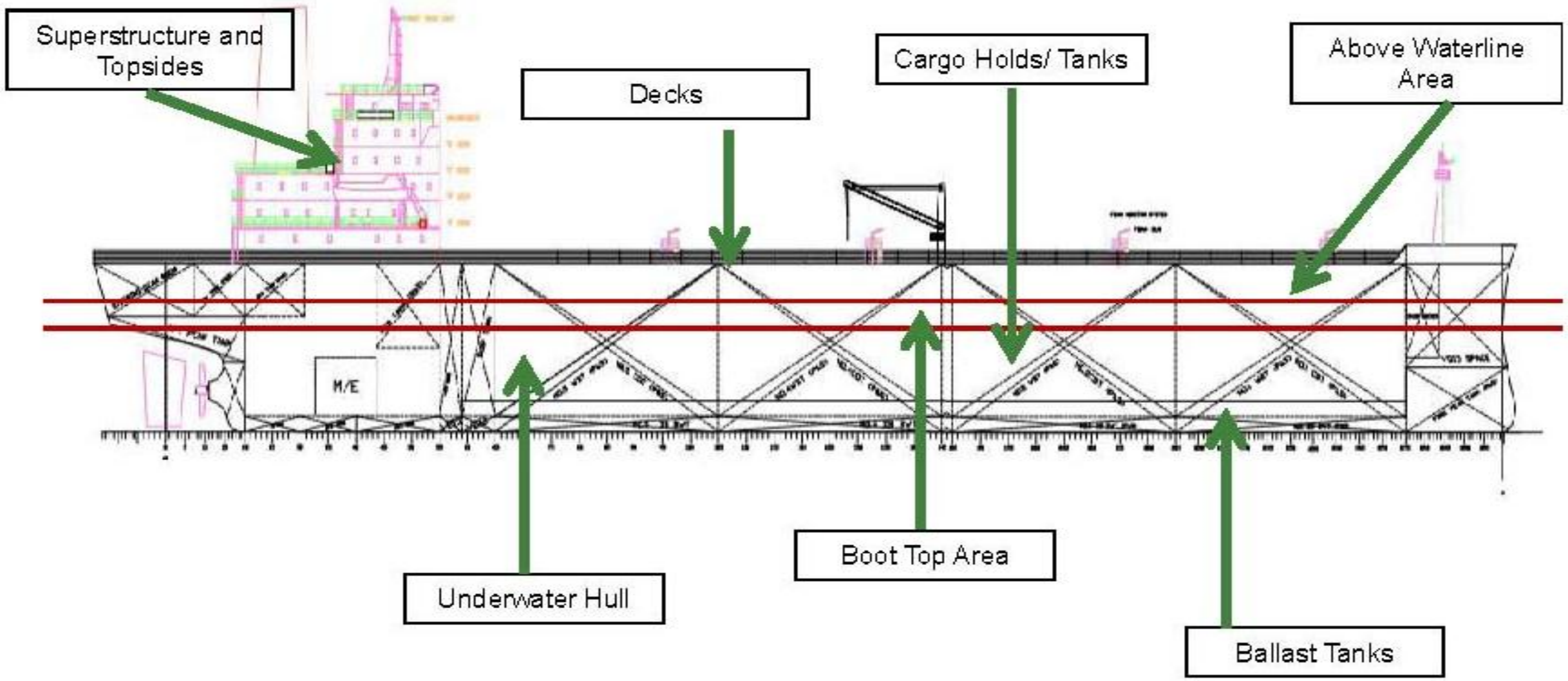


Fig 1.1 Ship structural components susceptible to corrosion

a) Corrosion of outer hull

b) Corrosion of super structure

c) Corrosion of internal structure

Fig 1.2 Corrosion of ships, illustrative pictures (BMT Defence Services, 2009)

Ayyub et al. (2000) have listed possible failure scenarios for a ship structure and classified the major consequences as impact on crew, cargo, environment, structure, cost of inspection and repair. The likely consequences due to corrosion of ship structures may be requirement for minor temporary repair, reduced operational availability, loss of capital etc. It may also result in more serious consequences such as adverse effect on ship safety, environment, injury or loss of human life. Further, the hull roughness due to various levels of corrosion and fouling would increase the frictional resistance of the ship. This additional resistance would demand higher power for a given speed, thereby adversely affecting the efficiency of propulsion system. It is therefore necessary to assess the impact level for each of the observed corrosion. The experience and judgment of corrosion inspector will be crucial in identifying the consequences of observed corrosion.

Depending upon the structure to be protected and its exposed environment, there is a wide range of anti-corrosion strategies that may be used. Major corrosion prevention and control methods for ship structures include addition of corrosion allowance to the thickness, additional layers of protection such as protective coating and the use of cathodic protection systems. Coatings are the primary line of defense against corrosion and selection of suitable painting scheme, application technique and maintenance practice will go a long way towards corrosion control of ships. Cathodic protection may be either a sacrificial anode system or an Impressed Current Cathodic Protection (ICCP) system. Cathodic protection systems that use sacrificial anodes to prevent the corrosion of the outer hull or ballast water tanks will be effective only when the sacrificial anodes and the structure are both under water. Once the sacrificial anodes are consumed, the protection will cease until they are replaced. Impressed current, i.e. ICCP, systems are used on the outer hull only, as they can generate hydrogen if they malfunction. Regular checks on ICCP performance is essential to ensure that the system is providing the required level of protection for the steel. Corrosion protection of spaces in ships that needs to be sealed for long periods of time can be achieved using vapour phase inhibitors. Larger spaces may be protected by dehumidification methods. In some instances, it may not be possible to mitigate corrosion either by design or material selection and so the management of the corrosion and its process must be actively considered. The strategies for the inspection, maintenance and repair of the components that can corrode and their protections systems, are necessary in all stages of the life cycle of a ship.

The cost of corrosion in India has been estimated as approximately ₹2 Lakh Crore per year (The Times of India, 2012). The direct cost of corrosion in India during 2011-12 is USD 26.1 billion (2.4% of GDP) and the avoidable cost of corrosion is estimated as USD 9.3 billion, which is equivalent to 35% of the direct cost of corrosion (Bhaskaran et al. 2014). Annual cost of corrosion in the shipping industry in USA is approximately $2.7 billion, which can be broken down into new ship construction ($1.1 billion), maintenance and repairs ($0.8 billion) and corrosion-related downtime ($0.8 billion) (NACE, 2002). JSCE and JACC (1999) have reported that the percentage of corrosion prevention measures in the total costs to build ships in Japan is approximately 6.2%. These costs include coating, corrosion resistant materials, cathodic protection, additional plate thickness, etc. and manpower costs. ASM International (2000) has reported that the cost of metallic corrosion in USA is approximately 4.9% of its GNP and 60% of which is unavoidable whereas remaining cost can be reduced by adopting certain best practices. They have also presented several generalized elements that combine to make up the total cost of corrosion. Long periods in service with short maintenance periods are necessary for the economical operation of ships and for this an effective corrosion assessment and monitoring system must be put in place. The massive cost of corrosion provides many opportunities to various stakeholders in the industry to reduce corrosion costs and risks of failure as well as to develop new mitigation strategies.

In a modern business environment, successful ship owners cannot afford major corrosion failures involving injuries, fatalities, unscheduled maintenance and environmental contamination. Ship owners and operators recognize that combating corrosion impacts significantly upon vessels' availability, reliability, through life costs and budget availability for future projects. Considerable efforts are therefore expended on corrosion control at the various stages of ship's life cycle. Decisions regarding the future integrity of ship structure or its components depend on an accurate assessment of existing corrosion condition. Corrosion inspections and monitoring are used to determine the corrosion condition of ship structure and to determine the effectiveness of corrosion control systems. With the knowledge on corrosion condition of the structure, feasible decisions can be made with regard to the type, cost and urgency of repair works. Irrespective of the age of the ship or trading areas, ship owners/ operators have now begun to see the benefits of preserving the outer hull and internals in terms of repair costs and downtime.

The shipping industry is very complex with the presence of a large number of stakeholders viz. Ship Designers, Shipbuilders, Ship Recyclers, Classification Societies, Ship owners/ charterers/ operators, Port/ Terminals, Government/ Regulators, Employees/ Unions, Customers, Investors/ Banks/ Insures, Public, and Media. The adverse effect of corrosion on cost, safety of cargo and employees, environment and operational availability makes almost all stakeholders concerned about corrosion in some way or other.

1.2 Literature Review

Publications available in the field of corrosion have been reviewed and classified into four broad categories viz. corrosion of ship structure and its control, corrosion inspections, monitoring and management, application of decision support systems and condition indices. The review and comments are given in the subsequent sections.

1.2.1 Corrosion of Ship Structure and its Control

The basics of corrosion, corrosive environments, corrosion protection systems, corrosion modeling, corrosion failure modes, corrosion inspections and monitoring of engineering structures have been discussed by Roberge (1999). Parente et al. (1996) have reviewed the corrosion control practices during the design, fabrication and operation phases of ships' life cycle. They have reported typical coating system failures, coating inspections, and methods to improve the coating life and also presented few recommendations for improving the corrosion control.

Berendsen (1998) has presented ship painting practices and systems that existed in Europe. The paper has described the most critical parts of a ship for coating protection, including the underwater/ boot top areas, ballast tanks, and cargo tanks. Particular attention has been given to the role of anticorrosive and antifouling systems for the underwater hull as well as boot top areas. Further, painting schemes for other areas of a ship such as the topside, superstructure and the decks have also been discussed.

DNV (1999) has presented a classification note describing the quality levels with regard to coating systems and their applicability to cargo tanks, holds and spaces. DNV (2000) has presented recommended practices and various recognized methods for corrosion protection of ships, with emphasis on tanks and holds. General specifications of coating systems, standards for coatings, check list for coating inspectors, materials and corrosion resistance, surface preparation of steel and coating condition evaluation on existing ships have also been presented.

Eliasson (2003) has reported the generic methods of preventing or mitigating corrosion of ship hulls such as preventing access to electrolyte, reversing the flow of electrons, use of corrosion resistant alloys and design corrosion allowances. Important areas that need protection have been identified as ballast tanks, underwater hull, topsides, decks, internal dry spaces and cargo tanks. Department of Defence, USA (2004) has presented a report on DoD Strategic Plan for corrosion prevention and mitigation articulating policies, strategies, objectives and plans to prevent, detect and treat corrosion and its effects on military equipment and infrastructure.

Paik et al. (2004) have described the mechanism of corrosion in marine structures and pointed out that in addition to general corrosion (which reduces the plate thickness uniformly); there will be other types of more localized corrosion patterns identifiable in ships. They have listed locations of a ship most susceptible to corrosion as wing ballast tanks, due to exposure of seawater, humidity, a salty atmosphere when empty, and increase in temperature when deck and sides are exposed to sunlight. The time in ballast is typically 50% for seawater ballast tank spaces which are usually empty in the loaded condition.

De Baere et al. (2009) and De Baere (2011) have presented parameters quantifying the corrosion in ballast tanks and evaluation of improving alternatives. BMT Defence Services (2009) have presented a report to draw the attention of potential ship owners to design considerations that will mitigate the risk of unexpected corrosion of vessels and significantly reduce their through life costs. They have also discussed the salient features of marine environment, types of marine corrosion, generic corrosion susceptible areas in a ship and various corrosion control strategies. Various types of corrosion prevalent in the ship structure include uniform corrosion, crevice corrosion, pitting corrosion, galvanic corrosion, stress corrosion cracking, microbiological corrosion, hydrogen embrittlement, erosion corrosion, high temperature corrosion, stray current corrosion, waterline corrosion, weld corrosion, corrosion under lagging and heat exchanger corrosion.

IMO (2004) has presented the report "International Convention for Safety of Life at Sea (SOLAS)", which was intended to provide an easy reference to SOLAS requirements applicable as on 1st July 2004. According to SOLAS Regulation 3.2, all dedicated seawater ballast tanks shall have an efficient corrosion prevention system such as hard coatings and cathodic protection systems. Tator (2004) has reported that cracking of paint due to brittleness or loss of flexibility with aging is considered a primary factor in corrosion damage to the steel structures of ships' hulls, notably in seawater ballast tanks. This cracking is typically found in areas of high stress concentrations such as sharp angles, fillet welds, transitions between structural details, etc. The cracking is more severe for structural details made of high strength steels than for normal strength steels. This is because of the thinner sheets of high strength steel compared to normal strength steel, and the lesser thickness results in greater flexing when the vessel is underway in rough seas.

IMO (2010) has stipulated the performance standards and guidelines for protective coatings for ballast tanks and provided recommendations to assist surveyors, ship owners, shipyards, Flag Administrations and other interested parties involved in the survey, assessment and repair of protective coatings. Technical fundamentals on corrosion and the rules applying to corrosion protection on ships, structural parts, components and structures under maritime environmental conditions has been presented by Germanischer Lloyd (2010). Classification requirements for structural materials, coating selection and application, coating repair and cathodic protection have been presented in detail. Examples of coating systems for different areas such as underwater hull, above water, ballast tanks, cargo holds, and void spaces were also presented.

A study on effects of corrosion and fouling on the performance of ocean going vessels has been reported by Munk et al. (2009). The operational factors influencing corrosion of cargo holds, ballast and oil tanks have been reviewed by Panayotova et al. (2010). Hydrex nv (2011) has presented an executive manual on how to choose the right ship hull coating system, from an economic and environmental perspective. Many factors which must be taken into consideration in devising a hull coating and maintenance system (such as protection of the hull from corrosion, erosion, cavitation and galvanic reactions, long-lasting, harmful effect on the environment, invasive species translocated by ships in the form of fouling attached to the hull, hydrodynamic qualities, resistance to biofouling and cost) have been discussed.

Lloyd’s Register (2012) has provided guidance notes on new IMO regulations regarding corrosion protection of crude oil cargo tanks, which will be useful for ship owners and ship builders. Following the incidents resulting from structural failure in oil tankers, the IMO has developed requirements aimed at mitigating corrosion in cargo oil tanks by way of performance standards. These performance standards are now being made mandatory by an amendment to SOLAS: regulation II-1/3-11, “Corrosion Protection of Cargo Oil Tanks of Crude Oil Tankers, adopted by Resolution MSC.291 (87)”.

Class NK (2013) has presented the technical background for providing corrosion additions and corrosion wastages for different structural members. Concepts of net thickness, wastage allowance and corrosion additions and their method of determination have been explained. They have considered minimum values of corrosion additions required as per common structural rules requirements appropriate for a 25 year operational life. The corrosion wastage allowance varies for different structural members. For example, the allowance for main deck plating, bottom plating, side shell plating, inner bottom plating and transverse bulk head plating for Tankers are 4 mm, 3 mm, 3.5 mm, 4 mm, 2.5 mm respectively.

Hydrex NV (2013) has presented best practices for corrosion prevention of submerged hulls and tanks of offshore vessels engaged in offshore oil and gas exploration such as drill ships, Floating Storage and Offloading units (FSOs), Floating Production, Storage and Offloading Vessels (FPSOs), and Floating Liquefaction, Re-gasification and Storage Units (FLRSUs). Unlike other ocean going ships, offshore vessels are required to stay on station without dry-docking for 20 to 40 years and present numerous risks of corrosion. The maintenance system of cargo holds, ballast tanks, and other surfaces which are susceptible to corrosion during the long operating cycle of a ship, can significantly impact the reduction or acceleration of the corrosion process. Naturally, high quality ship maintenance is expected to postpone corrosion, while poor maintenance accelerates it (Ivosevic et al. 2018).

1.2.2 Corrosion Inspections, Monitoring and Management

Roberge (2007) has discussed the corrosion maintenance, management and inspection strategies applicable for all industries. It has been brought out that corrosion management includes all activities throughout the lifetime of a structure or system that are to mitigate corrosion and corrosion induced damage, and also to replace the structure/ system that has become unusable as a result of corrosion. Corrosion management is the overall management system which is concerned with the development, implementation, reviews, and maintenance of the corrosion policy (Geary et al. 1997). The goal of corrosion management is to achieve desired level of ship operation at least cost. Corrosion audit is a corrosion management tool, which should be in place if effective corrosion management is to be achieved (Milliams, 1993). A cost-benefit assessment model for inspection and repair planning for ship structures subjected to corrosion deterioration has been proposed by Dianquing et al. (2005).

Assessing or predicting the extent of corrosion damage is a difficult objective. Sipes et al. (1991) have presented a methodology and data collection requirements that could be used to assess corrosion rates, damage and margins. A review of techniques for corrosion assessment and monitoring for reinforced concrete structures has been presented by Song and Saraswathy (2007). The test methods for evaluation of the degree of rusting on painted steel surfaces have been described by ASTM standard D610-01. The visual examples which depict the percentage of rusting also form part of the standard. This test method provides a standardized means for quantifying the amount and distribution of visible surface rust. The degree of rusting is evaluated using a zero to ten scale based on the percentage of visible surface rust. The distribution of the rust has been classified as spot rust, general rust, pinpoint rust or hybrid rust. ASTM D 714 describes methods for evaluating degree of blistering in paints.

A Hull Inspection and Maintenance Program (HIMP) to assist owners and operators to effectively inspect and maintain the hull structure on their vessels has been presented by ABS (2012). Though the ABS encourages the HIMP as a means for maintaining compliance with classification and statutory requirements between surveys, these are not an alternative to, or a substitute for, classification and/or statutory surveys of the hull by the Classification Societies. The manual describes various inspections (annual, intermediate and 5 year inspections) as well as the ship structural members that are to be inspected.

A document titled “Inspection Grading Criteria” for the ABS Hull Inspection and Maintenance Programme has also been presented by ABS. The hull condition assessment and rating in accordance with a set of six general condition criteria as per the finding of corrosion inspections have been documented. The proposed six inspection criteria are coating condition, presence of general corrosion, presence of pitting or grooving or other localized linear corrosion, presence of deformation, presence of fractures and compartment or space cleanliness. A rating system of “0 through 6 scale” for each compartment has been presented along with tabular and visual highlights for easy understanding.

Guidance notes on application and maintenance of marine coating systems have been presented by ABS (2007) and ABS (2009) incorporating pictorial representation of coating assessment scales. The coating conditions have been classified to Good, Fair and Poor. This grading system can be utilised for the purpose of assessing the effectiveness of existing coating systems. DNV (2012) has reported a practical risk based approach to corrosion management as per the principles of ISO 31000:2009 ‘Risk Management - Principles and Guidelines’. The objective of this approach has been to improve the cost-effectiveness of corrosion inspection and treatment of offshore vessels in operation, and at the same time to reduce the risks of incidents and downtime. It has further provided a practical guidance for the surveyor to inspect and assess the condition of the structure related to corrosion and corrosion protection. A typical risk assessment matrix for an offshore structure has also been presented. It has proposed a five step approach viz. pre-assessment, screening and risk ranking, detailed examination, remediation and life cycle management for the condition assessment.

IACS No 127 (2012) has presented classification of risks in ship operations into five groups viz. Trivial, Tolerable, Moderate, Substantial and Intolerable. The recommended responses for the above cases have also been discussed. The risk should be reduced to a level that is “As Low As is Reasonably Practicable (ALARP)”. Regulations on Performance Standard for Protective Coatings (PSPC) for dedicated seawater ballast tanks in all types of ships have been promulgated by IMO Resolution MSC.215 (82) (2006). Regulations for new construction stage, in-service maintenance, repair and partial recoating, coating technical file, coating performance standards, design of coating system, approval procedures, coating inspections have also been described in this IMO resolution.

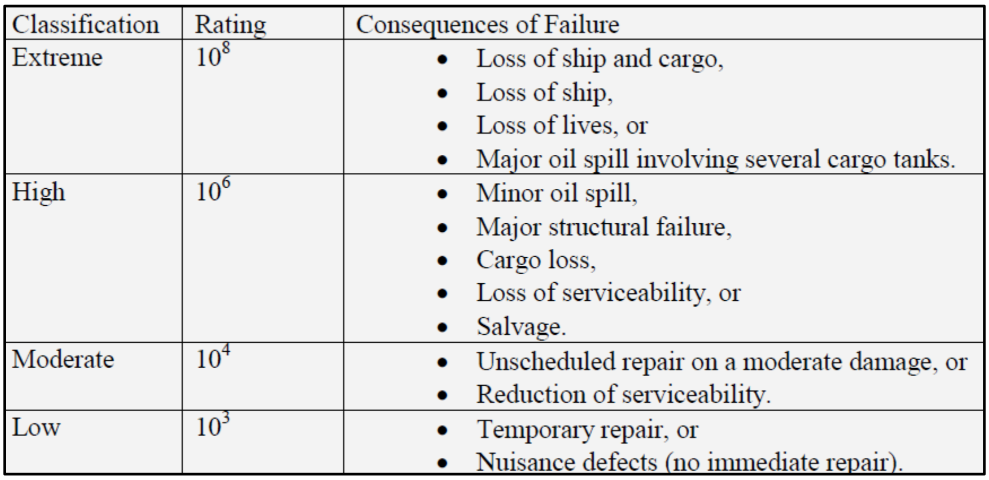
Condition Assessment Programme (CAP) is a quality measurement tool for older vessels. A rating system of such vessels with a scale varying from 1 (best) to 4 (lowest) has been described by DNV (2005). Main benefit of CAP is to have a vessel judged based on the actual condition onboard rather than the age. The CAP has been described as a consultancy service, which is independent, yet complementary, to ship classification. CAP rating scales 1, 2, 3 and 4 indicate vessel’s condition as very good, good, satisfactory and poor condition respectively. The CAP rating is based on an extensive inspection of the vessel to identify the extent of corrosion and defects. It has proposed separate rating of ballast tanks, cargo tanks and void spaces, external structure (main deck, ship sides and bottom) and for structural strength. Owner’s hull inspections and maintenance schemes have been encouraged as a means of maintaining compliance with classification and statutory requirements by IACS PR 33 (2009). Major Classification Societies have published guidance for the implementation of IACS PR 33. Few Classification Societies provide software tools to assist owners in planning inspections and storing data of vessel conditions. A summary of guidance and software provided by Classification Societies to assist inspections has been reported by Wang et al. (2009).

The requirements of a Structural Health Monitoring System for US naval ships have been presented by Ignacio et al. (2010) and stated that the health monitoring technologies can contribute to reducing the vessel's life cycle cost. They have reported some of the potential benefits such as better understanding of the materials, input for future structural designs, enhancing confidence levels, aiding decision making process of life extension programs or sales to commercial companies/ foreign governments and providing monitoring capability.

Ayyub et al. (2000) have presented risk based guidelines for managing and maintaining integrity of ship structures in a life cycle framework. They have listed possible failure scenarios for a ship structure and a cause-consequence diagram has been presented which can be used to assess the severity of consequences. They have classified the consequences as effect on crew, cargo, environment, structure, cost of inspection and repair. Wang et al. (2009) have presented statistical information on aging ship structures, various forms of structural degradation and measures in mitigating them. The report has provided a consolidated list of various maritime inspections (by IMO, Classification Societies, Port State, Flag State, insurance companies, cargo owners and ship owners), Performance Standards for Protective Coatings (PSPC), non-destructive inspection methods and management of hull condition data. They have also presented consequences of corrosion wastage such as influence on hull girder strength, local strength, fatigue strength and leaking potential. They have further predicted that there will be continuous activities in research and development related to structural health monitoring. A summary of rating system for consequence of failures, various ship inspections and guidance/ software tools provided by Classification Societies to assist ship are given in Tables 1.1, 1.2 and 1.3 respectively.

Ringsberg et al. (2018) have investigated the effect of progressive deterioration due to corrosion on the ultimate strength of a ship which has been collided by another vessel. They have found that the crash worthiness of the vessel reduces significantly as the corrosion margin reduces. Corrosion causes loss of cross sectional area of the structural members. Two additional factors that have an impact on strength reduction are stress concentration due to corrosion pits and change in material parameters caused by corrosion (Garbatov et al. 2016.

Table 1.1 Rating system for Consequences of Failures (Ayyub et al. 2000)



Classification	Rating	Consequences of Failure
Extreme	10^8	• Loss of ship and cargo, • Loss of ship, • Loss of lives, or • Major oil spill involving several cargo tanks.
High	10^6	• Minor oil spill, • Major structural failure, • Cargo loss, • Loss of serviceability, or • Salvage.
Moderate	10^4	• Unscheduled repair on a moderate damage, or • Reduction of serviceability.
Low	10^3	• Temporary repair, or • Nuisance defects (no immediate repair).

Capcis (2001) has documented the best practices from the offshore industry on corrosion management for processing facilities. Many of the problems and solutions described in this report have application to oil & gas production including design, installation, production and transportation for onshore and offshore facilities. It has defined corrosion management as "that part of the overall management system, which is concerned with the development, implementation, review and maintenance of the corrosion policy." Kalghati et al. (2009) have reported the various stakeholders for a vessel's hull condition, drivers/ opportunities, traditional inspections and use of management hull inspections through software. Cabos et al. (2008) have presented a Hull Condition Model (HCM) to increase ship safety through improved hull condition monitoring. Particular focus of the project has been on increase in the efficiency and quality of the thickness measurement process including the use of a robot.

Table 1.2 Summary of Various Ship Inspections

Organization	Survey Types	Inspection Area/ Item	Applicability
IMO	Initial, Annual, Intermediate, Periodical/ Renewal Surveys	Safety, Pollution, Load line, ISM, ISPS	All types of ships
Classification Societies		Hull & Machinery	
Port State	On purpose	Hull and Machinery, Safety, Pollution, Load line	
Flag State	Initial, Occasional, Periodical		
Insurance Company	Insurance Inspections	CAS / ESP (mandatory)	Tanker, Bulk, Carriers (mainly)
Terminal Operators	Safety & pollution prevention survey	Cargo handling equipment, Procedures	Oil & Chemical Tanker, Bulk Carriers, Gas Carriers
Cargo Owners	Charterer/ Vetting (oil majors, CDI, OCIMF/SIRE, etc.)	CAP, Cargo operation survey on purpose, Risk-based analyses	
Ship Owners			

Table 1.3 Guidance and Software Provided by Classification Societies to Assist Hull Inspections

Classification Society	Guidance for Qualified Inspectors	Hull Monitoring Guidance	Online Access of Inspection Record	Software for Inspection and Data Management
ABS	Yes	Yes	Yes	Safenet
DNV	Yes	Yes	Yes	Nauticus
BV	Yes	Yes	Yes	VeriSTAR Hull 5
GL	PSC Checklist	Yes	Yes	Poseidon, Pegasus, Ship Manager
LR	PSC Checklist	Yes	Yes	Class Direct Live, Ship Right, Hull Integrity
KR	Yes	Yes	Yes	InfoShips, Sea Trust
NKK	-	Yes	Yes	PrimeShip- HULL Care
RINA	PSC Checklist	Yes	Yes	Leonardo Hull

1.2.3 Application of Decision Support Systems

Waterman and Donald (1986) have defined an expert system as “a computer program that uses expert knowledge to attain high levels of performance in a narrow problem”. These programs typically represent knowledge symbolically, examine and explain their reasoning processes, and address problem areas that require years of special training and education for humans to master. Turban et al. (2007) have presented various features of Decision Support Systems (DSS) such as System Development Life Cycle (SDLC), prototyping, forming the development team, complex process, technical issues, behavioral issues and different approaches.

Decision makers have been seeking help from information technology over the past few decades in order to cope with the decision environment and make better decisions. Decision Support Systems are one of the most widely used management information systems in current operations management in many industries. The managers use Knowledge Based DSS (KB-DSS) to improve their decision making not only in terms of speed and accuracy but also consistency. The DSS can provide the right information at the right time in the right format with “what-if” analysis of decision alternatives. It can also provide effective interaction mechanisms so that information and analysis of results can be presented to decision makers in an easy to understand manner (Shaofeng et al. 2015).

The classic DSS architecture typically comprises of three core components viz. a Database Management Sub-system (DBMS), a Model Base Management Sub-system (MBMS), and user interaction management sub-system which is also called a Human Computer Interface (HCI). The integration of the knowledge management function into classic DSS can improve decision making performance by enhancing the quality of services by having an "expert" readily available to users when human experts are in short supply. It can also assist users to make their decisions more consistently. The most important component of a KB-DSS is a Knowledge Base and an Inference Engine (Akerkar and Sajja, 2010).

Vikas (2016) has presented development of web based decision support system for port planning, design and green port rating incorporating the modular design. Katsoulakos and Hornsby (1989) and Sivaprasad (2010) have listed application of expert systems in the following areas of marine technology:-

a) Classification type of expert system which is used for fault diagnostics, communication and ship classification.

b) General advice category is useful in implementing international convention guidelines in life cycle activities of ships, operation costing of ships and generation of shipping information.

c) Design oriented expert systems are used to develop decision support in ship machinery designs.

d) Planning and scheduling type of expert systems are implemented in voyage planning/ scheduling and planning of maintenance and surveys.

e) Monitoring category type of systems is suitable for fleet management and equipment monitoring.

f) Simulation and prediction based expert systems are helpful in predictive maintenance programmes and freight rate predictions.

g) Identification oriented systems are applied in weather monitoring, surveillance, navigation and position control.

h) Control based systems are widely used in ship management, bridge integrated control and dynamic positioning.

The requirements of a Corrosion Control Information Management System (CCIMS) for warships have been reported by Pluta (2002). Ardian and Condanni (1994) have presented an expert system developed for the assessment of fluid corrosivity in oil and gas production wells and for the selection and evaluation of metallic materials. Main aim of the system has been corrosion assessment, material selection and compatibility evaluation, risk assessment and analysis of suitable corrosion control methods. The system has been developed as individual specialist modules, able to provide the user with some partial answers (such as corrosion rate, likelihood of localized corrosion, stress corrosion cracking susceptibility, suitability of a material, etc.) or the final solution (i.e. the corrosion control method).

An expert system for the diagnosis of corrosion problems in underground electricity distribution equipment has been reported by Mayer (1994). The function of this expert system (CORRUND) was to assist utility personnel during equipment inspection and/or failure investigation to recognize, identify and assess corrosion damage. The paper has described the method of knowledge collection, software development, user interface as well as actual usage at site.

Makkonen and Foster (2001) have presented an expert system to assist the analysis of super heater fireside corrosion in boilers. The corrosion chemistry is determined by the measured and calculated quantities of the corrosion products. Two different methods based on rule-based boolean logic and on fuzzy logic have been tested. The output comprises of estimated corrosion rates, wall thicknesses, detected corrosion chemistry and calculated remaining lifetime for the tube material. Unar (2007) has reported the application of Artificial Neural Networks (ANN) in Naval Architecture and Marine Engineering and presented a method for identification of hydrodynamic coefficients particularly roll damping coefficient of a ship. Major applications of ANNs reported are preliminary ship design, stability calculations, estimation of wave induced bending moment, automatic hull form generation, identification of damping and restoring moments, simulation of motions and control systems.

Development of an expert system for diagnosis of problems in reinforced concrete structures has been reported by Peter (1996). The Reinforced Concrete Diagnosis Expert System (RCDES) has been implemented as a prototype rule based system by integrating the different modules. The report has discussed the typical knowledge acquisition process for building an expert system, design, development and validation process of expert systems.

Rule based requirements and the practical need for a decision support system in the case of flooding emergency on a passenger ship has been presented by Pennanen et al. (2015). The DSS has considered integration of status of water tight doors, flood level sensor data and the loading condition with time-domain prediction method for progressive flooding and stability of a damaged ship. The development of an inference engine in an intelligent ship course keeping system has been reported by Borkowski (2017) using the hydrodynamic data obtained by sensors. The author has reported that this expert system will be useful for decision making during ship navigation. Insel et al. (2018) have presented development of an online decision support system for energy efficient ship propulsion arrangement for cargo ships. The operational parameters considered are based on selecting the optimized trim, speed, propeller rpm and pitch for energy efficiency. Variation of these parameters according to the loading conditions, weather and sea state conditions (such as wave height/ direction and wind speed/ direction) have been considered by this DSS.

1.2.4 Condition Indices

The condition assessment of any structure is based upon objective and repeated measurements which, when processed by an algorithm, produce a numeric indicator, the Condition Index (C.I). It is a snapshot look at the condition of a part or component of a particular structure or a structural component. The development of C.I and potential benefits in C.I utilization has been presented by Stuart et al. (2001). They have also presented a list of specific examples where C.I data have been successfully utilized.

Review of various indices used in the field of shipping was also carried out. Environmental Ship Index (ESI) is a measure of ship’s air emission performance (WPCI, 2009). Clean Shipping Index (CSI) is being used as a tool for cargo owners and transport purchasers to select environmentally well-performing shipping services (Sara, 2011). Emissions from ship’s exhausts into the atmosphere can potentially be harmful to human health and may also contribute to global warming. As a measure to reduce emissions of greenhouse gases from international shipping, IMO’s Marine Environment Protection Committee (MEPC) has developed the

Energy Efficiency Design Index (EEDI) since 01 Jan 2013. Other shipping economic indices being used are Baltic Dry Index (BDI), Harper Petersen Index (HARPEX) and Clark Sea Time Charter Index.

1.2.5 Inference

There are many published technical papers, research reports and regulations on corrosion, corrosion protection, inspections and standards with respect to corrosion of ships. Though there are well established methods such as corrosion allowance, protective coating and cathodic protection for fighting against corrosion, it was observed that corrosion was generally treated as a reactive subject and was not getting the attention it deserves. Ships are expected to be in service for more than 25 years to be financially viable. A definite need was felt to develop a comprehensive method to assess the corrosion condition of the ship during her operation period which can be an indicator of fitness for the future operation in the seas.

Decision Support Systems are widely used for several applications in the field of shipping and a few cases of development are reported for corrosion problems. However, there is no reported development of a Knowledge Based Decision Support System (KBDSS) in the field of corrosion condition assessment and monitoring of ship structures. The DSS can facilitate as a user friendly web based application to guide the user to systematically interpret the corrosion observations and accurately predict the corrosion condition of ship structures by giving expert advice.

Shipping is a complex industry with the presence of several stakeholders, whose action has direct or indirect effect on the corrosion condition of structures. Ships are very costly assets and the management of corrosion is also very expensive from a life cycle perspective. It is felt that an overall Corrosion Control Model (C.C.M) is necessary to oversee the corrosion control aspects incorporating the involvement of all stakeholders, and recommended practices during design, building and operation periods. Such a model will be highly beneficial to reduce the overall life cycle cost of ships.

1.3 Scope and Objectives

The major objectives of the proposed research work are as follows:-

- To review the existing industrial practices for corrosion control during the design, construction and operation phases of ships making use of classification society guidelines, shipyard practices, design guidelines, research articles/ documents, user manuals etc.
- To develop a system to assess the corrosion condition of hull steel at any point of ship's service life and to assign a Corrosion Condition Index (C.C.I) to a ship which will be a measure of its susceptibility to corrosion.
- To develop a Knowledge Based Decision Support System (KBDSS) to help in the decision making process for corrosion monitoring of ship structures during the operation phase.
- To suggest best practices for:-
    - Corrosion control during each phase in the life cycle of ships.
    - Development of a corrosion control model for effective corrosion monitoring of ship structures.
    - Integration of the roles of all stakeholders involved in the shipping industry for corrosion monitoring of ship structures.

Corrosion assessment and monitoring is an unavoidable continuous activity during a ship's operational period. The primary objective of the research is to develop a system to assess the corrosion condition of a ship at any point in the service life and to assign a Corrosion Condition Index

(C.C.I), which will be a measure of its susceptibility to corrosion. Being the most important material used for shipbuilding, only structural steel components would be considered in the present work. Further, a qualitative assessment of parameters influencing corrosion of ship structure will be attempted based on the type, extent as well as the envisaged severity of consequences. The research would recommend a C.C.I rating system based on which decisions on future operations may be arrived.

The KBDSS may be developed as a corrosion assessment and monitoring tool for an existing vessel or for a new vessel. For an existing vessel, any change in the level of corrosion at any location will change the overall corrosion condition. The users of KBDSS would be able to access the built-in knowledge and input data by answering the questions with a user interface. Further, the KBDSS would generate an easy to understand report and be implemented as a web application to make it available for all stake holders from any part of the world.

The best practices will constitute a set of broad guidelines/ instructions based on the domain knowledge base collated as part of the research work. Separate recommendations would be made for the design, building as well as operational phase of ships. The stakeholders involved at different stages of ship's life cycle will be identified and their roles will be specified. The Corrosion Control Model would integrate the activities of all stakeholders with respect to corrosion and describe the flow of information between life cycle phases.

1.4 Research Methodology

Extensive review of literature on corrosion and corrosion control of ship structure has been carried out in order to make a comprehensive assessment of research problem. Available literature from text books, research papers, theses, statutory body documents, classification society rules, inspection manuals etc. has been reviewed. Further, visits to ships and shipyards to physically observe the corrosion problems, corrosion control practices during ship’s life cycle (design, building and operational) phases were undertaken.

Detailed study on inspections to detect corrosion and factors that contribute to corrosion control has been made. A corrosion system approach in which whole ship structure is divided into corrosion zones and subzones for systematic corrosion assessment has been proposed. The zoning methodology is based on the environment to which the zones are exposed. The types of corrosion prevalent as well as the corrosion protection strategy are different for different zones. The external structure of the ship has been divided into three zones viz. submerged zone, splash zone and atmospheric zone. The internal structure is also divided into three zones viz. ballast tank zone, cargo hold zone and other internal structures zone. The zones can be further divided into subzones depending on the size and complexity of zones. A set of six criteria which are important for assessing the zones and a rating scale (Assessment Level – A.L) for each criterion developed. Also a method to account for the severity of corrosion was proposed through a concept of Corrosion Weightage (C.W). With the help of ALs and CWs, a qualitative assessment of corrosion condition with the help of Corrosion Condition Index (C.C.I) for a given subzone/ zone/ whole structure was developed. Recommendations for a C.C.I rating system for future ship operations have been developed and validated with the help of case studies.

The Knowledge Base (KB) has been organized to 15 KB groups and used as expert knowledge for the Decision Support System. A modular design approach was selected for DSS, comprising of four functional modules viz. “Project setup module” (for registration of users and ships, definition of corrosion zones and subzones etc.), “Corrosion observation module” (for corrosion inspection data input with support of the knowledge base), “CCI calculation module” (for C.C.I calculations and report generation) and “Administrative functions Module”. User friendly interface for selection of answers to the pre-defined questions with reference pictures has been provided for obtaining consistent results. The domain knowledge base is not static and provision has been made to regularly update the existing knowledge base by an administrator. The DSS has been developed as a web based application using ASP .Net 4.0 as front end and Microsoft SQL studio as back end.

The life cycle of ships can be broadly divided into three stages viz. ship design, shipbuilding and ship operation. Major factors that contribute to the corrosion condition of ships have been identified for all phases and represented as tables. Based on this data, recommendations are proposed as best practices for all three phases. Further, a Corrosion Control Model (C.C.M) has been proposed integrating the role of all stakeholders in the form of a flow chart supported by explanations.

1.5 Expected Outcome

The expected outcomes from the research work are as follows:-

(a) A comprehensive method for assessing the corrosion condition of steel ship structures during the operation phase would be developed in the form of an index (C.C.I). The research would identify the major parameters that are important for corrosion assessment of ships as well as their consequences on safety of crew, cargo and structure. The proposed C.C.I may be used as an indicator for future operation of ships and to promote safer ships.

(b) Based on the knowledge base compiled and the concept of C.C.I developed as part of the research work, a user friendly Knowledge Based Decision Support System (named SCCI software) would be developed as a tool for corrosion condition assessment and monitoring of steel ship structures and would be made available over the web. The SCCI software will enable access to the expert knowledge similar to any other website and will be highly useful for all stakeholders.

(c) A model for integrating the various corrosion control activities throughout the lifecycle of a ship would be proposed in the form of flow chart. It will highlight the flow of information during the life cycle phases and the role of various stakeholders.

(d) Major corrosion considerations to be adopted in the design, production as well as operation stages of ships would be compiled. A set of best practices for life cycle stages would be proposed as part of strategy to keep the cost and downtime due to corrosion minimum.

1.6 Thesis Organisation

The thesis has been organized in 5 Chapters. Chapter 1 deals with the general introduction to the research topic and a detailed literature review on corrosion and corrosion protection systems of ships. The scope of work, research methodology and the expected outcome are also mentioned in this chapter. Development and formulation of Corrosion Condition Index (C.C.I) has been presented in Chapter 2. In Chapter 3, the development and application of Knowledge Based Decision Support System (KBDSS) has been described. The recommendations for best practices for corrosion control in various life cycle phases of ships and the concept of Corrosion Control Model are described in Chapter 4. Chapter 5 deals with summary, conclusions, significant contributions and scope for further studies.

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Chapter 2

DEVELOPMENT OF CORROSION CONDITION INDEX (C.C.I) FOR STEEL SHIP STRUCTURES

Contents

2.1 General

The problem of hull corrosion is a major concern for ship owners in their endeavour to safeguard the structural integrity of ships and protect their investment. Continuous exposure to marine environment will adversely affect the performance, lead to high maintenance cost and loss of operational period. Most of the spaces in the ship such as outer hull, super structure, tanks (ballast, fuel, fresh water, grey water and black water), bilges, pipe works, cargo holds, boilers and engines, rudders, propellers, bearing, valves, pumps, void spaces, sea chests, stabilizers etc. are all susceptible to corrosion in the marine environment. Major types of commonly recognizable corrosion prevalent in ships include uniform corrosion, pitting corrosion, crevice corrosion, galvanic corrosion, stress corrosion cracking, waterline corrosion, hydrogen embrittlement, erosion corrosion, weld corrosion, microbiological corrosion, stray current corrosion, coating related corrosion, and corrosion under lagging (BMT Defence Services, 2009). Corrosion of only structural steel components has been c1onsidered in the present work. However, the concept can be extended to include all equipment, piping, valves etc.

Ships are very costly assets to build as well as to operate. As brought out in Chapter 1, corrosion represents one of the largest cost components in the life cycle of ships. It can also adversely affect the safety of crew/ cargo, fuel consumption and the environment. A definite need was felt to assess and monitor the corrosion condition of ships during the long operational period to take important decisions on future operations. Representation of complex corrosion condition of ship structure with a numeral number along with explanations will be highly advantageous to all stakeholders. This chapter focuses on development of a system to assess the corrosion condition of steel ship structures and to assign a Corrosion Condition Index (C.C.I) at any point in her operational life. Ship structure has been considered as a corrosion system and may be subdivided into a number of corrosion zones based on their exposure condition. The assessment of each corrosion zone is based on the status of corrosion, performance of corrosion protection systems, design factors and envisaged severity level of corrosion consequences. As on date there are various indices being used in the field of shipping industry such as Environmental Ship Index (ESI). Clean Shipping Index (CSI), Energy Efficiency Design Index (EEDI), Baltic Dry Index (BDI), Harper Petersen Index (HARPEX) and Clark Sea Time Charter Index (Odom, 2010). The proposed Corrosion Condition Index (C.C.I) shall be used along with these indices to promote safer ships and can also be used as an indicator of ship’s fitness for future operations.

2.2 Corrosion Condition Index (C.C.I.)

The condition assessment of any engineering system is based upon objective and repeatable measurements which, when processed by an algorithm, produce a numeral indicator, called the Condition Index (C.I). The C.C.I is intended to be used as an effective tool for ship owners/ prospective buyers to take critical decisions. The objective of C.C.I is to provide comprehensive information about the corrosion condition of steel ship structures. This would provide important input for planning medium-long term maintenance requirements and future operations of ships. The C.C.I can play a vital role in the overall corrosion management system of ship structures. The C.C.I can be used along with various other indices used in the field of shipping to assess the performance of ships.

2.2.1 Factors affecting C.C.I

The rate of corrosion varies with ship’s age and over the same ship from one area to another, between bottom, vertical and top areas. Accordingly there will be a change in the corrosion condition and therefore the C.C.I between different locations in a ship. The design features incorporated, building practices followed in the shipyard, environmental conditions as well as the operational conditions will affect the corrosion condition. Preservation of corrosion control systems such as cathodic protection and protective coating are highly essential to minimise the adverse effects of corrosion. The causes for coating failures are poor coating specification, poor surface preparation, low thickness, incorrect paint application procedure, etc. Major factors that affect the rate of corrosion on ship structures have been reported by Shama (1996) and the same is summarised in Table 2.1.

Table 2.1 Factors Affecting Corrosion Condition of Ship Structures (Shama, 1996)

Sl. No	Category	Factors Affecting Corrosion
(a)	General	Material used, Effectiveness of corrosion control system, Coating condition, Orientation of the structure, Frequency of inspection and maintenance.
(b)	Environmental	Salinity of sea water, Temperature, Pollution, Marine Fouling, Humidity, Presence of oxygen.
(c)	Operational	Type of cargo, cargo residues, mechanical abrasion, frequency of tank washing, presence of stray current.

2.3 Consequences of Corrosion

Each observed corrosion will have a consequence on future operation of ships. Corrosion causes loss of cross-sectional area of the structural members and excessive loss of material may lead to fracture, buckling or yield failure. Corrosion is a major cause for the deformations and fracture of steel structure and its components. If left unattended, it will be a disaster waiting to happen and may lead to structural failure, fuel oil or cargo contamination, environmental pollution or even loss of the ship itself. Corrosion of ship structures reduces local and global strength and may finally lead to unfortunate casualties in rough seas under certain circumstances. Literature on the influence of corrosion wastage on hull girder strength, local strength, fatigue strength, and leaking potential has been reviewed by Wang et al. (2009). Ayyub et al. (2000) have listed possible failure scenarios for a ship structure and classified major consequences as impact on crew, impact on cargo, impact on environment, impact on structure, impact on cost of inspection and repair. The likely corrosion consequences may be the requirement for minor temporary repair, reduced operational availability, loss of capital etc. It may also result in more serious consequences such as adverse effect on ship safety, environment, injury or loss of human life. Therefore it is necessary to assess the impact level for each of the observed corrosion. The experience and judgment of corrosion inspector will be crucial in identifying the consequence of corrosion. The possible consequences due to corrosion have been categorized in to six groups and are discussed in the subsequent paragraphs.

2.3.1 Impact on Structure

The impact of corrosion on structural strength and stiffness of ship hull girder and local structural members are reduction of scantlings, increase of stresses, reduction of load carrying capacity, increase of local stress concentration, reduction of safety factors, reduction of fatigue strength of structural connections, reduction of local and hull girder flexural rigidity and reduction of buckling strength (Shama, 1996). The effect of corrosion on a ship’s hull cross-section geometrical characteristics has been investigated by Ivanov (1986) who suggested that the impact on structure depends on the extent of corrosion on the global strength members (primary strength members including side shell, watertight decks and bulkheads, bottom structure, stringers, web frames, girders etc.) and can vary from no significant impact to catastrophic effects like loss of ship. The consequence would increase as the corrosion damage to global strength members increases. Cumulative structural wastage due to corrosion will reduce local scantlings and thus the hull girder section modulus, which will make the ship more susceptible to local bucking or hull girder failure. The possible impact on ship structure due to observed corrosion may be qualitatively assessed based on the corrosion on global strength members and may be categorized as follows and as shown in Table 2.2:-

(a) None (no corrosion to global strength members observed).

(b) Minor damage to global strength members (the observed cases of corrosion on the global strength members are minor in nature and do not have any adverse effect on the structural integrity of ships).

(c) Moderate damage to global strength members (the adverse effect of observed corrosion problems on the global strength members are significant and require regular monitoring till remedial repairs are undertaken).

(d) Major structural damage to global strength members (the observed cases of corrosion are critical and may need remedial actions before future operations).

(e) Likely loss of ship (the observed cases of corrosion on global strength members are severe and may lead to loss of ship).

2.3.2 Impact on Cargo

The primary purpose of a merchant vessel is to carry cargo from one port to another for commercial purposes. Safe transportation of cargo is one of the biggest concerns of ship owners. Cargo hold structural members are prone to corrosion due to wear/ tear as a result of frequent cargo operations, presence of chemicals of corrosive nature, high sulphur content, etc. Some cargoes like coal and sulphur can cause severe corrosion to the structural members. They may react with any retained water and produce acids which may corrode parts of the ship. Severe corrosion may lead to contamination of cargo, water ingress or even cargo loss. Water ingress may result from leaking hatch covers, back flow through bilge systems, leaking manhole lids etc. The most obvious operational parameter affecting cargo hold corrosion is the relative frequency of transporting coal or iron ore cargoes. Coal is more corrosive than iron ore due to the presence of sulphates and chlorides. The wear of protective coatings varies for different locations within the cargo hold, depending on which cargo is loaded. Utilization of cargo carrying equipment inside the holds can cause damage to the hold floor, frames and ladders. This not only causes material damage to the ship's structure, but can also break down the paint coatings exposing the base steel to the atmosphere (http://bulkcarrierguide.com, 2010).

Impact on cargo due to corrosion is therefore another important factor while assessing the severity of consequences. Any possibility of damage/ loss of cargo will adversely affect the future operations of a ship. Minor corrosion may not cause any adverse impact on ship's cargo in certain cases. But it may cause damage or even loss of cargo in case of critical cases of corrosion. The impact on cargo due to observed corrosion may be qualitatively assessed as any of the following and as shown in Table 2.2:-

(a) None (there is no corrosion observed or there is no effect on the safety of cargo due to corrosion).

(b) Likely damage to cargo (presence of corrosion is significant and there is a likelihood of corrosion causing damage/ contamination to the cargo).

(c) Likely loss of cargo (the observed cases of corrosion are severe and there is a likelihood of loss of cargo if operated in the present condition).

2.3.3 Impact on Passengers/ Crew

Safety of passengers and crew members is one of the primary responsibilities of ship owners and therefore the observed corrosion needs to be looked at with respect to likely impact on their safety. Severe state of corrosion can lead to substantial weakening of the entire ship structure. If left unattended for a long time, the integrity of ship will become dangerously compromised, and can make the vessel unsafe and present a risk to the people on board. Eventually, corrosion will reduce the ship's ability to remain afloat. The impact of observed corrosion on the safety of passengers/ crew in a vessel can be qualitatively classified into the following four categories (increasing order of severity) and as shown in Table 2.2:-

(a) None (no corrosion was observed on structural members or there is no adverse effect of corrosion on the safety of crew/ passengers).

(b) Discomfort (the observed corrosion may cause discomfort to the living/ working conditions for the personnel onboard ship).

(c) Likely injury (significant levels of corrosion were observed which are likely to cause injury to the personnel onboard ship).

(d) Likely loss of life (the observed cases of corrosion on ship structures are severe and there is a likelihood of loss of life if operated in the present condition).

2.3.4 Impact on Environment

Marine pollution from an extensively corroded vessel is a major global concern. The degree of the damage caused by an oil spill event will depend upon the quantity spilled, the chemicals involved and the sensitivity of the marine area impacted as well as the wind and weather conditions at the moment of the incident. Shipping is the most important mode of transportation for a significant number of chemicals and corrosion of the aged structures can lead to the leakage of several toxic substances to the sea (Victoria and George, 2016). The regulations promulgated by Marine Environment Protection committee (MEPC) of IMO and SOLAS are to be complied by the ship owners throughout the operational period. The cases of corrosion observed during the inspections therefore need to be looked at with respect to its impact on the environment. Corrosion also results roughening of the hull surface and this leads to more resistance, more power requirement for the same speed, more fuel consumption, more emission and thus causes adverse impact on environment. However, possibility of oil spill is a major limiting factor, which will decide ship's fitness for future operations. Therefore the impact on environment due to corrosion may be qualitatively classified into following four categories and as shown in Table 2.2:-

(a) No effect on environment (no corrosion was observed on structural members or there is no impact on the environment due to corrosion).

(b) Likely contamination with oil (though there is no possibility of oil spill, there is a likelihood of contamination with oil due to localized corrosion of ship structural members).

(c) Minor oil spill likely (significant levels of corrosion were observed on the structure with the possibility of minor oil spill from a particular tank to the environment).

(d) Major oil spill involving several cargo tanks (the observed cases of corrosion on ship structures are severe and there is a likelihood of major oil spill involving several tanks).

2.3.5 Impact on Operational Availability

The aim of every successful ship owner will be to maximize the operational availability of their ships by minimizing the downtime for repairs. The extent of corrosion has a direct impact on the operational availability of ships and may be qualitatively classified into following five categories and as shown in Table 2.2:-

(a) No effect (no corrosion was observed on structural members or there is no impact on the operational availability due to corrosion).

(b) No immediate repair/ no loss of serviceability (the observed cases of corrosion are minor with no loss of serviceability of the ship and does not warrant immediate repair).

(c) Unscheduled repair necessary causing reduction in operational availability (the extent of corrosion is significant and may cause reduction in the operational availability of the vessel and the repair works cannot wait till the next scheduled repair period).

(d) Ship not available for operation for a long time (observed cases of corrosion on ship structures are severe warranting major repair works which may cause non-availability for a considerable period of time).

(e) Complete loss of operational availability (extremely high levels of corrosion have been observed and there is a complete loss of operational availability).

2.3.6 Impact on Repair/ Maintenance Cost

The financial aspects also play crucial role in regular maintenance and upkeep of ships by owners. Though expensive, the timely repair/ maintenance of corrosion protection systems or the corroded structural members are essential for the seaworthiness of the vessel. Any delay may cause further deterioration of the structure and escalation of financial commitments. The classification of cost would vary depending on the type/ urgency of repair, financial capacity of the owner as well as the overall operational cost. The impact on repair/ maintenance cost due to observed corrosion can therefore be qualitatively classified into following five categories and as shown in Table 2.2 without specifying the exact amount for the repairs:-

(a) None (no corrosion was observed on structural members or there is no cost involved for repair/ maintenance due to corrosion).

(b) Low (minor cases corrosion observed which can be rectified during the operational period with low financial commitments).

(c) Moderate (observed corrosion problems are to be monitored and rectified in the next possible opportunity and significant level of financial commitment is anticipated).

(d) High (the observed cases of corrosion on ship structures are severe warranting urgent major repair works involving high financial commitments).

(e) Very high (extremely high levels of corrosion observed warranting very high financial commitment for rectifying the defects and making the ship seaworthy).

The consequences due to observed corrosion on ship structures can be grouped under six categories such as impact on structure, impact on crew/ passengers, impact on cargo, impact on environment, impact on operational availability and impact on repair/ maintenance cost as discussed in the previous section. Various options for the qualitative assessment of the above consequences were also discussed. All six categories and their classification are combined and presented in Table 2.2. Any corrosion observation may be qualitatively assessed against the above six criteria and a consolidated classification is presented in the first column in Table 2.2. A five level classification system to represent the consequences due to corrosion has been proposed and are designated as “None”, “Low”, “Moderate”, “High” and “Extreme”. The overall classification for an observed case of corrosion will be the lowest option among the six assessment categories as shown in the first column of Table 2.2.

Table 2.2 Classification of Consequences due to Corrosion

Overall Corrosion Classification	Impact on Structure	Impact on Cargo	Impact on Crew	Impact on Environment	Impact on Operational Availability	Impact on Repair/ Maintenance Cost
None	None	None	None	None	None	None
Low	Minor corrosion damage to global strength members	None	None	None	No immediate repair, no loss of serviceability	Low
Moderate	Moderate corrosion damage to global strength members	Likely damage to cargo	Discomfort	Likely contamination with oil	Unscheduled repair, Reduction in operational availability	Moderate
High	Major corrosion damage to global strength members	Likely damage to cargo	Likely injury	Minor oil spill likely	Ship may not be available for operation for a long time	High
Extreme	Likely Loss of ship	Likely loss of cargo	Likely loss of Lives	Major oil spill likely involving several cargo tanks	Loss of operational availability	Very High

2.4 Corrosion Weightage (C.W)

Corrosion consequence estimations (Table 2.2) are formed qualitatively to indicate the severity of corrosion observations on the ship structural members and assigning a notional value of Corrosion Weightage (C.W) for each category is the starting point of the process of developing Corrosion Condition Index (C.C.I). For example, the consequence of corrosion on the underwater hull will be more severe than the same level of corrosion on the superstructure or on some internal structures. Also, oil spills from a small tanker may have a milder consequence than one from a Very Large Crude Carrier (VLCC). The rate of oil spill depends on the extent and location of damage and loading condition of hold /tank. But the quantity of oil spill depends on the size of cargo tanks, which in ton depend on the vessel size. Establishment of a suitable Corrosion Weightage (C.W) depends on the corrosion management policies of the owner. A proposed system of assigning Corrosion Weightage for the classification presented in Table 2.2 along with descriptions has been presented in Table 2.3. The consequences due to corrosion has been classified/ rated into five categories viz. None, Low, Moderate, High and Extreme with corresponding C.W values as 10, 9, 8, 7 and 6 respectively. A higher value of C.W indicates higher classification levels or lesser impact of corrosion, which implies that the impact of corrosion on structure, cargo, crew, environment, operational availability or maintenance expenses is low.

Table 2.3 System of Allocating Corrosion Weightage Based on Consequences

Classification of Consequence due to Corrosion	Corrosion Weightage, C.W	Description
None	10	The corrosion has no impact on structure, cargo, safety of crew, environment, operational availability or repair/ maintenance expenses
Low	9	Lowest priority for repair. The corrosion problems are to be noted and regular inspection, monitoring and repair recommended
Moderate	8	Moderate priority for repair. The corrosion problems if unattended may lead to serious operational constraints in the future. Recommended for frequent inspection, monitoring and repairs
High	7	High priority for repair. The corrosion problems are severe and are recommended for close monitoring and repair at the earliest opportunity
Extreme	6	Highest priority for repair. Ship is not fit for further sailing in the present corrosion condition and recommended for extensive repair

2.5 System Approach to Formulation of C.C.I

The ship structure as a whole is too large to be considered as a single component for inspection and corrosion condition assessment. A system approach in which the whole ship structure may be considered as a "Corrosion System" is proposed for development of C.C.I of ship structures (Mathiazhagan and Babu, 2012). The overall system could be divided into subsystems of manageable size as well as with similar properties such as exposed environment. The proposed system of dividing overall ship structure (corrosion system) into subsystems (corrosion zones) is explained in the subsequent paragraphs.

2.5.1 Corrosion Zones

Most of the steel structural components of a given ship structure are susceptible to corrosion and may be grouped into "Corrosion Zones" based exposure conditions, characteristics of envisaged corrosion and corrosion protection systems. Each of the corrosion zones encounter different type corrosion problems and also have varied severity of consequences. A typical corrosion zone approach for offshore structures has been reported by DNV (2012). Various aspects of inspection, maintenance, and application of marine coating systems at different zones of ship structure have been presented by ABS (2007). The corrosion zones identified for typical merchant ships and their characteristics are described in the subsequent paragraphs (Babu et al. 2014):-

(a) **Submerged Zone.** This zone is continuously submerged in seawater and includes underwater hull and various appendages (rudder, propeller, bilge keel, shaft brackets etc.). This zone is susceptible to corrosion (uniform as well as localized) and fouling due to marine organisms and protection is critical being directly related to the watertight integrity of ships. The submerged zone is protected against corrosion using a combination of compatible coatings and Cathodic Protection (C.P) system. The coating system comprises of both anticorrosive and antifouling coatings and the surface preparation, number of coats/ coating thickness/ coating interval etc. are determined by the approved painting scheme. The use of TBT based anti-fouling paint has been completely banned in 2008 by the International Maritime Organization. The ban was effected since several environmental studies showed that TBT compounds persist in seawater/ sediments killing sea life and possibly entering the food chain (IMO, 2002). The C.P can be either a sacrificial anode system or Impressed Current Cathodic Protection (I.C.C.P) system or a combination of both. The C.P is designed to maintain the hull potential in the protective range and the system should be able to function once coating damage or deterioration has occurred.

(b) **Splash Zone.** This zone is subjected to one of the most aggressive marine environments, because of its exposure to fully aerated seawater, repeated drying and wetting, ultra violet radiation, and possibly salt accumulation. This zone covers the region between the submerged and atmospheric zones i.e. between the highest and lowest waterlines. NAVSEA (2018) has defined this zone as the area from minimum load waterline at which the ship is expected to operate to 12 inches above the maximum load waterline). Corrosion in this zone can occur at a rapid rate, causing severe localised or general thickness loss, if left unattended. The Cathodic Protection system is not suitable to this zone, since the upper splash zone (above the ship's waterline) is not fully and continuously immersed in seawater. Consequently suitable hard coatings and corrosion allowance are the only possible methods of corrosion control.

(c) **Atmospheric Zone.** The atmospheric zone is also prone to corrosion, though to a lesser degree than the submerged zone or splash zone. High humidity with consequent condensation, rain, spray, etc. all creates a corrosive environment in this zone. The components of this zone include side shell of the ship (above splash zone), main deck/ helo deck and super structure. Coatings are the only cost-effective means to control atmospheric corrosion in this zone and they must be flexible and resistant to ultra violet radiation. The main deck structure may be subjected to abrasions due to onboard activities causing inception of corrosion.

(d) **Ballast Tanks Zone.** A ballast tank is a compartment within a ship that holds sea water. All vessels have ballast water tanks to adjust the ship's draft, buoyancy and trim under different operating conditions and large vessels will have several such tanks (Heyer et al. 2013). Ballast tanks generally pose the highest threat from corrosion, because they contain varying levels of seawater inside the tank. Further the ballast water structures are heavily exposed to water pressure, sloshing loads, temperature variation, and repeated drying and wetting. The dynamic loading on the ballast tank structure due to water pressure and sloshing may cause coating breakdown exposing the bare metal to seawater. Apart from varying seawater levels, there is also aeration of ballast water due to sloshing, which causes corrosion. The structure of ballast tanks are often complex, with restricted access, inadequate drainage, etc. The flow rates near outlets and inlets within the tank are high and may result in increased corrosion and erosion. Another major concern is the presence of sand particles in the ballast water. These tanks require a combination of protective coating and sacrificial anode cathodic protection system to control corrosion. The cathodic protection will be effective only for the fully submerged area. The residues or salt deposit on the structure in the not submerged area can cause local corrosion problems. Corrosion conditions of ballast water tanks are critical in determining the life of the vessel.

(e) **Cargo Tanks/ Cargo Holds Zone.** Cargo holds form the revenue earning spaces of the vessel, but are also the areas subject to the harshest of operating environments. Various forms of impact, abrasion and mechanical damage occur from the loading and carriage of dry cargoes and are also prone to corrosion with some cargoes. Application of suitable coating system is the only practical corrosion control method for these spaces. The selected protective coatings should be corrosion resistant, free from pores, and easy to clean. Further, the wear of protective coatings varies for different locations within the cargo hold, depending on which cargo is loaded. Utilization of cargo carrying equipment inside the holds can cause damage to the hold floor, frames and ladders. This can also break down the paint coatings exposing the base steel. (http://bulkcarrierguide.com, 2010). The coating should also resist the cargo to be carried and substances released by cargo, tank cleaning procedures, and cross contamination between different cargoes and ballast water. They must not contaminate or affect the colour or taste of the cargo, particularly those intended for human consumption and pure chemical cargoes. Application of maintenance coatings can be carried out in case of minor coating damages during return voyage when holds are empty. Recoating of these spaces is not possible without layup of ships for a long time (Berendsen, 1989 and 1998). Stainless steel cladding may be provided in the cargo tanks of chemical carriers to improve corrosion resistance.

(f) Other Internal Structures Zone. In order to restrict the number of corrosion zones for a given ship, all internal structural components not included in the above zones are grouped as "other internal structures zone'. This zone shall include tanks other than cargo and ballast tanks (fuel, fresh water, grey water, black water etc.), bilge spaces, void spaces, accommodation spaces, etc. within the ship. Suitable coating systems as per the Classification Society guidelines are the practical method of corrosion control for the structures forming part of this zone.

The submerged zone, splash zone and atmospheric zone together constitute the external part of ship structure. The ballast tank zone, cargo hold zone and other internal structures zone would together form internal part of the ship structure. The proposed arrangement of zones will facilitate systematic determination of corrosion condition of the whole ship from the corrosion condition of individual zones. The corrosion zones discussed above are illustrated on a ship's profile and sectional view in Figures 2.1(a) and 2.1(b) respectively. The corrosion zones are also explained schematically in Figure 2.1(c) and the Corrosion Condition Index (C.C.I) notations for each of the corrosion zones and overall structure are also indicated. The zones forming the external structure and internal structure of a ship have been labeled in blue and green colours respectively. Subdivision of these corrosion zones to subzones are explained in subsequent sections.

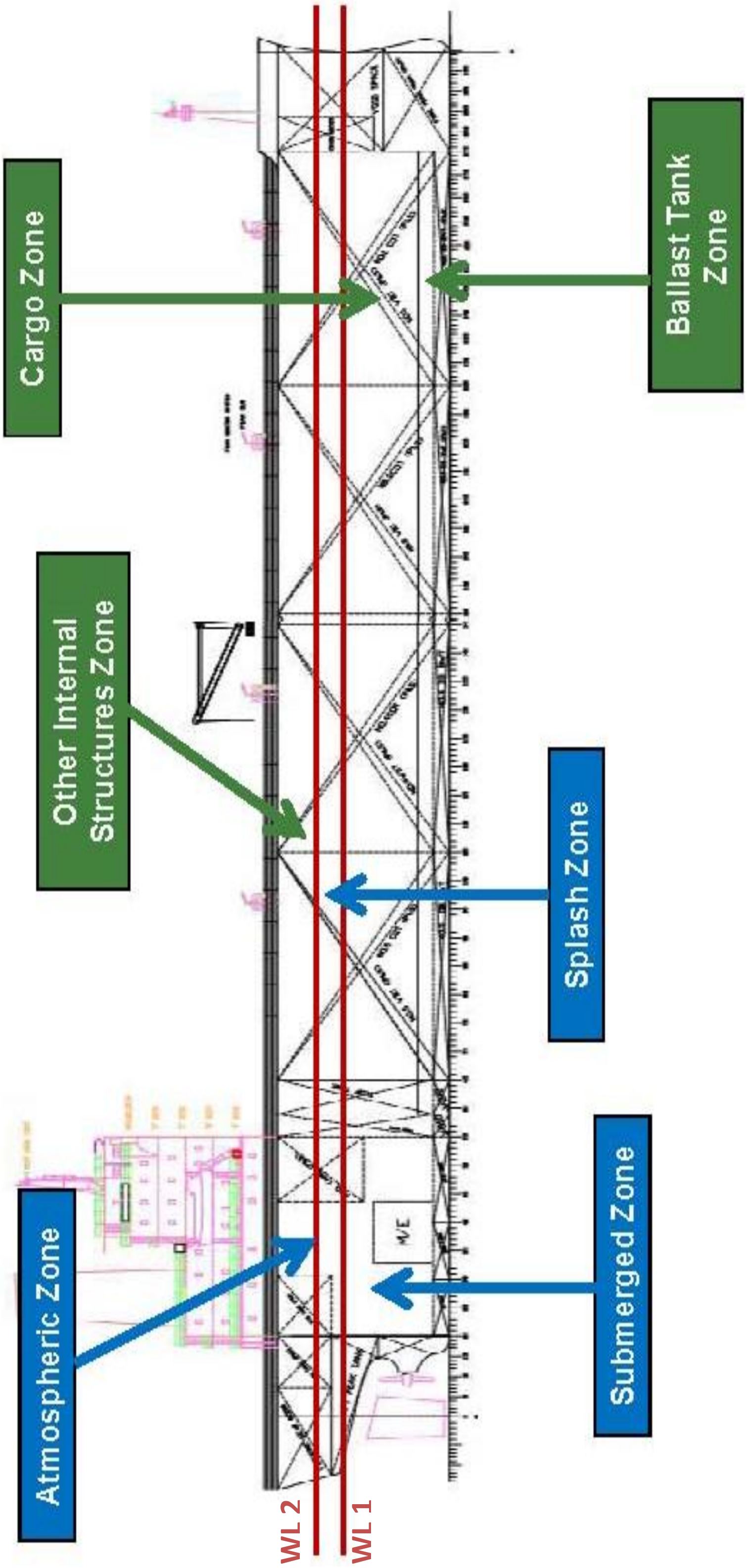


Fig 2.1(a) Six major corrosion zones for a typical merchant ship in a profile view

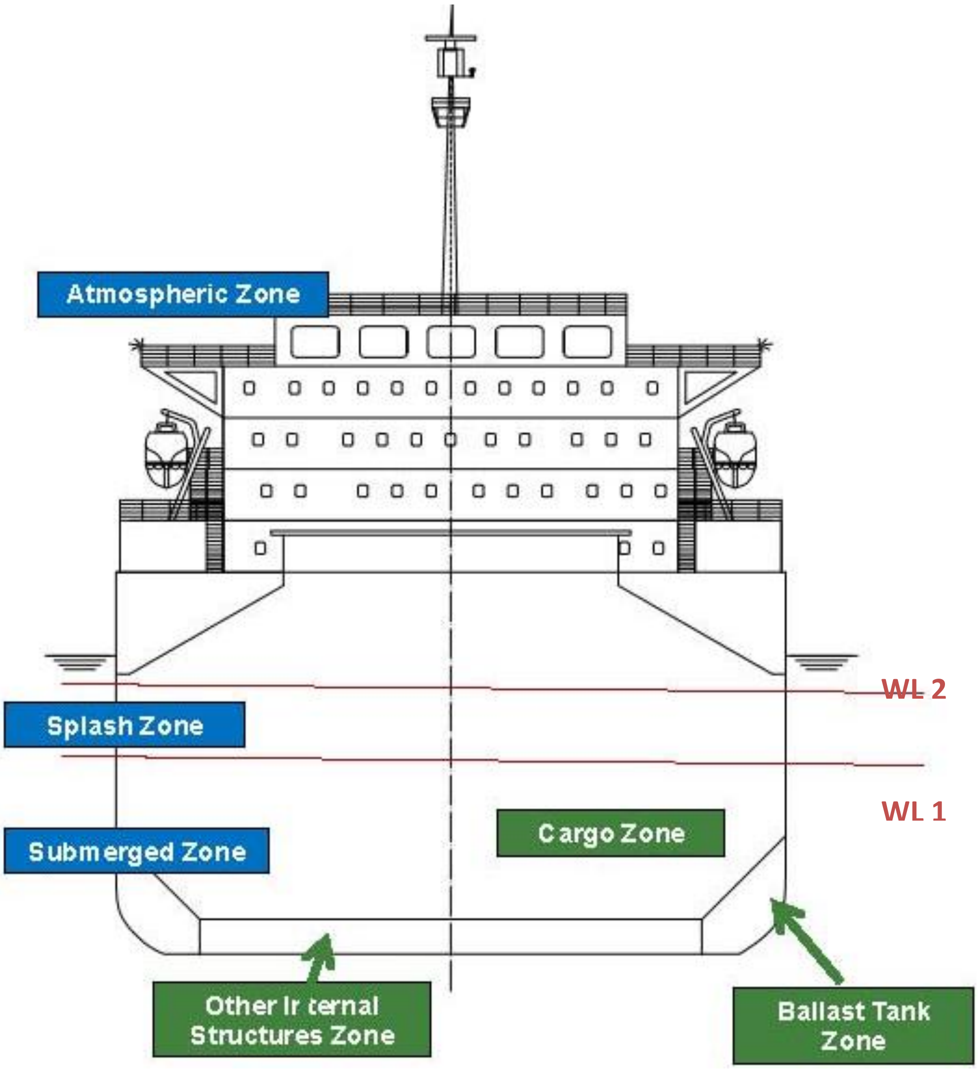


Fig 2.1(b) Six major corrosion zones for a typical merchant ship in a sectional view

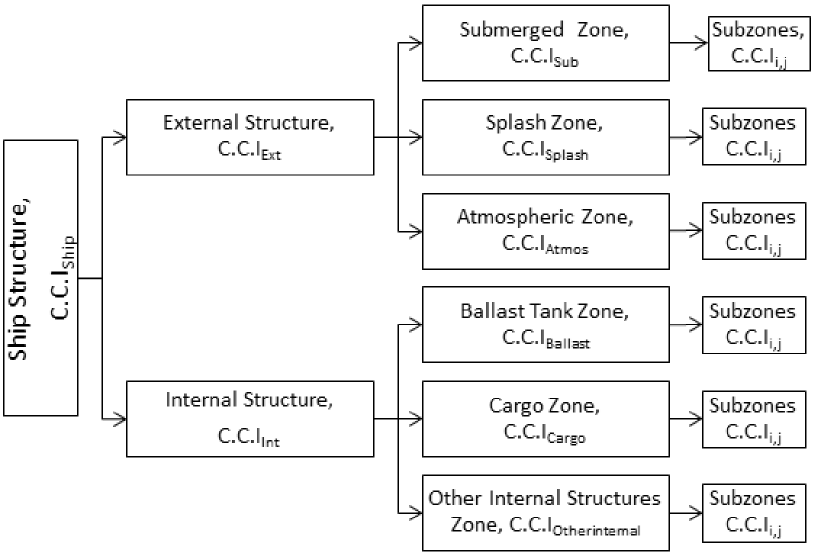


Fig 2.1(c) Schematic diagram of corrosion zones

2.5.2 Subdivision of Corrosion Zones to Subzones

Each of the above corrosion zones in a ship is too large and complex to be considered as a single component and therefore to be further subdivided into a number of subzones for a step by step corrosion condition assessment. A recommended method of dividing the corrosion zones into subzones along with the system of assigning subzone C.C.I values are enumerated below and summarised in Table 2.4. The proposed extent of each subzone is based on a practical way of subdividing each corrosion zone and a suitable naming convention has been followed.

- The submerged zone may be divided into 8 subzones, with corresponding C.C.I values from $C.C.I_{Sub,1}$ to $C.C.I_{Sub,8}$ and the subscript ‘Sub’ denotes submerged zone.
- The splash zone may be divided into 6 subzones, with corresponding C.C.I values from $C.C.I_{Splash,1}$ to $C.C.I_{Splash,6}$ and the subscript ‘Splash’ denotes splash zone.

- The atmospheric zone is recommended to be divided into 8 subzones, with corresponding C.C.I values from C.C.$I_{Atmos,1}$ to C.C.$I_{Atmos,8}$ and the subscript 'Atmos' denotes atmospheric zone.
- The corrosion condition of ballast tanks are critical for overall assessment of ship structures and each ballast tanks is therefore considered as a separate subzone with C.C.I values C.C.$I_{Ballast,j}$, where j = 1 to n and n is the number of ballast tanks.
- Each cargo tanks/ holds are similarly considered as separate subzones with C.C.I values C.C.$I_{Cargo, j}$, where j = 1 to k and k is the number of cargo holds/ tanks.
- All other major internal spaces are grouped under the heading "other internal structures zone", which may be subdivided into 5 subzones viz. fresh water tanks, grey/ black water tanks, bilge spaces, void spaces and accommodation spaces with C.C.I values C.C.$I_{Otherinternal, j}$, where j = 1 to 5.

Table 2.4 Proposed Subdivision of Corrosion Zones into Subzones

Zone, i	Subzones (i,j)	Description	Corrosion Condition Index
Submerged Zone	Keel strake	Full length of ship	C.C.$I_{Sub, 1}$
	Midship, Port side	40% Length Between Perpendiculars at midships	C.C.$I_{Sub, 2}$
	Aft end, Port Side	Aft of midship region	C.C.$I_{Sub, 3}$
	Fore end, Port Side	Forward of midship region	C.C.$I_{Sub, 4}$
	Midship, Starboard side	40% Length Between Perpendiculars at midships	C.C.$I_{Sub, 5}$
	Aft end, Starboard Side	Aft of midship region	C.C.$I_{Sub, 6}$
	Fore end, Starboard Side	Forward of midship region	C.C.$I_{Sub, 7}$
	Appendages	Rudder, propeller, bilge keel, shaft brackets	C.C.$I_{Sub, 8}$

Zone, i	Subzones (i,j)	Description	Corrosion Condition Index
Splash Zone	Midship, Port side	40% Length Between Perpendiculars at midships	C.C.I$_{\text{Splash, 1}}$
	Aft end, Port Side	Aft of midship region	C.C.I$_{\text{Splash, 2}}$
	Fore end, Port Side	Forward of midship region	C.C.I$_{\text{Splash, 3}}$
	Midship, Starboard Side	40% Length Between Perpendiculars at midships	C.C.I$_{\text{Splash, 4}}$
	Aft end, Starboard Side	Aft of midship region	C.C.I$_{\text{Splash, 5}}$
	Fore end, Starboard Side	Forward of midship region	C.C.I$_{\text{Splash, 6}}$
Atmospheric Zone	Side shell, above splash zone, midship, port	40% Length Between Perpendiculars at midships	C.C.I$_{\text{Atmos, 1}}$
	Side shell, above splash zone, aft end, port	Aft of midship region	C.C.I$_{\text{Atmos, 2}}$
	Side shell, above splash zone, fore end, port	Forward of midship region	C.C.I$_{\text{Atmos, 3}}$
	Side shell, above splash zone, midship, Starboard	40% Length Between Perpendiculars at midships	C.C.I$_{\text{Atmos, 4}}$
	Side shell, above splash zone, aft end, Starboard	Aft of midship region	C.C.I$_{\text{Atmos, 5}}$
	Side shell, above splash zone, fore end, Starboard	Forward of midship region	C.C.I$_{\text{Atmos, 6}}$
	Upper Deck	Full length of upper deck	C.C.I$_{\text{Atmos, 7}}$
	Superstructure	All surfaces of superstructure	C.C.I$_{\text{Atmos, 8}}$
Ballast Tanks Zone	Ballast Tanks (Numbered as BT$_1$, BT$_2$, ------- , BTn)	All ballast tanks are considered as separate subzones being the most critical components in corrosion assessment	C.C.I$_{\text{Ballast ,j,}}$ j=1 to n where n is the number of ballast tanks
Cargo Tanks/ Holds Zone	Cargo holds/tanks (Numbered as CH$_1$, CH$_2$, ----------, CH$_k$)	All cargo holds/ tanks are considered as separate subzones and assessed individually	C.C.I$_{\text{Cargo, ,j,}}$ j = 1 to k, where k is the number of cargo tanks
Other Internal Structures Zone	1. Fresh Water	All fresh water tanks	C.C.I$_{\text{Otherinternal,j}}$ j = 1 to 5
	2. Grey/ Black water	All grey/ black water tanks	
	3. Bilge Spaces	All bilge spaces	
	4. Void Spaces	All void spaces	
	5. Accommodation Spaces	All accommodation spaces	

2.6 Pre-Assessment of Zones

All corrosion zones can be specified with their known parameters such as structural materials used for construction, coating systems, exposed environment, specifications of cathodic protection and past maintenance/ repair works carried out. Understanding of these known data will be helpful while assessing the corrosion condition of the structure. The information shall be identified and collated with respect to various zones, during the process of pre-assessment of zones. Pre-assessment of zones will be useful in understanding the corrosion related properties incorporated during the design and shipbuilding stages and also the historic information of various maintenance works performed. The details of pre-assessment parameters identified for a given corrosion zone are summarised in the Table 2.5.

Table 2.5 Parameters for Pre-Assessment of Corrosion Zones

Sl. No	Data Collected	Remarks
1.	Material data	The structural material and grade used for construction including the physical properties
2.	Coating data	Type of coating, date of application of coating, etc.
3.	Environment Data	The environment to which the particular corrosion zone/ subzone is exposed to
4.	Cathodic protection Data	Type of cathodic protection system installed and the present hull potential readings
5.	Past Maintenance/ Repair data	Details such as type of repair, date, agency which carried out repair are noted

2.7 Selection of Corrosion Inspection Techniques

Corrosion inspections may be used to acquire data on present corrosion condition of ship structures. Such data may need to be converted into useful information for incorporating in a corrosion assessment programme. Ship structural inspections typically cover the assessment of coating condition, type and extend of corrosion, effectiveness of cathodic protection system, presence of structural defects, cleanliness of compartments and, most importantly, the remaining thickness of plates and profiles (ABS, 2012). Corrosion monitoring of ships is very complex because there are a number of critical areas susceptible to different types of corrosion. Nature of corrosion may be uniform and localized, rate of corrosion varies substantially at different locations and there is no single measurement technique that will detect all corrosion conditions (Roberge, 2007). Permanent corrosion records can be obtained by photography and digital imaging. A paint deterioration sensor was developed to measure the change in the potential distribution in a ballast tank (Nakayama et al. 2008).

The most important inspection methods and their relative ability to detect corrosion defects are reported by Bardal and Drugli (2009). The various corrosion inspection methods commonly practiced are visual inspection, hammer survey and nondestructive tests. Salient aspects of these inspection methods are brought out in the subsequent sections.

2.7.1 Visual Inspection

Visual inspection is the oldest and most common method used to inspect ship structural members for corrosion. It provides a quick and effective way of assessing coating condition, surface corrosion, etc. Visual inspections can be carried out as overall inspections followed by close up inspections at locations where the coating is inadequate, defective, or poorly maintained, restricted drainage, or there is possibility of localised corrosion such as crevice/ pitting corrosion. This method is suitable for all corrosion zones and the reliability of visual inspection technique depends on the experience and ability of the corrosion inspector. The inspector must know how to search for critical corrosion defects and failures.

Visual inspection is mostly conducted using a strong flash light and a magnifying aid. Magnifying aids range in power from 1.5X to 2000X. Fields of view typically range from 90 to 0.2 mm with resolutions ranging from 50 to 0.2 micrometer. A 10X magnifying glass is recommended for positive identification of corrosion damage (Roberge, 2007). The disadvantage of this technique is that the surface to be inspected must be relatively clean and accessible. Though this method is labour intensive and monotonous which may lead to errors, the advantages are the speed and the ease of inspection. Currently, the degree of paint coating degradation on ship structures is often judged by visual inspection method (IACS, 2006). Remote visual inspection through cameras has shown potential as an alternative to traditional visual inspection (Roy, 2000) and their advantages are minimal interruptions to operations and inspections from a safe distance in hazardous environments.

2.7.2 Hammer Survey

This is a simple process of noting down the difference in sounds while tapping the structure with a special hammer. A hollow sound may indicate delamination or core separation. A dull sound suggests high moisture content and a very dull sound suggests rotten core material. A sound structure will produce a clean "click" with very little bounce back of the hammer. Delamination of core will give more bounce back (like a drum) and saturated core will produce a dull thud with near zero bounce back (http://www.pcmarinesurveys.com/Marine%20Survey%20101.htm).

2.7.3 Nondestructive Tests

The nondestructive evaluation techniques provide ways to assess the integrity of the structure without affecting its performance. The sensors are used to collect information and are converted to defect parameters for predictions. A summary of various NDE methods used for corrosion inspections, their selection criteria and process steps are presented by Roberge (2007). Radiography, ultrasonic testing and magnetic particle crack detection are the main NDE techniques being used. Most important applications of these techniques in corrosion assessment are to determine the coating thickness and the remaining thickness of the structure at the corroded locations.

2.8 Corrosion Assessment Criteria

Assessment criteria are pre-determined standards against which the actual observations are to be compared with. A well-defined set of corrosion assessment criteria are necessary to judge the results of corrosion inspections. The major corrosion assessment criteria which are to be addressed during inspection, assessment and grading of ship's steel structures are reported by ABS (2004), ABS (2007), ABS (2012), IACS PR 33 (2009) and IACS No 127 (2012). Based on the above documents, six major assessment criteria have been identified which will contribute towards the overall corrosion condition assessment of ship structures. The six criteria are "Coating Condition (CC)", presence of "Uniform Corrosion (UC)", presence of "Localized Corrosion (LC)", effectiveness of "Cathodic Protection (CP)", "Fouling Condition (FC)" and contribution of "Design Factors (DF)". A proposed grading system to assign Assessment Level (AL) values to each of the above criteria, the range of ALs and their applicability to different corrosion zones are presented in Table 2.6.

Table 2.6 Corrosion Assessment Criteria for Ship Structures

Sl. No	Corrosion Assessment Criteria	Assessment Levels (AL)	Corrosion Zones Applicable
1	Coating Condition (CC)	AL_{CC},10 to 4 (Table 2.7)	All Zones
2	Presence of Uniform Corrosion (UC)	AL_{UC},10 to 4 (Table 2.8)	All Zones
3	Presence of Localised Corrosion (LC)	AL_{LC},10 to 4 (Table 2.9)	All Zones
4	Effectiveness of Cathodic Protection (CP)	AL_{CP},10to 6 (Table 2.10)	Submerged, Ballast Tank Zones
5	Fouling Condition (FC)	AL_{FC},10 to 6 (Table 2.11)	Submerged, Splash Zones
6	Contribution of Design Factors (DF)	$AL_{DF,}$10 to 7 (Table 2.12)	All Zones

The six corrosion assessment criteria mentioned above are described in the subsequent paragraphs. The proposed grading system for assessment of Coating Condition (CC), Uniform Corrosion (UC), Localised Corrosion (LC), Cathodic Protection (CP), Fouling Condition (FC) and contribution of Design Factors (DF) are illustrated in Tables 2.7, 2.8, 2.9, 2.10, 2.11 and 2.12 respectively. The grading system has been designed in such a way that a higher value of Assessment Level would indicate a better material state of ship structure or lower level of consequences due to observed corrosion.

2.8.1 Coating Condition Assessment Level (AL_{CC})

Organic paint coatings are generally the most common form of corrosion protection applied to marine structures. The coating system for various corrosion zones are to be decided during the design phase itself and applied during the shipbuilding phase following the recommended practices. The same is to be then maintained/ renewed regularly during the operational stage of ships. Presence of persons qualified in the field of corrosion at every stage is crucial for preserving the integrity of the coating system throughout the life cycle of ships. The coating breakdown area would become sites of accelerated corrosion which may become catastrophic if not detected in time.

Coating degradation can take the form of coating cracking, blistering, rust and flaking (Wang et al. 2009). Coating cracking takes place when structural deformation exceeds the elongation of the paint film. Blisters appear where an adhesion of the paint is locally lost. Blisters contain liquid, but there is no corrosion under the blister. Flaking refers to the lifting of paint from the underlying surface. The loss of paint adhesion is often a result of improper surface preparation, incompatibility with other layers and contamination between layers. Organic coatings also guard against undesirable effects such as rust staining, mechanical damage and deterioration due to weathering.

A 10 point scale has been proposed for assigning the coating condition Assessment Level (AL_{CC}) based on the ASTM D610-01 (Standard test method for evaluating degree of rusting on painted steel surfaces), ABS inspection grading criteria for hull inspection and maintenance programme, IACS PR33 (2009) (Owner's hull inspection and maintenance schemes) and SOLAS SC 223 (2008) (Performance Standards for Protective Coatings) regulations. A higher AL_{CC} would indicate a higher performance level of the coating system and the AL_{CC} will reduce as the coating condition deteriorates. The proposed grading system to assign Assessment Level (AL_{CC}) values and illustrative photographs are explained in Table 2.7 and in Fig 2.2 (a) to (f) respectively. An experienced corrosion inspector will be able to assign a suitable AL_{CC} referring to the given guidelines and photographs.

Table 2.7 Coating Condition Assessment Levels (AL_{CC})

Sl. No	**Coating Condition**	**Coating Condition Assessment Level** (AL_{CC})
1.	Freshly coated, Negligible coating breakdown	10
2.	Minor spot rusting	9
3.	General breakdown of coating 5% - 10%	8
4.	General breakdown of coating 10% - 20%	7
5.	General breakdown of coating 20% - 30%	6
6.	General breakdown of coating > 30%	4

Fig 2.2 (a) Freshly coated, negligible breakdown of coating

Fig 2.2 (b) Minor spot rusting

Fig 2.2 (c) General breakdown of coating 5% - 10%

Fig 2.2 (d) General breakdown of coating 10% - 20%

Fig 2.2 (e) General breakdown of coating 20% - 30%

Fig 2.2 (f) General breakdown of coating > 30%

Fig. 2.2 Coating assessment scale illustrative pictures (ABS inspection grading criteria for hull inspection and maintenance programme)

2.8.2 Uniform Corrosion Assessment Level (AL_{UC})

Uniform corrosion (which is also referred as general corrosion) usually appears as non-protective rust on surfaces where coating system has been deteriorated. The rust scale continuously breaks off, exposing fresh surface to corrosive attack. There is a continuous loss of material thickness which can be judged only after excessive loss has been occurred. Corrosion addition is the plate thickness added to the thickness required solely based on the structural strength aspect, which is the minimum scantling that must be kept throughout the service life of the ship (Class NK, 2013). Assessment Level for Uniform Corrosion (AL_{UC}) has been developed based on two options, viz. criteria of percentage area corroded and percentage reduction of corrosion addition. An increase in either of the above two criteria would indicate deterioration of corrosion condition. The guidance and pictorial representation have been provided by ABS (2004), ASTM D610-01, and ABS Inspection Grading Criteria for Hull Inspection and maintenance programme. The proposed grading system to assign Assessment Level (AL_{UC}) values and illustrative photographs are illustrated in Table 2.8 and Fig 2.3 respectively.

Table 2.8 Uniform Corrosion Assessment Levels ***(AL_{UC})***

Sl. No	% of Area Corroded	% Reduction of Corrosion Addition	Uniform Corrosion Assessment Level (AL_{UC})
1.	No rusting (0% Rust)	Nil	10
2.	Negligible rusting/ corrosion (<5% Light Rust)	<10%	9
3.	Minor spot rusting (5%-20% Light Rust)	10-20%	8
4.	Local corrosion at edges of stiffeners and weld connections OR Light rust >20% OR Hard Scale >20%	20-30%	7
5.	> 10-30% Hard Scale	30-50%	6
6.	> 30-50% Hard Scale	50-100%	5
7.	> 50% Hard Scale	> 100% (thickness less than design value)	4

Fig 2.3 (a) No rusting

Fig 2.3 (b) Negligible rusting/ corrosion (< 5% Light Rust)

Fig 2.3 (c) Minor spot rusting (5% - 20% light rust)

Fig 2.3 (d) Local corrosion at edges of stiffeners and weld connections or 20% Light rust or 5 - 10% Hard Scale

Fig 2.3 (e) > 10-30% Hard Scale

Fig 2.3 (f) > 30-50% Hard Scale

Fig 2.3 Uniform corrosion assessment level - illustrative pictures (ABS inspection grading criteria for hull inspection and maintenance programme)

2.8.3 Localised Corrosion Assessment Level (AL_{LC})

Localised corrosion is more dangerous than uniform corrosion since it is more difficult to detect, predict, control as well as to design against. Localised corrosion occurs when discrete areas of a material undergo rapid attack while most of the adjacent surfaces remain virtually unaffected. Ship structural members are prone to localised corrosion attacks in the form of pitting, crevice or grooving corrosion. Pitting corrosion is a localized form of corrosion by which cavities, or holes are produced in the material. Corrosion products often cover the pits making them difficult to detect. A small, narrow pit with minimal overall metal loss can lead to the failure of an entire structure. Pitting corrosion can produce pits with their mouth open (uncovered) or covered with a semipermeable membrane of corrosion products. Pits can be either hemispherical or cup-shaped. Crevice corrosion tend to occur at shielded areas such as under gaskets, insulation material, fastener heads, surface deposits, disbanded coatings, threads, lap joints and clamps (Roberge, 1999).

For coated surfaces, the localized attack produces deep and relatively small diameter pits that can lead to penetration of the steel member in isolated random places. Pitting of uncoated tanks, as it progresses, forms shallow but very wide patches. The appearance resembles a condition of general corrosion. Pitting is usually seen on horizontal hull parts such as the inner bottom or stringers. Grooving is a localized, linear corrosion which occurs at structural intersections in welds or heat affected zones. This form of corrosion is sometimes referred to as “in line pitting attack” and can also occur on vertical members and flush sides of bulkheads in way of flexing. Grooving is usually seen on the butt/seam welds and weldments of stiffeners to plating (ABS, 2012).

The Proposed system for assigning Assessment Level for the Localised Corrosion (AL_{LC}) and illustrative pictures are presented in Table 2.9 and Fig 2.4 respectively. There are two parameters viz. percentage of corroded area and depth of pits/ groove that are to be considered together while assigning $AL_{LC.}$ It may be noted from Table 2.9 that a higher value of

AL_{LC} indicates lower level of corrosion condition for the corrosion zone being inspected. As the percentage of corroded area or the depth of pits increases, there is a corresponding decrease in AL_{LC} values.

Fig 2.4 (a) No pits

Fig 2.4 (b) Shallow pits < 5%
Depth < 1/3 of original thickness

Fig 2.4 (c) Shallow pits < 15%
Depth < 1/3 of original thickness

Fig 2.4 (d) Shallow pits > 15%
Depth < 1/3 of original thickness

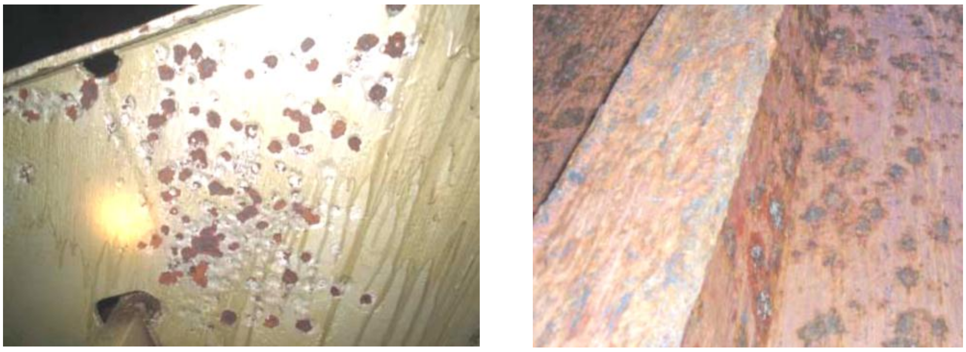


Fig 2.4 (e) Deep pits <15%
Depth >1/3 of original thickness

Fig 2.4 (f) Deep pits > 15%
Depth > 1/3 of original thickness

Fig 2.4 Localised corrosion assessment scale - illustrative pictures (ABS inspection grading criteria for hull inspection and maintenance programme)

Table 2.9 Localised Corrosion Assessment Level (AL_{LC})

Sl. No	% of Area Corroded	Depth of Pits/ Groove	Assessment Level, AL_{LC}
1.	Nil	No pits	10
2.	< 5%	Shallow pits, < 1/3 of original thickness	9
3.	< 15%	Shallow pits, < 1/3 of original thickness	8
4.	> 15%	Shallow pits, < 1/3 of original thickness	7
5.	< 15%	Deep pits, > 1/3 of original thickness	6
6.	> 15%	Deep pits, > 1/3 of original thickness	4

2.8.4 Cathodic Protection Assessment Level (AL_{CP})

Cathodic protection is a technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell. The process of suppressing the corrosion potential to a more negative potential is referred to as cathodic polarization (DNV, 2010). Cathodic protection provides additional corrosion protection to the submerged and ballast tank zones of ship structures apart from protective coatings. The submerged corrosion zone may be protected with either an Impressed Current Cathodic Protection (ICCP) system or sacrificial anode system whereas the ballast tank zone is protected only by the sacrificial anode system. The design principles of cathodic protection systems and protection criteria have been reported by Tashin and Yigit (2014) and Ashworth (2010). Typical arrangement of ICCP and sacrificial anode systems onboard ships are highlighted in Figures 2.5 and 2.6 respectively. Impressed current system anodes are fewer in number than galvanic anodes and are designed for much larger current outputs. This results in over protection and coating damage of nearby surfaces and therefore the ICCP anodes are surrounded by dielectric shields.

The condition of the sacrificial anodes indicates areas which require close corrosion inspection and monitoring. Specific features to note on the sacrificial anodes are metal loss and the degree of uniformity in metal loss.

Sacrificial anodes in usable and unusable conditions are highlighted in Fig 2.7. The sacrificial anodes must not be painted to ensure its contact with the environment. Replacement of sacrificial anodes is essential when significantly high metal loss has taken place or the anode is unevenly consumed. Knowledge of the initial dimensions of the sacrificial anode is required in order to carry out such estimates. To assess the consumption of sacrificial anodes it may be necessary to remove corrosion products and marine growth from their surfaces. In impressed current systems the cathodic protection is applied by means of an external power source and do not require replacement of anodes. This electrical current needs to be constantly monitored and regulated by the ship's crew to maintain the hull potential and to prevent onset of corrosion.

Another criterion for assessment of cathodic protection is the electrochemical potential of the ship's hull, which should be determined systematically at various locations around the ship. In case of a sacrificial anode system, the measurements are to be made by means of a high resistance volt meter, with negative terminal attached to the hull and positive terminal to a Reference Electrode (RE). The RE may be silver/ silver chloride, copper/ copper sulphate or high purity zinc electrodes. In case of an ICCP system, the REs are fitted permanently on the ship's hull. The hull potential varies with changes in wetted surface area, speed of the ship, salinity of water, and condition of the coating (BSRA, 1973). The protective potentials for various metals in seawater with respect to Ag/AgCL/Seawater reference electrode are presented in Germanischer Lloyd AG (2010).

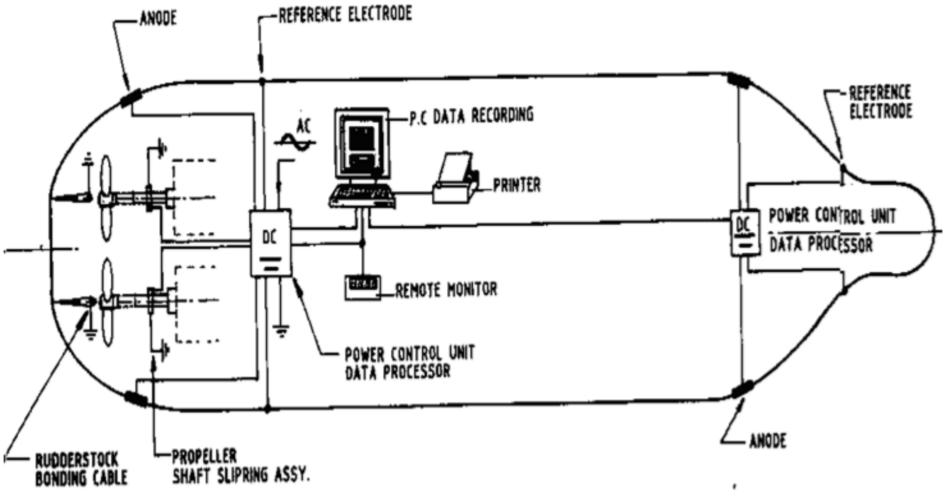
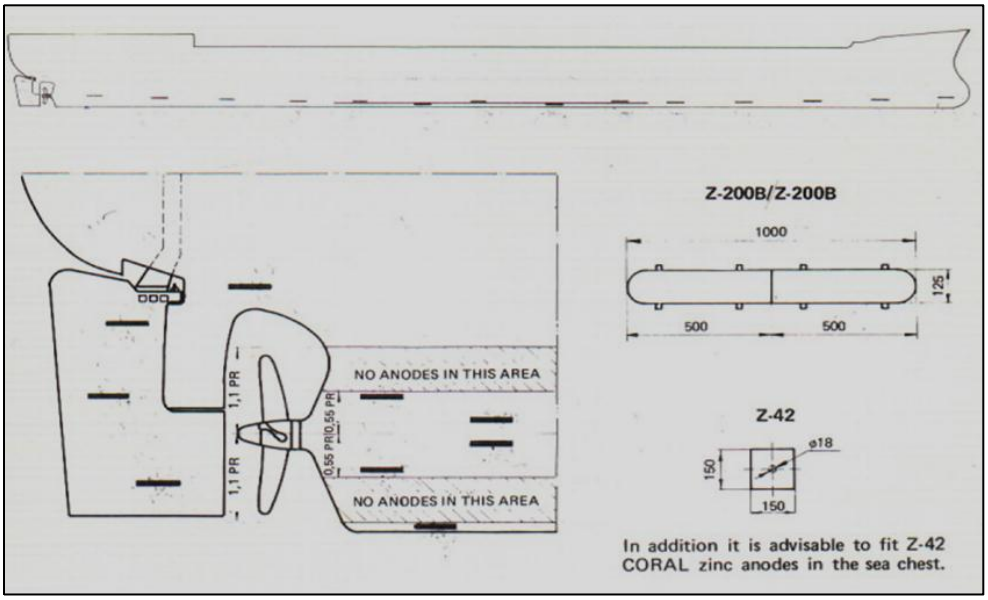


Fig 2.5 Typical ICCP system arrangement for ships (Jotun Cathodic Protection Manual)



In addition it is advisable to fit Z-42 CORAL zinc anodes in the sea chest.

Fig 2.6 Typical sacrificial anode cathodic protection system arrangement for ships (Jotun cathodic protection manual)

a) Sacrificial anodes in the stern region of a ship
(http://wordpress.mrreid.org/2013)

b) Sacrificial anodes in ballast tank of a ship (http://www.cathwell.com)

c) Sacrificial anodes on ship’s propeller housing (http://www.alamy.com)

d) Sacrificial anodes on a ship's hull being consumed (https://en.wikipedia.org)

e) Ineffective sacrificial anode on a ship's hull

f) Fully consumed sacrificial anode on a ship's hull

Fig 2.7 Sacrificial anodes fitted on ship structures (images from internet)

For a correctly designed CP System, the protective potential relative to the Ag/AgCl/Seawater reference electrode will remain for the main part of the design life in the range -0.9 V to -1.05 V. Towards the end of service life, the potential increases rapidly towards -0.80V, and eventually to even less negative values, referred to as under protection. Over protection is applicable to potentials more negative than -1.15 V (not for galvanic anodes based on Al or Zn) (DNV, 2010). The recommended system of assigning Assessment Levels (AL_{CP}) to qualitatively assess the condition of cathodic protection for a given ship's hull is presented in Table 2.10. As discussed above, the two parameters to be considered are the condition of sacrificial anodes and the electrochemical potential of the submerged surface. A higher AL_{CP} is an indication that the cathodic protection system is functioning as designed.

Table 2.10 Cathodic Protection Assessment Level (AL_{CP})

Sl. No	Sacrificial Anode Condition	Electrochemical Potential w.r.t Ag/AgCL/Seawater Reference Electrode	C.P Assessment Level (AL_{CP})
1.	Similar to newly built condition	Between -0.90 & -1.05 V	10
2.	> 75% anodes remaining, Cleaning not required	Between -0.90 & -1.05 V	9
3.	> 50% anodes remaining	Between -0.80 & -0.90 V (Partial protection)	8
4.	< 50% anodes only remaining, Sacrificial anodes need replacement	More than -0.80 V (Under protection). or Less than -1.15 V (Over protection)	6

2.8.5 Fouling Condition Assessment Level (AL_{FC})

The presence of marine fouling, both micro and macro-organisms, can affect the rate of corrosion. Development of efficient and environmental friendly anti-fouling coatings for ships is a challenge to the researchers. Schmitt (2009) has reported that biofouling of ship hulls by barnacles and other sea life increases fuel consumption by almost 8%. Based on an estimated fuel consumption of 350 million tons for the shipping industry worldwide in 2007, an excess of 28 million tons of fuel was consumed because of ship hull biofouling. Microbes (bacteria) can cause corrosion due to their corrosive waste products. The most common bacteria are Sulphate Reducing Bacteria (SRB) and Acid Producing Bacteria (APB). SRB causes corrosion even under anaerobic conditions (Wang et al. 2009). Fouling results from the growth of animals and plants on surfaces in contact with seawater. The adverse effects include damage to the protective coatings, oxidization of the material, reduction in the efficiency of the cathodic protection system, production of harmful environments such as H_2S, or increased resistance and stress, thus increasing the possibility of stress corrosion cracking (NAVSEA, 2006).

The submerged zone, and splash zones are therefore coated with antifouling paint coatings in addition to anticorrosive paint coatings. The antifouling paints gradually release the toxic substances into the water over a period of 3 - 5 years, after which time they become depleted and need to be replaced. Condition of antifouling system is therefore needed to be assessed as part of overall corrosion condition assessment programme. The ship owner may take advantage of any other scheduled underwater hull inspections to observe the condition of the antifouling paint as well as the degree and type of hull fouling.

The biological fouling is a recurring process over the ship’s hull. Tabular and photographic representation of types and categories of hull fouling, most frequently encountered fouling patterns, a fouling rating scale, representation of fouling percentages and a Paint Deterioration Rating (PDR) scale have been presented by NAVSEA (2006). The fouling percentage quantifies the density of fouling which covers a particular subzone area of the hull. The assessment may be carried out either after cleaning of the underwater hull or prior to cleaning and based on the fouling assessment scale proposed in Tables 2.11(a) or 2.11(b) respectively. Table 2.11(b) describes the ten most frequently encountered fouling patterns in the order of increasing severity. Illustrative photographs to identify the fouling ratings are highlighted in Fig 2.8. Table 2.11(a) represents a Paint Deterioration Rating (PDR) scale which describes hull coating condition after cleaning of underwater hull and the method of assigning a numerical rating of increasing severity. The proposed AL_{FC} after the underwater cleaning is based on the condition of antifouling paint system and the percentage of fouling area for the corrosion subzone being considered. Both Tables 2.11(a) and 2.11(b) indicate that the higher the value of AL_{FC}, the lower is the severity of fouling.

Table 2.11(a) Fouling Assessment Level (AL_{FC}) After Underwater Hull Cleaning (NAVSEA, 2006)

Sl. No	Condition of Antifouling Paint System	Fouling Area Percentage	Fouling Assessment Level (AL_{FC})
1.	Antifouling coating intact	Nil	10
2.	Antifouling coating missing from edges, corners, seams, welds, rivet or bolt heads to expose the anti-corrosive coating	< 2%	9
3.	Antifouling coating missing from slightly curved or flat areas to expose underlying anticorrosive paint	< 10%	8
4.	Antifouling and anticorrosive coating missing to expose steel substrate	< 30%	7
5.	Antifouling/Anticorrosive coating missing to expose steel substrate	> 30%	6

Table 2.11(b) Fouling Assessment Level (AL_{FC}) Before Underwater Hull Cleaning (NAVSEA, 2006)

Type of Fouling	**Fouling Rating**	**Description**	**Fouling Assessment Level (AL_{FC})**
Soft	FR 0	A clean, foul-free surface	10
Soft	FR 10	Incipient slime - Slime as light shades of red and green. Painted surfaces are visible beneath the fouling	10
Soft	FR 20	Advanced Slime - Slime as dark green patches with yellow/ brown colored areas. Painted surfaces may be hidden by the fouling	9
Soft	FR 30	Grass as filaments up to 76 mm in length, projections up to 6.4 mm in height **Or** Flat network of filaments green, yellow, or brown in colour **Or** Soft non calcareous fouling up to 6.4 mm in height The fouling cannot be easily wiped off by hand	9
Hard	FR 40	Calcareous fouling in the form of tubeworms less than 6.4 mm in diameter or height	8
Hard	FR 50	Calcareous fouling in the form of barnacles less than 6.4 mm in diameter or height	8
Hard	FR 60	Combination of tubeworms and barnacles, less than 6.4 mm in diameter or height	8
Hard	FR 70	Combination of tubeworms and barnacles, greater than 6.4 mm in diameter or height	7
Hard	FR 80	Tubeworms closely packed together and growing upright away from surface. Barnacles growing one on top of another, 6.4 mm or less in height	7
Hard	FR 90	Dense growth of tubeworms with barnacles, 6.4 mm or greater in height	6
Composite	FR 100	All forms of fouling present, Soft and Hard, particularly soft sedentary animals without calcareous covering growing over various forms of hard growth	6

Fig 2.8 (a) FR 10 approx. 30% area

Fig 2.8 (b) FR 20 approx. 80% area

Fig 2.8 (c) FR 30 approx. 40% area

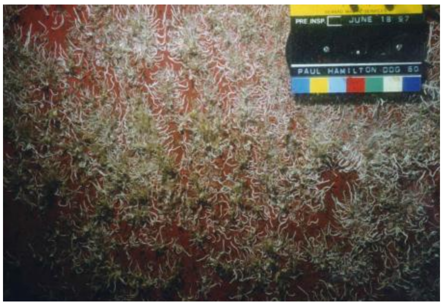


Fig 2.8 (d) FR 40 approx. 90% area

Fig 2.8 (e) FR 50 approx. 40% area

Fig 2.8 (f) FR 60 approx. 90% area

Fig 2.8 (g): FR 70 approx. 80% area

Fig 2.8 (h): FR 80 approx. 90% area

Fig 2.8 (i) FR 90 approx. 90% area **Fig 2.8** (j) FR 100 approx. 100% area

Fig 2.8 Fouling assessment scale illustrative pictures *(*NAVSEA Technical Manual, 2006)

2.8.6 Design Factors Assessment Level (AL_{DF})

Though all efforts might have been taken to follow the best practices during the design phase of ships, various decisions taken in the due course may contribute positively or negatively to the corrosion condition of ship structures. During the corrosion inspections, while in the operation stage, decisions can be made regarding contribution of design factors towards corrosion. Major design deficiencies from the point of view of corrosion which can promote corrosion are galvanic coupling between dissimilar materials, evidence of high stress concentration, restricted access for inspection/ maintenance and insufficient drainage of accumulated sediments, sludge etc. The proposed system of assigning Assessment Levels towards contribution of Design Factors (**AL_{DF}***)* to the corrosion condition is given in Table 2.12. Similar to assessment levels pertaining to other inspection criterion, a higher **AL_{DF}** would indicate less evidence of contribution by design factors to the corrosion condition of ships. Wherever possible, corrective steps need to be taken to rectify the contributing factors to improve the **AL_{DF}** values to higher levels.

Table 2.12 Design Factors Assessment Level (AL_{DF})

Contribution of Design Factors	Assessment Level (AL_{DF})
- No evidence of galvanic coupling - No evidence of stress corrosion - No restriction on access for inspection/ maintenance - No accumulation of sediments, sludge and other materials and there is sufficient drainage	10
Minor evidence of contribution of one or more of above design factors to corrosion	8
Any one or more of the following:- - Evidence of galvanic corrosion requiring major change in design - Evidence of stress corrosion - Restriction on access for inspection/ maintenance - Major accumulation of sediments, sludge and other materials indicating insufficient drainage	7

2.9 Corrosion Condition Index of Individual Zones ($C.C.I_i$)

The system approach in which ship structure may be divided into a number of corrosion zones for systematic determination of C.C.I of ship structure was discussed at Section 2.5. The corrosion zones themselves being large, have been divided into a number of subzones. The corrosion inspection and assessment therefore occurs at a subzone level and the overall corrosion condition assessment needs to be derived from the assessment of subzones/ zones. The proposed formulations of C.C.I for zones/ subzones are explained in the subsequent sections.

2.9.1 Corrosion Condition Assessment of Subzones ($C.C.I_{i,j}$)

The corrosion condition assessment of subzones is carried out based on the Assessment Levels (A.Ls) for the six assessment criteria discussed at Section 2.8 and the Corrosion Weightage (C.W) discussed at Section 2.4. A given subzone has been denoted as (i,j) which indicate j^{th} subzone of the i^{th} zone. Accordingly i varies from 1 to 6 indicating the six corrosion zones and j varies depending on the number of subzones selected for a given zone. A list of subzones for a typical merchant vessel has been given in Table 2.4.

Each subzone (i,j) is to be assessed with respect to Coating Condition, Uniform Corrosion, Localized Corrosion, Cathodic Protection Condition, Fouling Condition and Contribution of Design Factors (applicability of various corrosion assessment criteria to corrosion zones was brought out in Table 2.6) by multiplying the respective Assessment Levels (AL) and the assigned Corrosion Weightage values, as explained in Table 2.13. Following notations have been used for the six Condition Index values of a particular subzone (i,j) as represented in Table 2.13.

- $CC_{i,j}$ - Coating Condition for subzone (i,j)
- $UC_{i,j}$ - Uniform Corrosion condition for subzone (i,j)
- $LC_{i,j}$ - Local Corrosion condition for subzone (i,j)
- $CP_{i,j}$ - Cathodic Protection condition for subzone (i,j)
- $FC_{i,j}$ - Fouling Condition for subzone (i,j)
- $DF_{i,j}$ - Design Factors for subzone (i,j)

Table 2.13 Calculation of $(C.C.I)_{i,j}$ for a Corrosion Subzone (i,j)

Assessment Condition	Assessment Level $(AL)_{i,j}$	Corrosion Weightage $(CW)_{i,j}$	Condition Indices for Subzone (i,j)	C.C.I for Subzone (i,j) $C.C.I_{(i,j)}$
Coating Condition	$(AL_{CC})_{i,j}$	$(CW_{CC})_{i,j}$	$CC_{i,j} = (AL_{CC})_{i,j} \times (CW_{CC})_{i,j}$	**Lowest Condition Index is selected (being most critical)**
Uniform Corrosion	$(AL_{UC})_{i,j}$	$(CW_{UC})_{i,j}$	$UC_{i,j} = (AL_{UC})_{i,j} \times (CW_{UC})_{i,j}$	
Localised Corrosion	$(AL_{LC})_{i,j}$	$(CW_{LC})_{i,j}$	$LC_{i,j} = (AL_{LC})_{i,j} \times (CW_{LC})_{i,j}$	
Cathodic Protection Condition	$(AL_{CPC})_{i,j}$	$(CW_{CP})_{i,j}$	$CP_{i,j} = (AL_{CPC})_{i,j} \times (CW_{CP})_{i,j}$	
Fouling Condition	$(AL_{FC})_{i,j}$	$(CW_{FC})_{i,j}$	$FC_{i,j} = (AL_{FC})_{i,j} \times (CW_{FC})_{i,j}$	
Contribution of Design Factors	$(AL_{DF})_{i,j}$	$(CW_{DF})_{i,j}$	$DF_{i,j} = (AL_{DF})_{i,j} \times (CW_{DF})_{i,j}$	

The values of Assessment Level (AL) as well as the Corrosion Weightage (CW) will decrease as the corrosion condition of the structure deteriorates. Any adverse impact on ship's safety due to corrosion will lower the CW and hence the CCI of that subzone. Therefore, the lowest condition index among the six condition indices shown in Table 2.13 will be representative of the most critical condition index of the subzone and hence chosen as the C.C.I of the subzone.

2.9.2 Corrosion Condition Assessment of Corrosion Zones ($C.C.I_i$)

The Corrosion Condition Index ($C.C.I_{i,j}$) values for each subzone shall be estimated as illustrated Table 2.13. The C.C.I of each zone i ($C.C.I_{i,}$) may be represented by the lowest of the $C.C.I_{i,j}$ values of its constituent subzones i.e. $C.C.I_i$ = Minimum of $C.C.I_{i,j}$ for j = 1 to n, where n is the number of subzones for the given corrosion zone i. For example, in case of submerged zone with seven subzones for a given ship, the C.C.I values for all constituent subzones can be calculated as per Table 2.14. The lowest among them will be the C.C.I of the submerged zone. Following the similar procedure, the C.C.I of all corrosion zones may be estimated. The calculation method has been highlighted for a submerged zone with seven subzones as an example.

Table 2.14 Illustration of Zone Level C.C.I$_{i,}$ Calculation Method

Zone, i	**Subzones, i,j (as per Table 2.4)**	**Condition Index Values from assessment of subzone w.r.t. 6 criteria (Table 2.13)**						**Subzone C.C.I $_{i,i}$ (minimum of the six condition index values)**	**Zone C.C.I$_{Sub}$**
		CC (i,j)	**UC (i,j)**	**LC (i,j)**	**CP (i,j)**	**FC (i,j)**	**DF (i,j)**		
Submerged Zone	Keel strake	$CC_{i,1}$	$UC_{i,1}$	$LC_{i,1}$	$CP_{i,1}$	$FC_{i,1}$	$DF_{i,1}$	$C.C.I_{Sub,1}$	**Minimum of Subzone C.C.I $_{i,j}$ values**
	Midship, Port side	$CC_{i,2}$	$UC_{i,2}$	$LC_{i,2}$	$CP_{i,2}$	$FC_{i,2}$	$DF_{i,2}$	$C.C.I_{Sub,2}$	
	Aft end, Port Side	$CC_{i,3}$	$UC_{i,3}$	$LC_{i,3}$	$CP_{i,3}$	$FC_{i,3}$	$DF_{i,3}$	$C.C.I_{Sub,3}$	
	Fore end, Port Side	$CC_{i,4}$	$UC_{i,4}$	$LC_{i,4}$	$CP_{i,4}$	$FC_{i,4}$	$DF_{i,4}$	$C.C.I_{Sub,4}$	
	Midship, Starboard side	$CC_{i,5}$	$UC_{i,5}$	$LC_{i,5}$	$CP_{i,5}$	$FC_{i,5}$	$DF_{i,5}$	$C.C.I_{Sub,5}$	
	Aft end, Starboard Side	$CC_{i,6}$	$UC_{i,6}$	$LC_{i,6}$	$CP_{i,6}$	$FC_{i,6}$	$DF_{i,6}$	$C.C.I_{Sub,6}$	
	Fore end, Starboard Side	$CC_{i,7}$	$UC_{i,7}$	$LC_{i,7}$	$CP_{i,7}$	$FC_{i,7}$	$DF_{i,7}$	$C.C.I_{Sub,7}$	

2.10 Assessment of Whole Ship Structure, Internal/ External Structure

The Corrosion Condition Index of the whole ship structure ($C.C.I_{ship}$) may be assessed from the $C.C.I_i$ values of various corrosion zones. The definition of proposed corrosion zones was schematically illustrated in Fig 2.1 and has been used for further calculations. The whole ship structure has been divided into external structure and internal structure. The external structure comprises of three corrosion zones viz. submerged zone, splash zone and atmospheric zone. The internal structure also comprises of three zones viz. ballast tank zone, cargo hold zone and other internal structures zone. In order to ensure that the most critical corrosion observations decide the prediction of C.C.I, the lowest constituent C.C.I values are proposed to be representative of the C.C.I, as shown below and illustrated in Table 2.15. The reason for the low C.C.I values may be presence of critical corrosion or inadequate corrosion protection systems at a given zone, resulting concerns on ship’s safety. The lowest value will point to that zone, improvement of which is critical for safety of ship.

(a) Corrosion Condition Index of whole ship Structure

$\text{C.C.I}_{\text{Ship}}$ = Minimum of $\text{C.C.I}_{\text{Ext}}$ and $\text{C.C.I}_{\text{Int}}$ values

(b) Corrosion Condition Index of External Structure

$\text{C.C.I}_{\text{Ext}}$ = Minimum of $\text{C.C.I}_{\text{Sub}}$, $\text{C.C.I}_{\text{Splash}}$, and $\text{C.C.I}_{\text{Atmos}}$ values

(c) Corrosion Condition Index of Internal Structure

$\text{C.C.I}_{\text{Int}}$ = Minimum of $\text{C.C.I}_{\text{Ballast}}$, $\text{C.C.I}_{\text{Cargo}}$, and $\text{C.C.I}_{\text{Otherinternal}}$ values

Table 2.15 Illustration of Overall C.C.I Calculation Method

C.C.I of Corrosion Zones	**C.C.I of External/ Internal structures**	**C.C.I of Overall Ship**
Submerged Zone, $\text{C.C.I}_{\text{Sub}}$	$\text{C.C.I}_{\text{Ext}}$ = Minimum of $\text{C.C.I}_{\text{Sub}}$, $\text{C.C.I}_{\text{Splash}}$, and $\text{C.C.I}_{\text{Atmos}}$ values	$\text{C.C.I}_{\text{Ship}}$ = Minimum of $\text{C.C.I}_{\text{Ext}}$ and $\text{C.C.I}_{\text{Int}}$ values
Splash Zone, $\text{C.C.I}_{\text{Splash}}$		
Atmospheric Zone, $\text{C.C.I}_{\text{Atmos}}$		
Ballast Tank Zone, $\text{C.C.I}_{\text{Ballast}}$	$\text{C.C.I}_{\text{Int}}$ = Minimum of $\text{C.C.I}_{\text{Ballast}}$, $\text{C.C.I}_{\text{Cargo}}$, and $\text{C.C.I}_{\text{Otherinternal}}$ values	
Cargo Zone, $\text{C.C.I}_{\text{Cargo}}$		
Other Internal Structures Zone, $\text{C.C.I}_{\text{Otherinternal}}$		

2.11 Flow Chart of C.C.I Development Process

The concept of Corrosion Condition Index (C.C.I) and its formulation were discussed in Sections 2.2 to 2.10. The method involves a number of steps, which are to be repeated at subzone/ zone levels. A flowchart highlighting the process of systematically arriving at the C.C.I of a ship structure is presented in Fig 2.9.

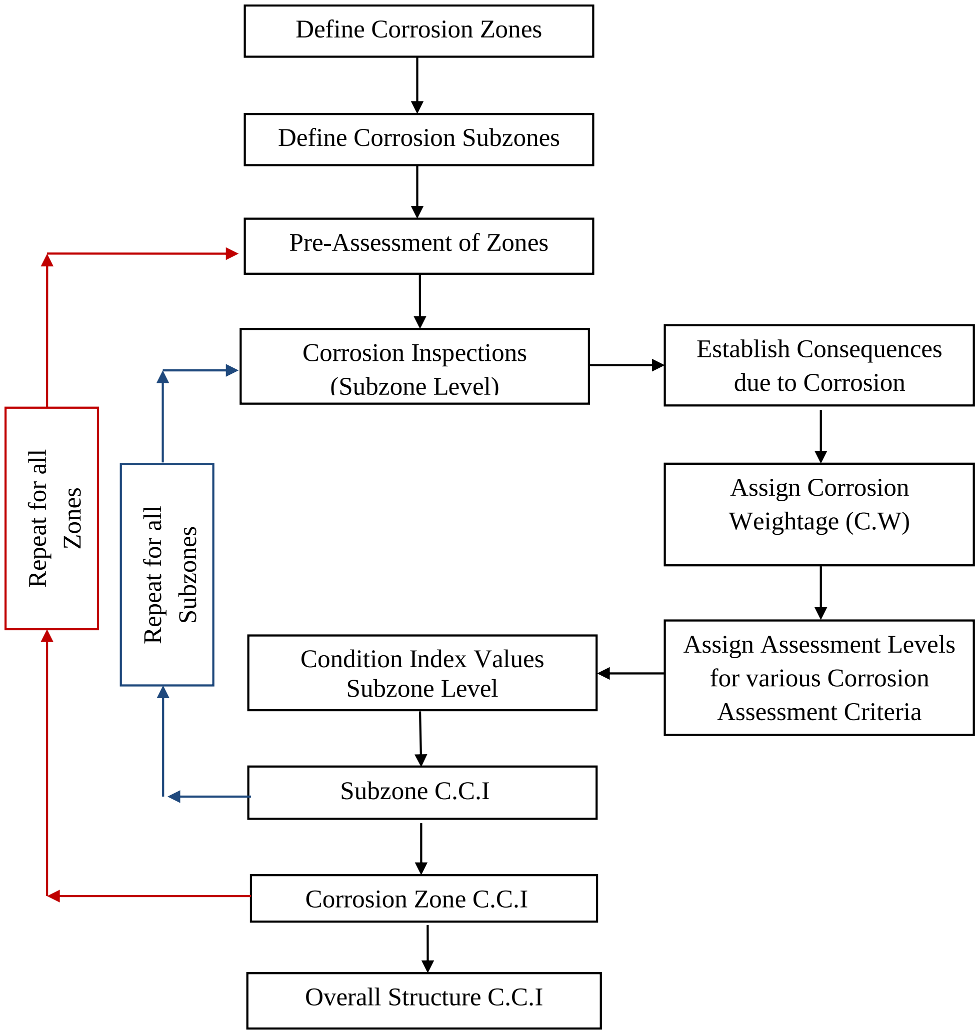


Fig 2.9 Flow chart – systematic development process of C.C.I

2.12 Recommendations Based on C.C.I Values

The C.C.I is a qualitative measure of corrosion condition of a steel ship at any time during her operational phase. According to the proposed formulation method, the C.C.I of ship structure would decrease as the corrosion condition deteriorates. The values would provide owners and maintenance managers the information required to optimise resource allocation for corrosion repair/ maintenance and replacement of ship's structural components. Through a well-executed C.C.I rating system, information on specific corrosion condition of the structure, consequence of existing condition and urgency of repair can be predicted. The major features of C.C.I are:-

a) It is an indicator of the corrosion condition of the steel ship structure and critical areas based upon corrosion inspection results processed by an algorithm.

b) It is a number with lower C.C.I values indicating deteriorating corrosion condition of the structure.

c) It can facilitate targeted corrosion inspections and monitoring at critical areas.

d) It is useful for decision making by maintenance managers and engineers at all hierarchical levels.

e) It is useful for the prospective buyers looking for second hand ships.

f) It is a voluntary system, helping to improve the environmental and operational performance of shipping industry.

g) The index is intended to promote safer ships and can also be used by shippers and ship owners as their own promotional instrument.

The recommended C.C.I rating system for a particular corrosion zone or for the overall structure with recommendations is presented in the Table 2.16. The C.C.I values are presented in steps of 10 points along with rating description and recommendations. Based on the C.C.I, the ship’s structure has been rated into six categories such as “As built condition”, “Excellent”, “Very good”, “Good”, “Satisfactory” and “Poor”. An appropriate colour coding is also suggested to highlight the corrosion conditions. Dark green indicates the “As built” and the “Excellent” conditions. The “Very good”, “Good”, “Satisfactory” and “Poor” conditions are respectively indicated by dark blue, light blue, yellow and dark red colours. Higher the C.C.I values better will be corrosion protection condition of ship structure. As the ship gets older, the C.C.I values may reduce as a result of corrosion and therefore the owner may need to invest more to maintain the vessel at higher C.C.I. It is recommended that the effort of the ship owner should be to maintain a minimum C.C.I of 70 and above (corresponding to very good condition) throughout ship's operational life. Ships with C.C.I of below 50 (corresponding to poor condition) must undergo immediate remedial actions/ extensive repairs to improve C.C.I rating to above 70 prior to further operations.

Table 2.16 C.C.I Rating System and Recommendations

C.C.I (Zone/ Overall)	Rating Description	Recommendations
90-100	**As built condition**	NIL
80-90	**Excellent**	No repair/ maintenance required
70-80	**Very Good**	No repair/ maintenance required, close monitoring of critical areas required
60-70	**Good**	Corrosion observations are minor in nature and are to be attended in the next planned maintenance
50-60	**Satisfactory**	Substantial local corrosion observed. Immediate possible repairs and close monitoring of the affected zones necessary
Below 50	**Poor**	Corrosion affects ship's potential to remain seaworthy, require immediate repair/ maintenance actions before the next sailing

2.13 Case Studies

Validation of the formulation method as well as the proposed rating system is an integral part of the C.C.I. development process before the same is implemented. One of the methods to validate the concept is with the help of case studies. Accordingly, an ocean going steel vessel has been considered as per details shown in Table 2.17 and details for fields “Name of the vessel”, “Year Built”, “Type”, “Built at”, “Owner”, and “Classification Society” has been entered as a dummy value XXX.

Table 2.17 Main Particulars of a Vessel Selected for Case Studies for Validation of C.C.I. Concept

Item	Details
Name of the vessel	XXX
Year Built	XXX
Type	XXX
Built at	XXX
Owner	XXX
Classification Society	XXX
Deadweight (T)	24000 T
Length Between Particulars (LBP)	162 m
Length Overall (LOA)	166.5 m
Breadth (B)	26 m
Depth (D)	16 m
Load Water Line Draught (LWL)	9 m

Three different corrosion conditions have been simulated for performing C.C.I calculations as three case studies. The ship structure has been considered to be divided into external structure (comprising of three corrosion zones viz. submerged zone, splash zone and atmospheric zone) and internal structure (comprising of three corrosion zones viz. ballast tank zone, cargo zone and other internal structures zone) as shown in Table 2.18. The number of subzones for each corrosion zones is also shown in this table. The case studies have been designed to confirm the C.C.I rating system and recommendations which was proposed in Table 2.16. Details of the three case studies indicating the corrosion conditions (very good, satisfactory and poor) such as descriptions, C.C.I ratings and assigned Corrosion Weightages (CW) are presented in Table 2.19.

Each of the corrosion conditions has been simulated by assigning Assessment Levels (ALs) as indicated in Tables 2.20, 2.21 and 2.22 for Case – 1 (very good condition), Case – 2 (satisfactory condition) and Case – 3 (poor condition) respectively. There is a deterioration in the corrosion condition as the ship move from very good to satisfactory to poor condition. There is a corresponding decrease in the values of ALs for various Assessment Criteria (presented at Table 2.6), which has been selected from the knowledge base compiled and presented in Tables 2.7 to 2.12. The corrosion condition assessment has been performed by the using MS Excel software (as per the knowledge base compiled) for the three cases discussed above. The summary of calculations is presented in Tables 2.23, 2.24 and 2.25 respectively for corrosion conditions very good, satisfactory and poor conditions. The summary of the calculations is presented in Table 2.26.

Table 2.18 Corrosion Zones and Subzones for the Ship Selected for the Case Studies

	Corrosion Zones		**No of Subzones**	**Remarks**
External Structure	Zone 1	Submerged Zone	*8*	Refer section 2.5.2
	Zone 2	Splash Zone	6	
	Zone 3	Atmospheric Zone	8	
Internal Structure	Zone 4	Ballast Tank Zone	3	3 ballast water tanks considered
	Zone 5	Cargo Zone	3	3 cargo holds tanks considered
	Zone 6	Other Internal Structures Zone	5	Refer section 2.5.2

Table 2.19 Corrosion Conditions and Corrosion Weightage (CW) for the Case Studies

Case Study	Case 1	Case 2	Case 3
Corrosion Condition	Very Good	Satisfactory	Poor
Description of Corrosion Condition	No repair/ maintenance required, close monitoring of critical areas required	Substantial local corrosion present. No effect on the seaworthiness. Immediate possible repairs to be undertaken	Corrosion affects ship's potential to remain seaworthy, require immediate repair/ maintenance actions before the next sailing
Range of C.C.I Values	70-80	50-60	Below 50
Assigned Corrosion Weightage for Subzones	CW = 10 (None) or CW =9 (Low)	CW= 10 (None) or CW = 9 (Low) or CW = 8 (Moderate)	CW= 10 (None), CW = 9 (Low) CW = 8 (Moderate) or CW = 7 (High)

Table 2.20 Assessment Levels for Various Corrosion Assessment Criteria, Case – 1

CASE 1 – VERY GOOD CONDITION		
Assessment Criteria	**Assessment Description**	**Assessment Level (AL)**
Coating Condition	Negligible coating breakdown	10
	Minor spot rusting	9
	General breakdown of coating: <5%	8
Uniform Corrosion	No Corrosion	10
	Negligible Corrosion, < 5% Light Rust, <10% reduction in corrosion allowance	9
	Minor Spot rusting, 5-20% Light Rust, <20% reduction in corrosion allowance	8
Localised Corrosion	NIL	10
	Shallow pits, < 1/3 of original thickness, < 5% area	9
Cathodic Protection	Anodes similar to newly built condition	10
	>75% anode remaining, Hull potential in the protective range	9
Fouling Condition	Clean, Foul free hull, Antifouling paint intact	10
	Soft Fouling, FR20, Antifouling paint missing < 2%	9
Design Factors	No evidence of galvanic coupling/ no restriction of access/ no accumulation of sediment etc.	10

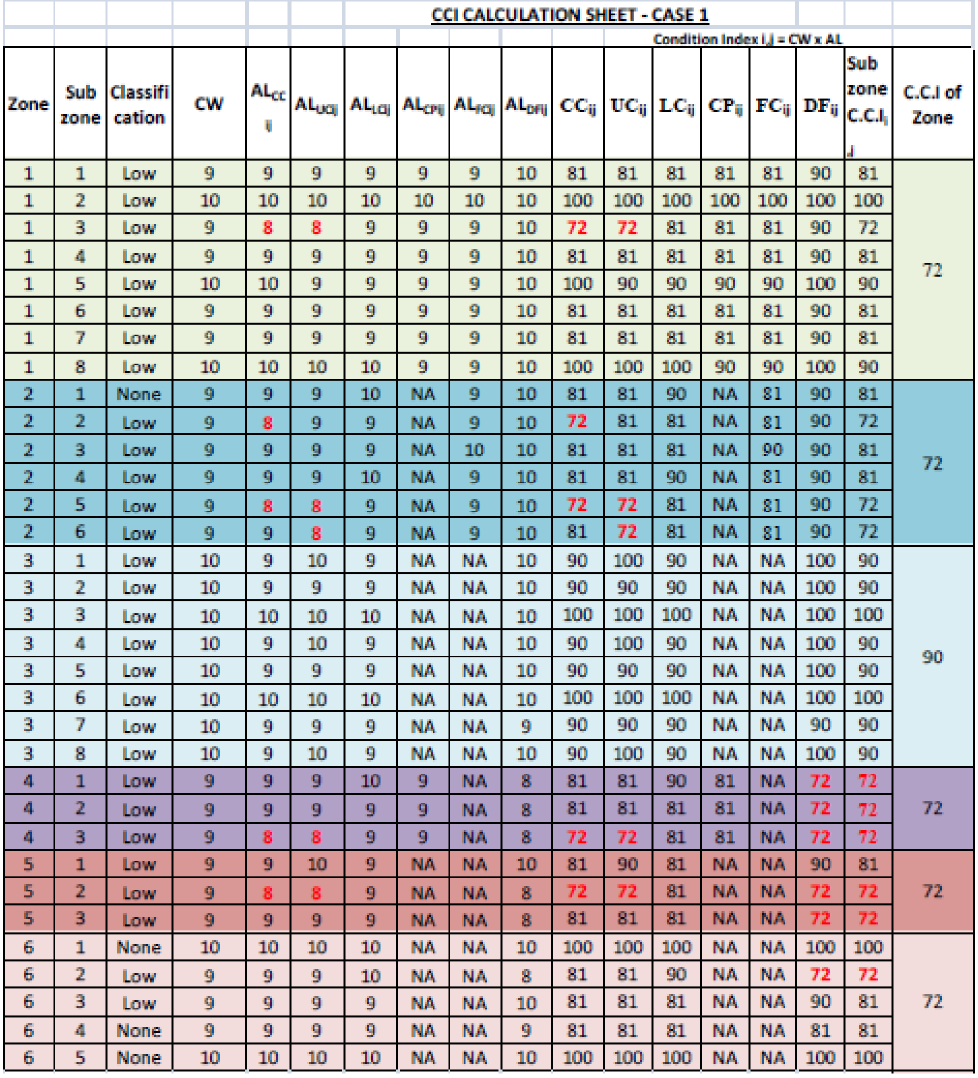
Table 2.21 Assessment Levels for Various Corrosion Assessment Criteria, Case – 2

CASE 2 – SATISFACTORY CONDITION		
Assessment Criteria	**Assessment Description**	**Assessment Level (AL)**
Coating Condition	Negligible coating breakdown	10
	Minor spot rusting	9
	General breakdown of coating < 5%	8
	General breakdown of coating 10 - 20 %	7
Uniform Corrosion	No Corrosion	10
	Negligible Corrosion, < 5% Light Rust <10% reduction in corrosion allowance	9
	Minor Spot rusting, 5-20% Light Rust < 20% reduction in corrosion allowance	8
	Rusting at edges of weld/ stiffeners, > 20% Light Rust, <10% hard scale, < 30% reduction in corrosion allowance	7
Localised Corrosion	NIL	10
	Shallow pits, < 1/3 of original thickness, < 5% area	9
	Shallow pits, < 1/3 of original thickness, > 15% area	7
Cathodic Protection	Anodes similar to newly built condition	10
	> 75% anode remaining, Hull potential in the protective range	9
	> 50 % anode remaining, Hull potential in the partially protective range	8
Fouling Condition	Clean, Foul free hull, Antifouling paint intact	10
	Soft Fouling, FR20, Antifouling paint missing < 2% area	9
	Soft Fouling, FR30, Antifouling paint missing < 10% area	8
Design Factors	No evidence of Galvanic coupling/ No restriction of access /No accumulation of sediment etc.	10
	Minor evidence of above factors	8

Table 2.22 Assessment Levels for Various Corrosion Assessment Criteria, Case – 3

CASE 3 – POOR CONDITION		
Assessment Criteria	**Assessment Description**	**Assessment Level (AL)**
Coating Condition	Negligible coating breakdown	10
	Minor spot rusting	9
	General breakdown of coating < 5%	8
	General breakdown of coating 10 - 20%	7
	General breakdown of coating 20 - 30%	6
Uniform Corrosion	No Corrosion	10
	Negligible Corrosion,< Light Rust, <10% reduction in corrosion allowance	9
	Minor Spot rusting, 5-20% Light Rust, < 20% reduction in corrosion allowance	8
	Rusting at edges of weld/ stiffeners, > 20% Light Rust, < 10% hard scale, < 30% reduction in corrosion allowance	7
	Hard Scale >10-30%, <50% reduction in corrosion allowance	6
Localised Corrosion	NIL	10
	Shallow pits, < 1/3 of original thickness, < 5% area	9
	Shallow pits, < 1/3 of original thickness, > 15% area	8
	Shallow pits, < 1/3 of original thickness, > 15% area	7
Cathodic Protection	Anodes similar to newly built condition	10
	> 75% anode remaining, Hull potential in the protective range	9
	> 50 % anode remaining, Hull potential in the partially protective range	8
	< 50% anodes only remaining, Cathodic protection system is not effective, Hull potential is outside the protection range (more than 0.80 V or less than -1.10 V)	6
Fouling Condition	Clean, Foul free hull, Antifouling paint intact	10
	Soft Fouling, FR20, Antifouling paint missing < 2% area	9
	Soft Fouling, FR30, Antifouling paint missing < 10% area	8
	FR 40, Antifouling paint missing < 30% area	7
Design Factors	No evidence of galvanic coupling/ no restriction of access/ no accumulation of sediment etc.	10
	Minor evidence of above factors	8
	Evidence of Galvanic corrosion or Evidence of stress corrosion or Restriction on access for inspection/ maintenance or Accumulation of sediments, sludge and other materials indicating insufficient drainage	7

Table 2.23 Corrosion Condition Index (C.C.I) Calculation Sheet, Case-1

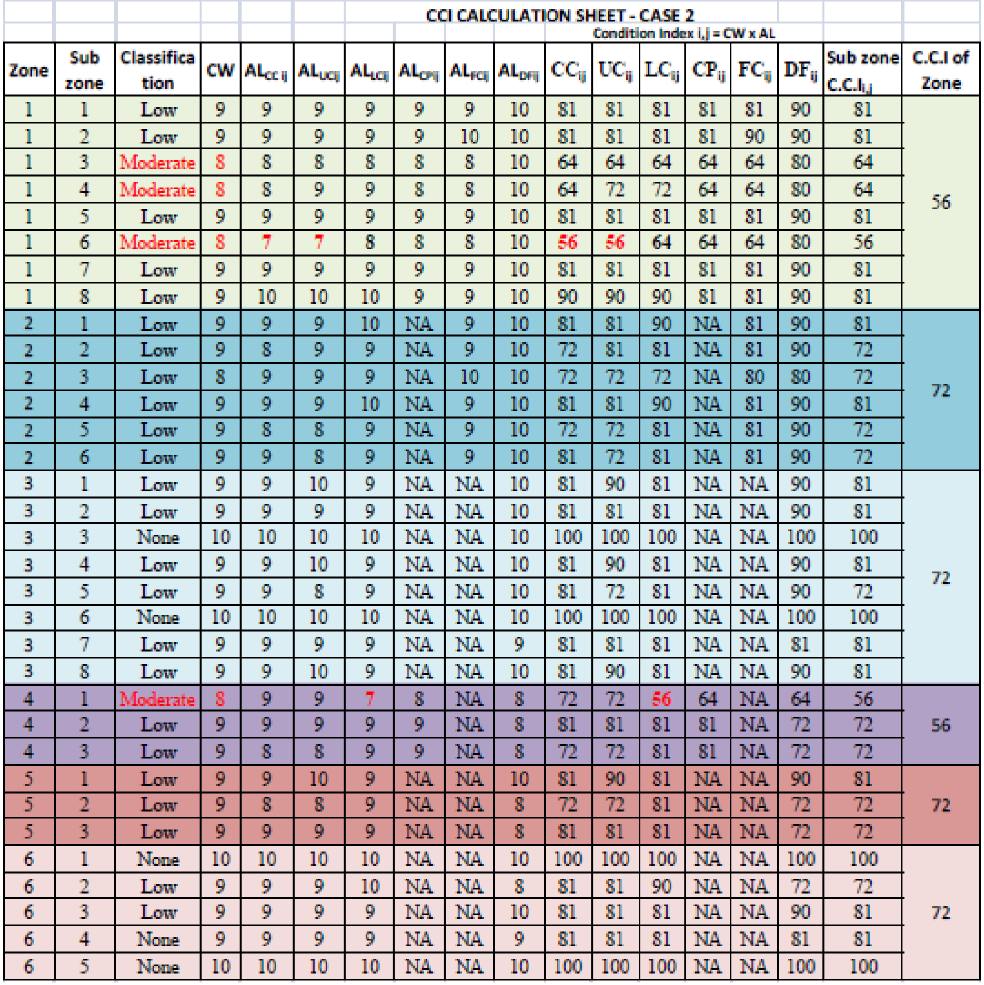


CCI CALCULATION SHEET - CASE 1

Condition Index i,j = CW x AL

Zone	Sub zone	Classification	CW	AL_{CCij}	AL_{UCij}	AL_{LCij}	AL_{CPij}	AL_{FCij}	AL_{DFij}	CC_{ij}	UC_{ij}	LC_{ij}	CP_{ij}	FC_{ij}	DF_{ij}	Sub zone $C.C.I_{i,j}$	C.C.I of Zone
1	1	Low	9	9	9	9	9	9	10	81	81	81	81	81	90	81	72
1	2	Low	10	10	10	10	10	10	10	100	100	100	100	100	100	100	
1	3	Low	9	8	8	9	9	9	10	72	72	81	81	81	90	72	
1	4	Low	9	9	9	9	9	9	10	81	81	81	81	81	90	81	
1	5	Low	10	10	9	9	9	9	10	100	90	90	90	90	100	90	
1	6	Low	9	9	9	9	9	9	10	81	81	81	81	81	90	81	
1	7	Low	9	9	9	9	9	9	10	81	81	81	81	81	90	81	
1	8	Low	10	10	10	10	9	9	10	100	100	100	90	90	100	90	
2	1	None	9	9	9	10	NA	9	10	81	81	90	NA	81	90	81	72
2	2	Low	9	8	9	9	NA	9	10	72	81	81	NA	81	90	72	
2	3	Low	9	9	9	9	NA	10	10	81	81	81	NA	90	90	81	
2	4	Low	9	9	9	10	NA	9	10	81	81	90	NA	81	90	81	
2	5	Low	9	8	8	9	NA	9	10	72	72	81	NA	81	90	72	
2	6	Low	9	9	8	9	NA	9	10	81	72	81	NA	81	90	72	
3	1	Low	10	9	10	9	NA	NA	10	90	100	90	NA	NA	100	90	90
3	2	Low	10	9	9	9	NA	NA	10	90	90	90	NA	NA	100	90	
3	3	Low	10	10	10	10	NA	NA	10	100	100	100	NA	NA	100	100	
3	4	Low	10	9	10	9	NA	NA	10	90	100	90	NA	NA	100	90	
3	5	Low	10	9	9	9	NA	NA	10	90	90	90	NA	NA	100	90	
3	6	Low	10	10	10	10	NA	NA	10	100	100	100	NA	NA	100	100	
3	7	Low	10	9	9	9	NA	NA	9	90	90	90	NA	NA	90	90	
3	8	Low	10	9	10	9	NA	NA	10	90	100	90	NA	NA	100	90	
4	1	Low	9	9	9	10	9	NA	8	81	81	90	81	NA	72	72	72
4	2	Low	9	9	9	9	9	NA	8	81	81	81	81	NA	72	72	
4	3	Low	9	8	8	9	9	NA	8	72	72	81	81	NA	72	72	
5	1	Low	9	9	10	9	NA	NA	10	81	90	81	NA	NA	90	81	72
5	2	Low	9	8	8	9	NA	NA	8	72	72	81	NA	NA	72	72	
5	3	Low	9	9	9	9	NA	NA	8	81	81	81	NA	NA	72	72	
6	1	None	10	10	10	10	NA	NA	10	100	100	100	NA	NA	100	100	72
6	2	Low	9	9	9	10	NA	NA	8	81	81	90	NA	NA	72	72	
6	3	Low	9	9	9	9	NA	NA	10	81	81	81	NA	NA	90	81	
6	4	None	9	9	9	9	NA	NA	9	81	81	81	NA	NA	81	81	
6	5	None	10	10	10	10	NA	NA	10	100	100	100	NA	NA	100	100	

Table 2.24 Corrosion Condition Index (C.C.I) Calculation Sheet, Case -2

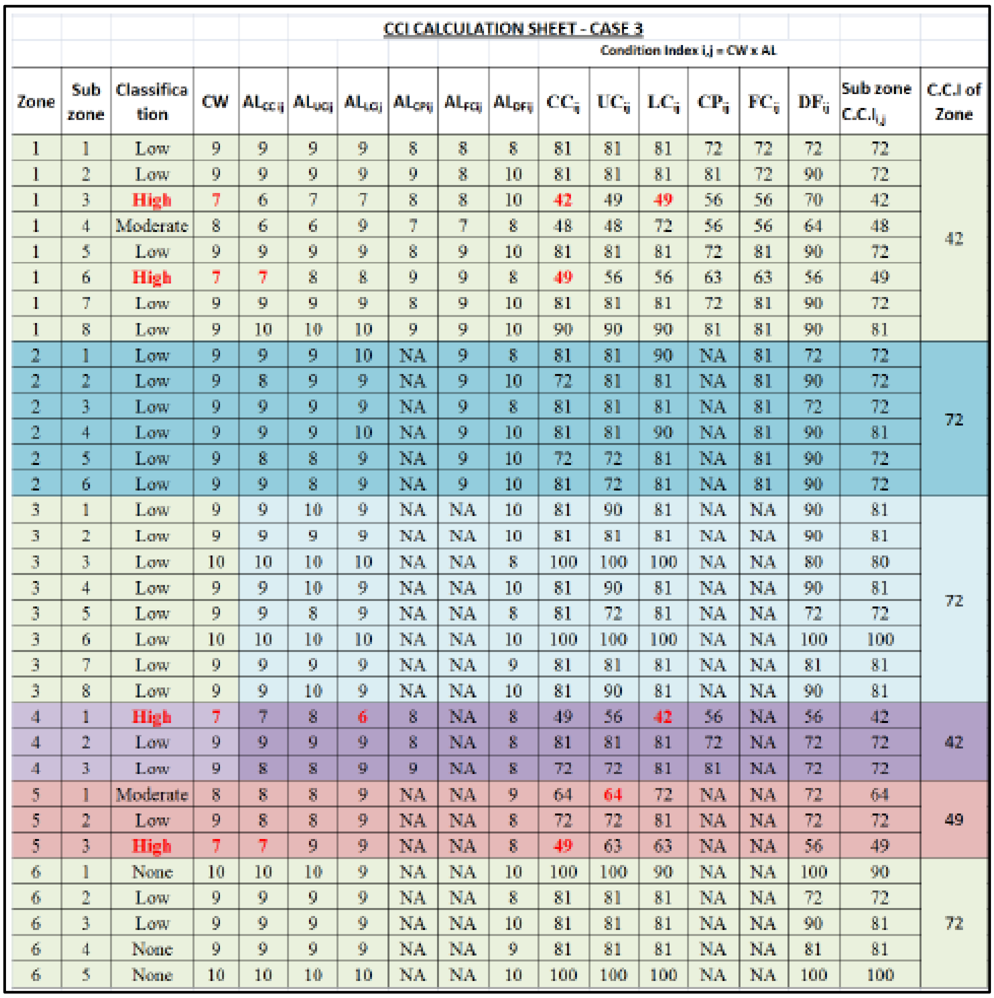


CCI CALCULATION SHEET - CASE 2

Condition Index i,j = CW x AL

Zone	Sub zone	Classification	CW	$AL_{CC\,ij}$	AL_{UCij}	AL_{LCij}	AL_{CPij}	AL_{FCij}	AL_{DFij}	CC_{ij}	UC_{ij}	LC_{ij}	CP_{ij}	FC_{ij}	DF_{ij}	Sub zone $C.C.I_{i,j}$	C.C.I of Zone
1	1	Low	9	9	9	9	9	9	10	81	81	81	81	81	90	81	56
1	2	Low	9	9	9	9	9	10	10	81	81	81	81	90	90	81	
1	3	Moderate	8	8	8	8	8	8	10	64	64	64	64	64	80	64	
1	4	Moderate	8	8	9	9	8	8	10	64	72	72	64	64	80	64	
1	5	Low	9	9	9	9	9	9	10	81	81	81	81	81	90	81	
1	6	Moderate	8	7	7	8	8	8	10	56	56	64	64	64	80	56	
1	7	Low	9	9	9	9	9	9	10	81	81	81	81	81	90	81	
1	8	Low	9	10	10	10	9	9	10	90	90	90	81	81	90	81	
2	1	Low	9	9	9	10	NA	9	10	81	81	90	NA	81	90	81	72
2	2	Low	9	8	9	9	NA	9	10	72	81	81	NA	81	90	72	
2	3	Low	8	9	9	9	NA	10	10	72	72	72	NA	80	80	72	
2	4	Low	9	9	9	10	NA	9	10	81	81	90	NA	81	90	81	
2	5	Low	9	8	8	9	NA	9	10	72	72	81	NA	81	90	72	
2	6	Low	9	9	8	9	NA	9	10	81	72	81	NA	81	90	72	
3	1	Low	9	9	10	9	NA	NA	10	81	90	81	NA	NA	90	81	72
3	2	Low	9	9	9	9	NA	NA	10	81	81	81	NA	NA	90	81	
3	3	None	10	10	10	10	NA	NA	10	100	100	100	NA	NA	100	100	
3	4	Low	9	9	10	9	NA	NA	10	81	90	81	NA	NA	90	81	
3	5	Low	9	9	8	9	NA	NA	10	81	72	81	NA	NA	90	72	
3	6	None	10	10	10	10	NA	NA	10	100	100	100	NA	NA	100	100	
3	7	Low	9	9	9	9	NA	NA	9	81	81	81	NA	NA	81	81	
3	8	Low	9	9	10	9	NA	NA	10	81	90	81	NA	NA	90	81	
4	1	Moderate	8	9	9	7	8	NA	8	72	72	56	64	NA	64	56	56
4	2	Low	9	9	9	9	9	NA	8	81	81	81	81	NA	72	72	
4	3	Low	9	8	8	9	9	NA	8	72	72	81	81	NA	72	72	
5	1	Low	9	9	10	9	NA	NA	10	81	90	81	NA	NA	90	81	72
5	2	Low	9	8	8	9	NA	NA	8	72	72	81	NA	NA	72	72	
5	3	Low	9	9	9	9	NA	NA	8	81	81	81	NA	NA	72	72	
6	1	None	10	10	10	10	NA	NA	10	100	100	100	NA	NA	100	100	72
6	2	Low	9	9	9	10	NA	NA	8	81	81	90	NA	NA	72	72	
6	3	Low	9	9	9	9	NA	NA	10	81	81	81	NA	NA	90	81	
6	4	None	9	9	9	9	NA	NA	9	81	81	81	NA	NA	81	81	
6	5	None	10	10	10	10	NA	NA	10	100	100	100	NA	NA	100	100	

Table 2.25 Corrosion Condition Index (C.C.I) Calculation Sheet, Case – 3



CCI CALCULATION SHEET - CASE 3

Condition Index i,j = CW x AL

Zone	Sub zone	Classification	CW	AL_{CCij}	AL_{UCij}	AL_{LCij}	AL_{CPij}	AL_{FCij}	AL_{DFij}	CC_{ij}	UC_{ij}	LC_{ij}	CP_{ij}	FC_{ij}	DF_{ij}	Sub zone $C.C.I_{i,j}$	C.C.I of Zone
1	1	Low	9	9	9	9	8	8	8	81	81	81	72	72	72	72	42
1	2	Low	9	9	9	9	9	8	10	81	81	81	81	72	90	72	
1	3	**High**	**7**	6	7	7	8	8	10	**42**	49	**49**	56	56	70	42	
1	4	Moderate	8	6	6	9	7	7	8	48	48	72	56	56	64	48	
1	5	Low	9	9	9	9	8	9	10	81	81	81	72	81	90	72	
1	6	**High**	**7**	**7**	8	8	9	9	8	**49**	56	56	63	63	56	49	
1	7	Low	9	9	9	9	8	9	10	81	81	81	72	81	90	72	
1	8	Low	9	10	10	10	9	9	10	90	90	90	81	81	90	81	
2	1	Low	9	9	9	10	NA	9	8	81	81	90	NA	81	72	72	72
2	2	Low	9	8	9	9	NA	9	10	72	81	81	NA	81	90	72	
2	3	Low	9	9	9	9	NA	9	8	81	81	81	NA	81	72	72	
2	4	Low	9	9	9	10	NA	9	10	81	81	90	NA	81	90	81	
2	5	Low	9	8	8	9	NA	9	10	72	72	81	NA	81	90	72	
2	6	Low	9	9	8	9	NA	9	10	81	72	81	NA	81	90	72	
3	1	Low	9	9	10	9	NA	NA	10	81	90	81	NA	NA	90	81	72
3	2	Low	9	9	9	9	NA	NA	10	81	81	81	NA	NA	90	81	
3	3	Low	10	10	10	10	NA	NA	8	100	100	100	NA	NA	80	80	
3	4	Low	9	9	10	9	NA	NA	10	81	90	81	NA	NA	90	81	
3	5	Low	9	9	8	9	NA	NA	8	81	72	81	NA	NA	72	72	
3	6	Low	10	10	10	10	NA	NA	10	100	100	100	NA	NA	100	100	
3	7	Low	9	9	9	9	NA	NA	9	81	81	81	NA	NA	81	81	
3	8	Low	9	9	10	9	NA	NA	10	81	90	81	NA	NA	90	81	
4	1	**High**	**7**	7	8	**6**	8	NA	8	49	56	**42**	56	NA	56	42	42
4	2	Low	9	9	9	9	8	NA	8	81	81	81	72	NA	72	72	
4	3	Low	9	8	8	9	9	NA	8	72	72	81	81	NA	72	72	
5	1	Moderate	8	8	8	9	NA	NA	9	64	**64**	72	NA	NA	72	64	49
5	2	Low	9	8	8	9	NA	NA	8	72	72	81	NA	NA	72	72	
5	3	**High**	**7**	**7**	9	9	NA	NA	8	**49**	63	63	NA	NA	56	49	
6	1	None	10	10	10	9	NA	NA	10	100	100	90	NA	NA	100	90	72
6	2	Low	9	9	9	9	NA	NA	8	81	81	81	NA	NA	72	72	
6	3	Low	9	9	9	9	NA	NA	10	81	81	81	NA	NA	90	81	
6	4	None	9	9	9	9	NA	NA	9	81	81	81	NA	NA	81	81	
6	5	None	10	10	10	10	NA	NA	10	100	100	100	NA	NA	100	100	

Table 2.26 Summary of Case Studies - Corrosion Condition Assessment Calculations

	Case - 1	**Case – 2**	**Case - 3**
Corrosion Zone	**C.C.I**	**C.C.I**	**C.C.I**
Submerged zone	72.0	56.0	42.0
Splash zone	72.0	72.0	72.0
Atmospheric zone	90.0	72.0	72.0
Ballast tank zone	72.0	56.0	42.0
Cargo zone	72.0	72.0	49.0
Other internal structures zone	72.0	72.0	72.0
External structure C.C.I$_{Ext}$	72.0	56.0	42.0
Internal structure C.C.I$_{Int}$	72.0	56.0	42.0
Overall C.C.I$_{Ship}$	72.0	56.0	42.0
Remarks	**Conforms to the Very Good condition**	**Conforms to the Satisfactory condition**	**Conforms to the Poor condition**

The C.C.I values of all corrosion zones as well as that for the overall ship structure for the three different cases are presented in Table 2.26. The C.C.I values for Case - 1, Case - 2 and Case - 3 are respectively 72, 56 and 42. These results confirm the corrosion conditions assumed in Table 2.19 for the three case studies (very good, satisfactory and poor). Further the C.C.I rating scale as well as the recommendations presented in Table 2.26 has also been validated for all three cases since C.C.I values obtained lie in the proposed range. The developed concept of C.C.I can therefore be implemented for use by stakeholders in the shipping industry for corrosion assessment of ship structures at any point in her operational life.

2.14 Conclusions

Representation of complex corrosion condition of ship structure with a numeral number along with explanations will be highly advantageous. A systematic approach to develop a concept of Corrosion Condition Index

(C.C.I) which will qualitatively represent the corrosion condition of a steel ship structure during her operational phase has been developed. Existing knowledge base on current practices in the field of corrosion and corrosion protection of ships has been collated and six major assessment criteria and a system for assigning Corrosion Weightage (CW) to represent the corrosion consequence have been developed. The whole ship structure has been considered as a corrosion system and is divided into a number of corrosion zones and subzones for systematic corrosion inspection and assessment.

A C.C.I rating scale with colour coding and suitable recommendations has been suggested for future operation of ships. The C.C.I rating scale varies from 100 to 50 and below, indicating a corresponding deterioration in the corrosion condition of ships. Higher the C.C.I, higher will be the integrity of corrosion protection systems. Based on the C.C.I, the ship's structure has been rated as "As built condition", "Excellent", "Very good", "Good", "Satisfactory" and "Poor". Three Case studies for a given ship (in three different corrosion conditions) have been carried out to validate the proposed C.C.I rating system. It has been recommended that the ship owner shall maintain a minimum C.C.I of 70 (corresponding to very good condition) throughout ship's operational life. Ships with C.C.I of below 50 (corresponding to poor condition) must undergo immediate remedial actions/ extensive repairs to improve C.C.I rating to above 70 prior to further operations.

The C.C.I system is being proposed as a voluntary system, helping to improve the environmental and operational performance of shipping industry. It may be used along with other already existing indices in the shipping industry such as Environmental Ship Index (ESI), Clean Shipping Index (CSI), Energy Efficiency Design Index (EEDI) etc. to promote safer ships and can also be used by shippers and ship owners as their own promotional instrument. The C.C.I system can also facilitate targeted corrosion inspections at critical areas. It will be useful for all stakeholders and can be an indicator for the prospective buyers looking for second hand ships.

*****

Chapter 3

DEVELOPMENT OF KNOWLEDGE BASED DECISION SUPPORT SYSTEM (DSS) FOR CORROSION CONDITION ASSESSMENT OF SHIP STRUCTURES - (SCCI SOFTWARE)

Contents

3.1 General

A Decision Support System (DSS) is a computer based information system that supports decision making process. A properly designed DSS is an interactive software based system intended to help decision makers to compile useful information from a combination of raw data, documents, and personal knowledge to identify and solve problems and make decisions. Decision makers have been seeking help from technologies over the past few decades in order to cope with the decision environment and make better decisions. Decision Support Systems are one of the most widely used management information systems in current operations management in many industries. The managers use Knowledge Based DSS (KB-DSS) to improve their decision making not only in terms of speed and accuracy but also consistency. The DSS can provide the right information at the right time in the right format with “what-if” analysis of decision alternatives. It can also provide effective interaction mechanisms so that information and analysis can be presented to decision makers in an easy to understand manner (Shaofeng et al. 2015).

Decision Support systems are widely used for several applications in the field of shipping and few cases of development have been reported in the field of corrosion problems. Katsoulakos and Hornsby (1989) and Sivaprasad (2010) have presented various applications of expert systems in marine technology fields. Vikas (2016) has presented development of a web based decision support system for port planning, design and green port rating incorporating the modular design concept. Development of Decision Support Systems in the field of corrosion are reported by Ardian and Condanni (1994), Mayer (1994), Makkonen and Foster (2001), Unar (2007) and Peter (1996). From the detailed literature review it was identified that there is no reported development of DSS in field of corrosion assessment and monitoring of ship structures. Long term corrosion protection of any metallic structure is difficult when exposed to an aggressive environment and this is particularly true for vessels in marine environment. Corrosion being one of the largest through life cost component of ships in her life cycle need focussed attention by all stakeholders. Corrosion has tremendous adverse impact on structure, environment, equipment and personal safety of ships. Corrosion also poses numerous safety risks and is therefore a source of major concern to ship owners and platform managers. In the absence of a stipulated corrosion prevention programme that would guarantee continuity of initiatives, ship owners are often forced to trade off corrosion resistance as a cost saving measure especially when under financial constraints.

The development of a concept of C.C.I as an indicator of corrosion condition of steel ship structures during operation phase has been presented in Chapter 2. The method involves large number of corrosion inspections, assigning Corrosion Weightage (C.W) as well as Assessment Levels (A.L) for the various corrosion assessment criteria identified. Based on the observations of the inspections, the important decisions on corrosion conditions are to be taken at every stage as if it is taken with the help of a domain expert. The expert knowledge may be consulted in the absence of a domain expert at the site. Further, the knowledge base is not static and would need continuous amendments to incorporate new research findings, international regulations and standards. A definite need was therefore felt to develop a KB-DSS to guide the user to systematically interpret the corrosion observations and accurately predict the C.C.I of a ship structure. The KB-DSS will facilitate easy book keeping, quick retrieval of data, recommending decisions referring to the knowledge base, multi-user access, and access to historical corrosion condition data etc. apart from its commercial applications. It can also offer the much needed flexibility to the user with respect to overall management of corrosion condition. Making the KB-DSS available as a web based application would facilitate portability and easy access through internet.

3.2 Fundamental Elements of Decision Support Systems

The classic DSS architecture is typically comprised of three core components Viz. a Database Management Sub-System (DBMS), a Model Base Management Sub-System (MBMS), and user interaction management sub-system which is also called a Human Computer Interface (HCI). The integration of the knowledge management function into classic DSS can improve decision making performance by enhancing the quality of services by having an “expert” readily available to users. It can also assist users to make their decisions more consistently. These programs represents the knowledge symbolically, examine and explain their reasoning processes, and address problem areas that require years of special training and education for human to master. The most important component of a KB-DSS is a Knowledge Base (KB) and an Inference Engine (Akerkar and Sajja, 2010 and Sprague and Carlson, 1982). The same is pictorially represented in Fig 3.1.

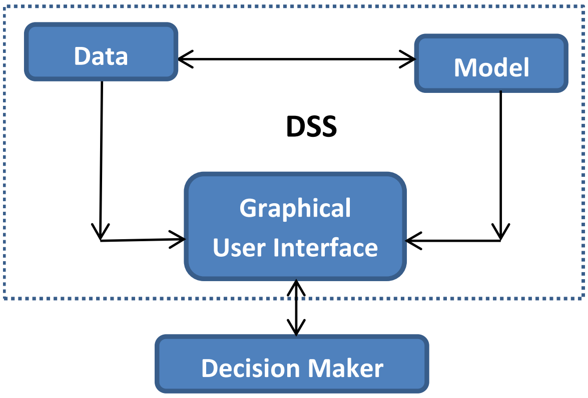


Fig. 3.1 Core components of a Decision Support System (DSS)

3.3 KB-DSS for Corrosion Assessment of Ship Structures

A new methodology for systematic assessment and monitoring of corrosion condition of steel ship structures was presented in Chapter 2 and a concept of C.C.I was proposed. The C.C.I is a numeral number which represents the complex corrosion condition of a steel ship structure during her operational period. A corrosion system approach in which the ship structure is divided into a number of corrosion subsystems (zones), which are further subdivided into corrosion subzones, was developed. The formulation involves of interpretation of large number of corrosion inspection data of various corrosion subzones depending on the severity of consequences on structure, environment, cargo, personnel etc. Assessment of each subzone is based on six corrosion assessment criteria, which is the most critical step in order to predict the corrosion condition. Finally the C.C.I of corrosion subzones, corrosion zones and entire ship structure can be estimated as per the concept developed. The corrosion condition assessment needs to be consistent and should be as per a well-defined procedure to ensure uniformity and to facilitate suitable recommendations which are globally applicable.

3.3.1 Requirement of a KB-DSS for Corrosion Assessment and Monitoring of Ship Structures

The advantages of developing a KB-DSS for corrosion condition assessment and monitoring of ship structures using C.C.I can be judged by estimating the number of input data required from the designated user for a typical ocean going vessel as shown in Table 3.1. The ship is assumed to be divided into six corrosion zones such as submerged zone, splash zone, atmospheric zone, ballast tank zone, cargo hold zone and other internal structures zone as discussed in Section 2.5. These zones are further assumed to be divided into 8, 6, 8, 5, 5 and 5 subzones respectively. Considering the number of selections for CW and Assessment Levels (AL) for the relevant corrosion assessment criteria, the number of input per subzone for each corrosion zone has been estimated. Multiplying this data with the number of subzones, total number of input data for each corrosion zone can be estimated. The total number of input necessary for prediction of C.C.I can be arrived at by adding the number of input for all zones and works out to be 531 (refer Table 3.1), which is a large number to process without the help of a software based tool.

The number of corrosion subzones and thereby the number of observations would increase further as the size and complexity of the ship structure increases. The users must also have the flexibility as regards to defining the number of corrosion zones and their subzones for effective assessment of corrosion condition. Corrosion inspection and assessment is a continuous process in a ship’s operational period. There may be a short supply of experts on board ships to make decisions. Further, the knowledge base would need continuous amendments to incorporate evolving research findings, international regulations and standards. A KB-DSS is therefore necessary to guide the user to systematically interpret the corrosion observations and accurately predict the C.C.I of a ship structure.

The KB-DSS will be highly beneficial when the shipping companies have to manage large fleet of ships travelling across the world. The corrosion condition data can be accessed by the corrosion inspector from any port and can update the condition on a regular basis. Monitoring of corrosion condition during the operational period is also a critical function of the platform managers. Proactive steps need to be taken to mitigate the detected corrosion problems to avoid major restrictions on future operations as wells as financial loss.

Table 3.1 Estimation of Number of User Input Data for Corrosion Assessment

Zone	**Submerged Zone**	**Splash Zone**	**Atmospheric Zone**	**Ballast Tanks Zone**	**Cargo Tanks Zone**	**Other Internal Structures Zone**
Number of Subzones	**8**	**6**	**8**	**5**	**5**	**5**
Input/ Subzone						
Selection of Zone	1	1	1	1	1	1
Selection of subzone	1	1	1	1	1	1
Selection of type of Inspection	1	1	1	1	1	1
Selection of Corrosion Weightage	6	6	6	6	6	6
Selection of ALs for Assessment Criteria	6	5	4	5	4	4
No of Input/ Subzone	**15**	**14**	**13**	**14**	**13**	**13**
Total Input per Zone	**120**	**84**	**104**	**70**	**65**	**65**
Total Input	**508**					
Other Initial Input						
Input Ship Data	11					
Identify Corrosion Zones	6					
Input Zone Details	6					
Total User Input	**531**					

3.4 Knowledge Base for Corrosion Assessment

In general, a Knowledge Base (KB) is a structured database of related information about a particular subject or a centralised repository for information. It may be used to optimise the collection, organisation, and retrieval of information pertaining to a given knowledge domain. The knowledge base represents the facts about the given problem and an inference engine can reason about those facts and use logical rules to infer new facts.

The Knowledge Base (KB) related to the present problem (i.e. corrosion assessment and monitoring of steel ship structures with the help of Corrosion Condition Index (C.C.I)), which was presented in detail in Chapter 2, has been organised into 15 KB groups. The Knowledge Base (KB) has been numbered from KB 1 to KB 15 for easy identification and is presented in Table 3.2 along with explanatory remarks. The reference details from Chapter 2 are also mentioned against each KB group. The grouping has been done in order to systematically develop a user friendly KB-DSS. The DSS uses the KB as expert knowledge for guiding the user while entering the inspection data as well as reporting output and recommendations.

Table 3.2 Details of KB Groups Representing the Knowledge Base for KB-DSS

Knowledge Base (KB)	Reference Details	Knowledge Description	Remarks
KB-1	Fig. 2.1(a) & (b), Section 2.5.1	Corrosion Zones	Pre-defined list for user to identify corrosion zones
KB-2	Table 2.5, Section 2.6	Pre-assessment data of corrosion zones	Pre-defined questions for user to enter salient features of corrosion zones
KB-3	Table 2.4, Section 2.5.2	Subdivision of Corrosion Zones to Subzones	Pre-defined list for user to identify corrosion subzones for each corrosion zone
KB-4	Section 2.7	Corrosion Inspection Techniques	Pre-defined list for user to select the inspection technique used

Knowledge Base (KB)	Reference Details	Knowledge Description	Remarks
KB-5	Table 2.2, Section 2.3	Classification of Corrosion Consequences	Pre-defined list for user to select impact of corrosion on structure, cargo, crew, operational availability and repair cost
KB-6	Table 2.3, Section 2.4	System of Assigning Corrosion Weightage (CW)	Pre-defined list for user to assign the Classification of Corrosion Consequences, Corresponding CW and its descriptions
KB-7	Table 2.6, Section 2.8	Corrosion Assessment Criteria	List of Corrosion Assessment Criteria, range of ALs and their applicability to zones
KB-8	Table 2.7, Section 2.8.1	Coating Condition Assessment Levels Criterion 1	Guide for assigning condition ALs with supporting figures
KB-9	Table 2.8, Section 2.8.2	Uniform Corrosion Assessment Levels Criterion 2	Guide for assigning condition ALs with supporting figures
KB-10	Table 2.9, Section 2.8.3	Localised Corrosion Assessment Levels Criterion 3	Guide for assigning condition ALs with supporting figures
KB-11	Table 2.10, Section 2.8.4	Cathodic Protection Assessment Levels - Criteria 4	Guide for assigning condition ALs
KB-12	Tables 2.11(A) & 2.11(B), Section 2.8.5	Foiling Condition Assessment Levels Criterion 5	Guide for assigning condition ALs with supporting figures
KB-13	Table 2.12, Section 2.8.6	Design Factors Assessment Levels Criterion 6	Guide for assigning condition ALs
KB-14	Table 2.13, Section 2.9 and 2.10	C.C.I calculation formulae	Formulae to calculate C.C.I. of subzones, zones, internal/ external structure and overall structure
KB-15	Table 2.16, Section 2.12	C.C.I Rating System and Recommendations	Recommendations based on C.C.I. values

3.5 Structure of the KB-DSS for Corrosion Condition Assessment of Ship Structures

The KB-DSS has been named as **SCCI Software** since the primary output of the proposed KB-DSS is the Ship's Corrosion Condition Index (S.C.C.I), which will represent the corrosion condition of a steel ship structure at any time in her operational life. The starting point of the KB-DSS is the setting up of the project by registration of the user as well as the ship to ensure access control. User may register by providing personal and organisational details. A particular ship may be added by a registered user by providing ship specific data such as main particulars, corrosion zones/ subzones, their existing condition, etc. Thereafter the provisions for entering the corrosion inspection data by answering to the pre-defined questions based on knowledge base are necessary. Then the DSS need to perform the calculations and report C.C.I data along with recommendations. There must also be provision to update the information based on future inspections and estimate the C.C.I values for monitoring of the corrosion condition. Further, there must be provision for editing the existing knowledge base as well as incorporating new research findings and statutory rules by an administrator. Administrator is a designated representative of the owner who has the control over the software to administer the users as well as to carry out modifications from time to time. The other necessary feature for any successful software is user friendly interface for the designated user. The proposed KB-DSS has been designed as four different modules to effectively discharge the above functions as listed below (the functions of each module are described in the subsequent sections):-

a) Module 1: Project Setup Module
b) Module 2: Corrosion Observation Module
c) Module 3: SCCI Calculation Module
d) Module 4: Administrative module.

3.5.1 Data Flow Diagram

A Data Flow Diagram (DFD) is a graphical model of the "flow" of data through an information system, representing its process aspects. DFD is often used as a preliminary step to create an overview of the system, which can be later elaborated. Fig. 3.2 shows the Data Flow Diagram developed for the overall Knowledge Based DSS. The interconnectivity between the main modules, knowledge base and user interface functions (output and input) are illustrated with the help of arrows.

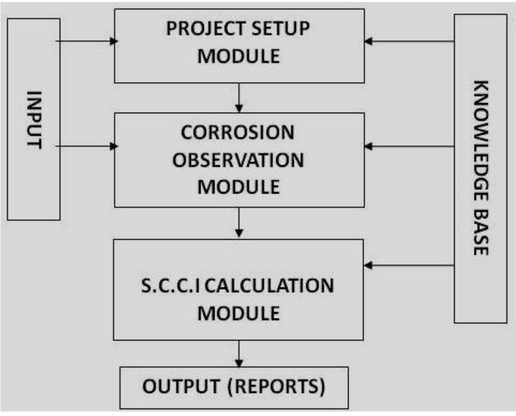


Fig 3.2 Data flow diagram for the overall knowledge based DSS

3.5.2 Module 1: Project Setup Module

This module has been designed to facilitate the user registration and setting up of the project. A new user is guided to register his project (ship) as well as an existing user is guided to select his existing ship at the beginning of the module. The new user then proceeds to input the main particulars of the ship, define of corrosion zones and the number of subzones for each zone, depending on the complexity and size of the vessel. The basic features such as the material data, coating data, environmental data, cathodic protection data and past maintenance details are then uploaded for pre-assessment of corrosion zones. An existing user may view the current C.C.I and can proceed to update C.C.I in the corrosion observation module if required. All user inputs are with the help of drop down menu items which are stored as the knowledge base by the administrator.

A schematic diagram highlighting the functions of Project Setup Module is shown in Fig. 3.3. Screenshots highlighting the various user interfaces of this module are presented in Section 3.7.1.

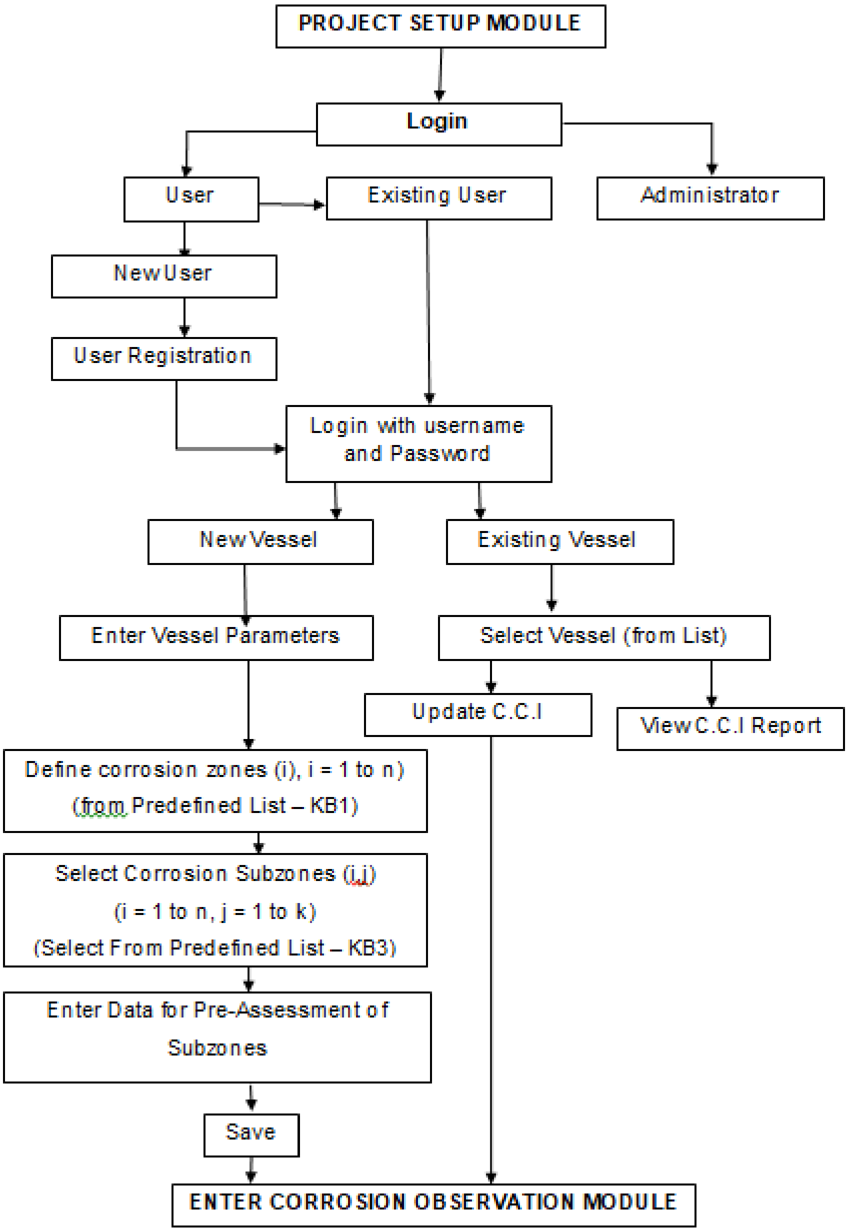


Fig 3.3 schematic diagram for the functions of user in the project setup module

3.5.3 Module 2: Corrosion Observation Module

This module has been designed to help the user to systematically input the corrosion problems observed during the inspection of ship structural members. The schematic diagram highlighting the functions of Corrosion Observation Module is shown in Fig. 3.4. The user is guided step by step to input the corrosion inspection data with the help of relevant knowledge base at every stage. The KB group details compiled in Table 3.2 are being used and the same is displayed as a drop down menu to help decision making by the user. This is the most critical part of the corrosion assessment process since error free reporting of corrosion inspection data is vital for consistent prediction of corrosion condition.

This module has been designed to guide the user to input data at a particular subzone level. After login, the user proceeds to select the type of inspection (KB-4) and assign Corrosion Weightage (KB-5 and KB-6) depending on the qualitative assessment of consequences due to corrosion. This is followed by providing the Assessment Levels (ALs) corresponding to all relevant pre-determined corrosion criteria (KB-8 to KB-13). Only the selection of correct option from the list of options is required and the numerical value of Assessment Level will be assigned by the KB-DSS. Once all observations of a given subzone is entered, user can proceed to the next subzone and then to the next zone. In this manner entering the corrosion observations for the subzones are systematically repeated for the selected corrosion zone. The process is repeated till data pertaining to all zones are entered in the KB-DSS guided by the expert knowledge. Subsequently the software would direct the user to the SCCI calculation module for the C.C.I calculations.

In this module, an existing user can also modify the corrosion data for a subzone keeping all other data unchanged to input results of new inspections/ corrosion problems observed during ship's service. Various screenshots highlighting the user interface are presented in Section 3.7.2.

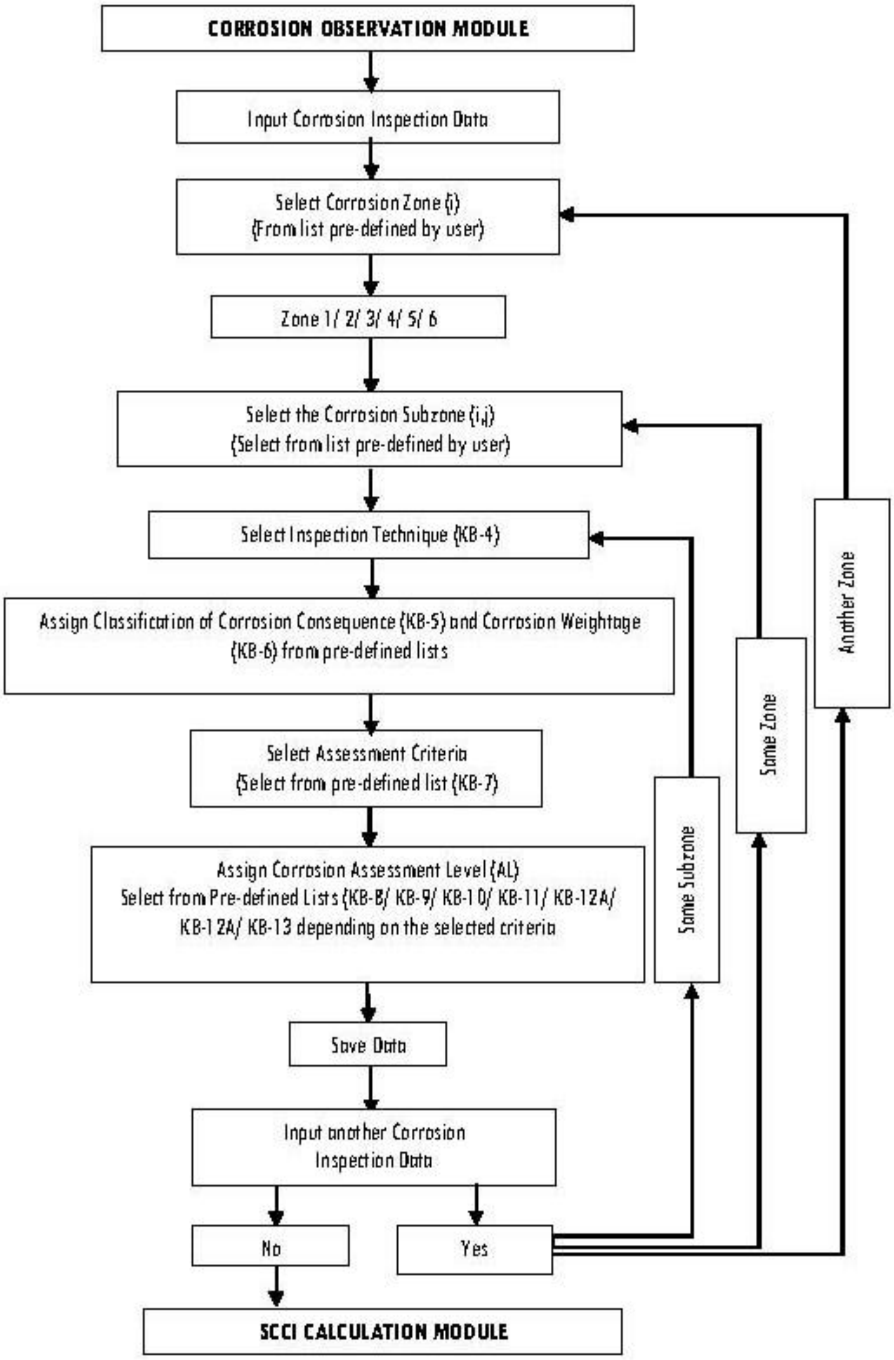


Fig 3.4 Schematic diagram for the function of user in the corrosion observation module

3.5.4 Module 3: SCCI Calculation Module

This module has been designed to facilitate calculation of C.C.I once all corrosion inspections are completed and observations entered into the KB-DSS in the project setup and corrosion observation modules. Provision for generating reports along with recommendations for repair/ maintenance actions have also been incorporated. The software accesses necessary formulae for the calculations from the knowledge base. The schematic diagram for the functions of user in the SCCI Calculation Module is highlighted in Fig. 3.5. Details of the calculations and output by this module are also indicated in the schematic diagram.

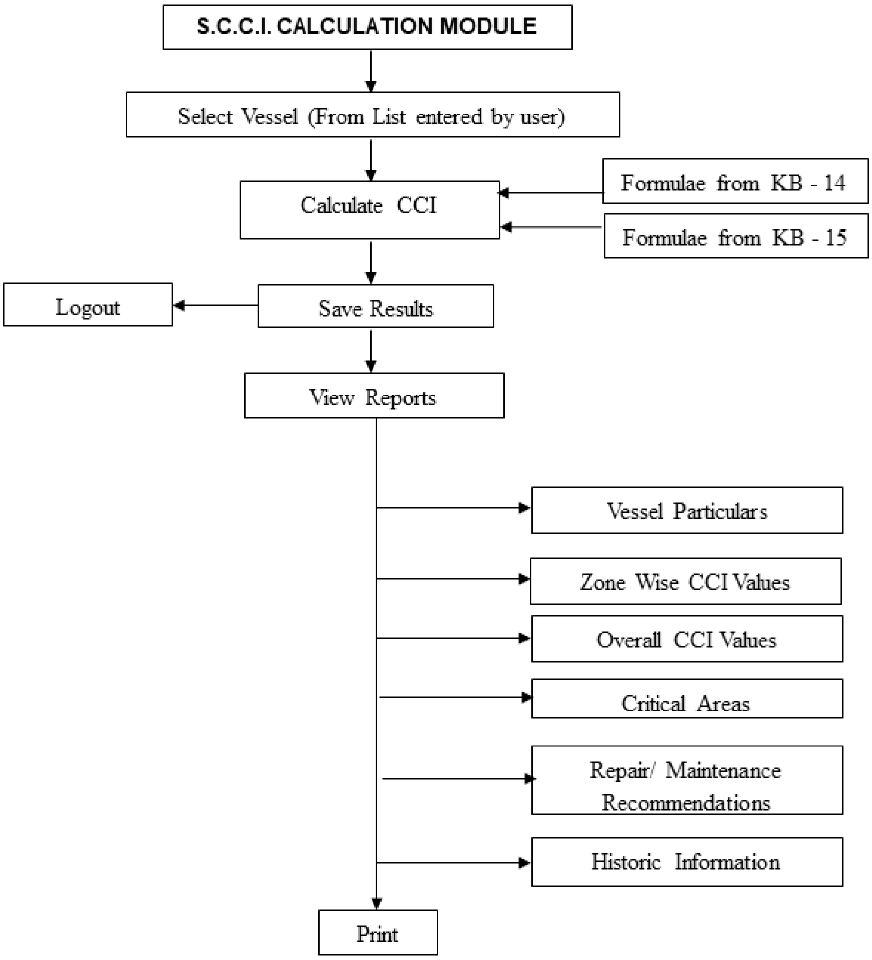


Fig 3.5 Schematic diagram for the function of user in the SCCI calculation module

3.5.5 Output of the SCCI Software

The SCCI software has been designed to generate reports that are useful for the owner or other stakeholders for efficient operation of the vessel in future. The output of the software is to be presented in a tabular form so that it is easy to understand with a provision for printing. Details of output reported by the software independently/ combined along with print facility, are listed below:-

(a) Main particulars of the vessel

(b) List of Corrosion Zones/ subzones and their C.C.I values

(c) C.C.I values for the internal/ external/ overall ship structure

(d) Critical areas based on C.C.I values which need immediate attention to undertake repair actions

(e) Recommendations based on the C.C.I values

3.5.6 Module 4: Administrative Module

The administrator will be responsible for the overall site maintenance and upkeep of the proposed KB-DSS over the internet. The administrator will also be responsible for the integrity of the database and performance of the software. The major functions envisaged for the administrator are summarised below and a schematic diagram highlighting the same is presented in Fig 3.6.

(a) Administration of the SCCI software over the internet

(b) Validation of software and correcting any errors reported

(c) Management of knowledge base including incorporation of regular amendments/ modifications as and when required

(d) Ship database management including inspection data

(e) Registration and access control of users

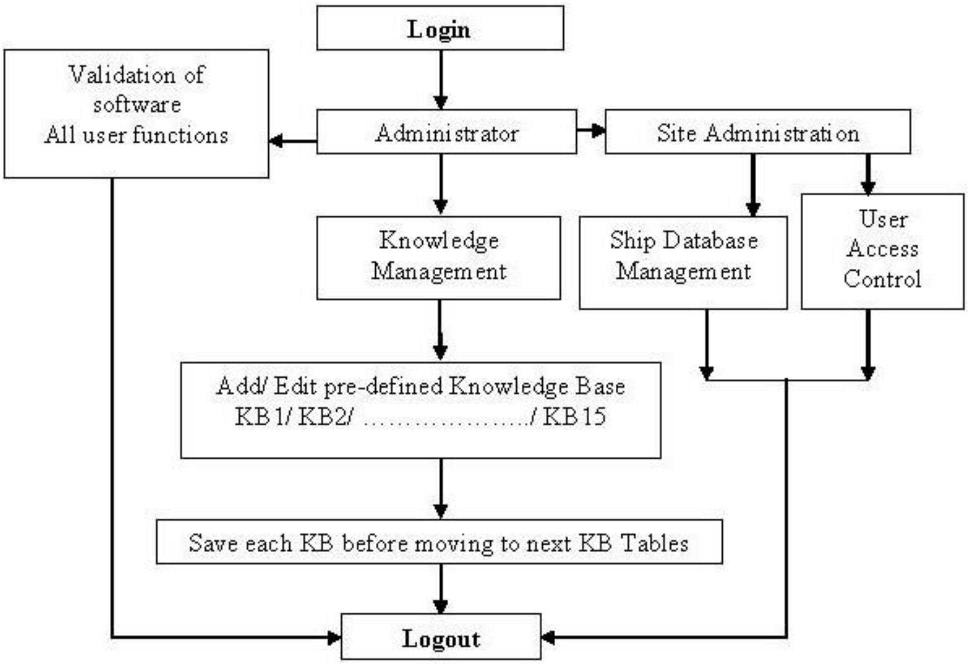


Fig 3.6 Schematic diagram for the administrative functions module

3.6 Development of the Software

The Knowledge Based Decision Support System (KB-DSS) has been developed as a web based application software. A web application is a client/ server application that uses a web browser as its client program, and performs an interactive service by connecting with servers over the internet. Browsers send requests to servers, and the servers generate responses and return them to the browsers as illustrated in Fig. 3.7. The web browsers are present on virtually every desktop and can be used to interact with many different web applications. There is no need to install several specialized client programs on the desktop, dramatically reducing maintenance (Leon and Richard, 2003).

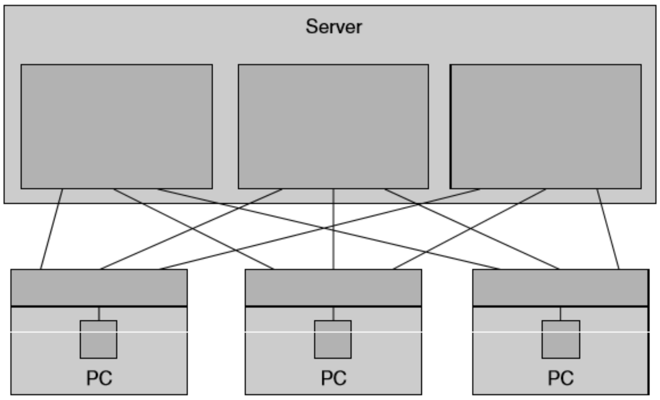


Fig 3.7 Illustration of a client server application

The web based SCCI software for corrosion condition assessment and monitoring will enable all stakeholders in the shipping industry to access the software similar to any other website. Typically the ships sail all over the world and may need to undergo corrosion inspections at different locations. The ship owners/ shipping agencies may contract local expertise to inspect and assess the corrosion condition of ship structure. The software will provide necessary user interface, supporting expert knowledge, historic information, calculations etc. and generate consistent reports. It will also free the user from multiple documentations and the stakeholders can view the reports from distant locations. The web based SCCI software will be highly useful when the owners/ shipping agencies have to manage a large fleet of ships, operating at multiple routes and are of varying age, type etc. Another major advantage of web based applications is that any revision/ correction of knowledge base/ international guidelines etc. can be easily incorporated by modifying the built-in knowledge base and hosting in the server. This feature will be helpful for continuous monitoring of corrosion condition during the operational phase of ships.

3.6.1 Hardware and Software Specifications

To be used efficiently, all computer software needs certain hardware components of minimum specifications to be present on a computer. The minimum recommended system requirements for the proposed KB-DSS are Intel Core 3 processor, 1 GB RAM and 128 GB hard disk. The software used to develop the SCCI software are listed and briefly described below:-

Operating system	:	Windows7
Front end	:	ASP.Net 4.0
Back end	:	Microsoft SQL Server 2008
Tool	:	Microsoft Visual Studio 2012
Browser	:	Any browsing Software such as Internet Explorer, Google Chrome, Mozilla Firefox, etc.

Windows 7 is a personal computer operating system which is part of the Windows NT family and is very stable and faster. The SCCI software will also perform on any other operating systems of higher versions. ASP.NET is a server-side web application framework designed for web development to produce web pages. It allows programmers to build dynamic web applications, web sites, and web services. ASP.NET is the successor to Microsoft's Active Server Pages (ASP) technology and is built on the Common Language Runtime (CLR), allowing programmers to write ASP.NET code using any supported .NET language. Harald (2003) has described the standard techniques and architectures that can be applied to .NET technology. A 3-tier architecture in asp.net has been used in creating and implementing the KB-DSS. The 3-Tier client-server architectures have three essential components viz. Client PC, Application Server and Database Server. The three layers are Presentation Layer, Business Access Layer

(BAL) or Business Logic Layer (BLY) and Data Access Layer (DAL). The Presentation Layer consists of pages from where the data is presented to users for getting input and to communicate with the backend structure. Business Logic Layer contains all the logic and is responsible to validate the rules of the component and communicating with the Data Access Layer, which contains methods to connect the data and perform desired functions.

Microsoft SQL Server is a relational database management system and its primary function is to store and retrieve data as requested by other software applications. The Structured Query Language (SQL) supports the creation and maintenance of the relational database and the management of data within that database. The structure of the relational database is based on the relation along with the ability to define complex relationship. Each relation can be accessed directly, without the cumbersome limitations of a hierarchical or owner/ member model that requires navigation of a complex data structure (Oppel and Sheldon, 2009).

3.7 User Interface of the Software

User interface (UI) is the front-end of the software to which the user will interact in order to make use of the application effectively. User interface is an integral part of KB-DSS and is designed to provide the insight of the software to the user. A form based interface using text-boxes, drop-down menus, text areas, check boxes and buttons has been created to in order to input data into the SCCI Software. The UI for the different modules are discussed in the subsequent sections.

3.7.1 Module 1 - Project Setup Module

The user interface for this module has been designed as per the schematic diagram presented in Fig. 3.3. A welcome screen has been designed to highlight the objective as well as the major features of the SCCI

Software. A screenshot of the welcome screen is shown is Fig. 3.8. The user can login to the software from the welcome page. New users will be promoted to register themselves by entering their mandatory personal and organisational particulars. The screenshot of login page is shown in Fig 3.9. Upon successful login to the software, the user has the option of adding a new vessel or selecting an existing vessel as shown in Fig 3.10. On selecting "Add New Vessels" the user will be guided to the page for entering the main parameters of the new vessel as shown in Fig. 3.11. The major parameters identified for a new vessel are "Ship Name", "Year Built", "Ship Type", "Built at", "Owner's Name", "Classification Society", "Dead Weight", "Length Between Perpendiculars (LBP)", "Length Overall (LOA)", "Breadth", "Depth" and "Load Waterline Draught".

The user can then commence defining of corrosion zones and subzones for the external and internal part of the structure by answering the pre-defined questions presented in a step by step manner, as per the scheme brought out in Knowledge Base groups KB-1 (Fig. 2.1) and KB-3 (Table 2.4). One typical user interface for this purpose is shown in Fig. 3.12. Provision for entering various pre-assessment details of corrosion zones such as material data, coating data, environmental data, cathodic protection data and repairs data as per KB-2 (Table 2.5) has also been provided, while defining the corrosion zones. The project setup can be completed on saving the data and the user may proceed to the corrosion observation module for entering the corrosion observations.

WELCOME TO SHIP'S CORROSION CONDITION INDEX

S C C I SOFTWARE

The objective of Corrosion Condition Index (C.C.I) is to provide comprehensive information about the corrosion condition of steel ship structures. The C.C.I is an effective tool for ship owners/ prospective buyers to take critical decisions.This would provide important input for planning medium-long term maintenance reqiurements, projecting remaining service life, and planning future exploitation of ships.The C.C.I can play a vital role in the overall corrosion management system of ship structures.The C.C.I can be used along with various other indices used in the field of shipping to assess the perfomance of ships. The index is intended to promote safer ships and can also be used by shippers and ship owners as their own promotional instrument.

Main features of CCI

1. It is a numeric indicator based on corrosion inspection results processed by an algorithm.
2. It is a number between 100 and 0 with lower index values indicating inferior corrosion condition of the structure.
3. It is an indicator of the corrosion condition of the structure and its critical areas.
4. It can fecilitates targeted corrosion inspection at critical areas.
5. It is useful to maintenance managers and engineers at all heirarchical level of management.
6. It is voluntary system, helping to improove the environmental and operational perfomance of the ship.

Fig 3.8 Screenshot of SCCI software welcome screen

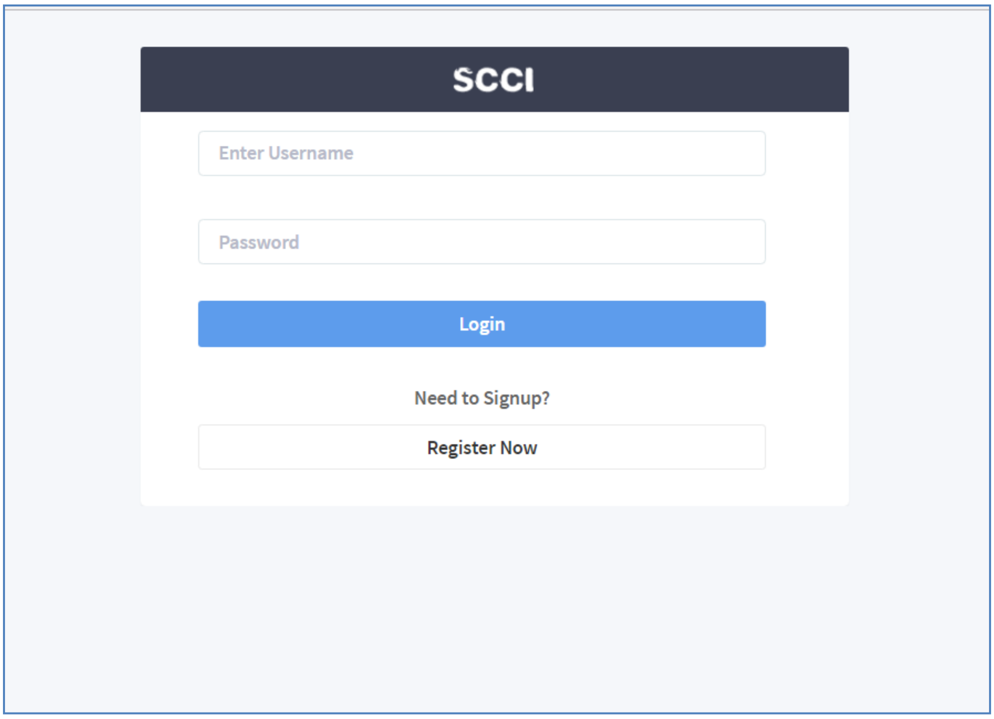


Fig 3.9 Screenshot of SCCI software login page

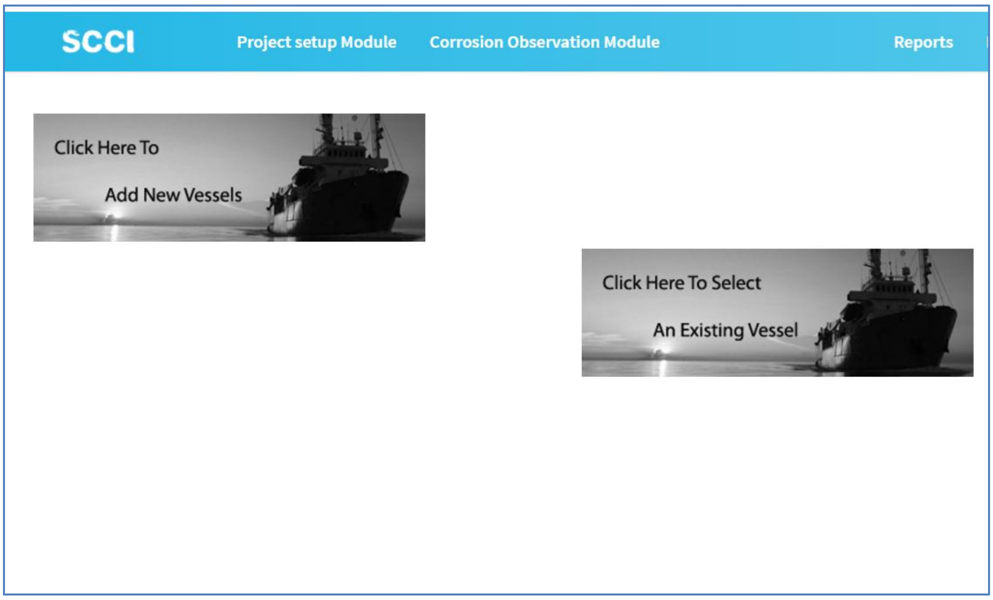


Fig 3.10 Screenshot of page for adding new vessels/ selection of existing vessels

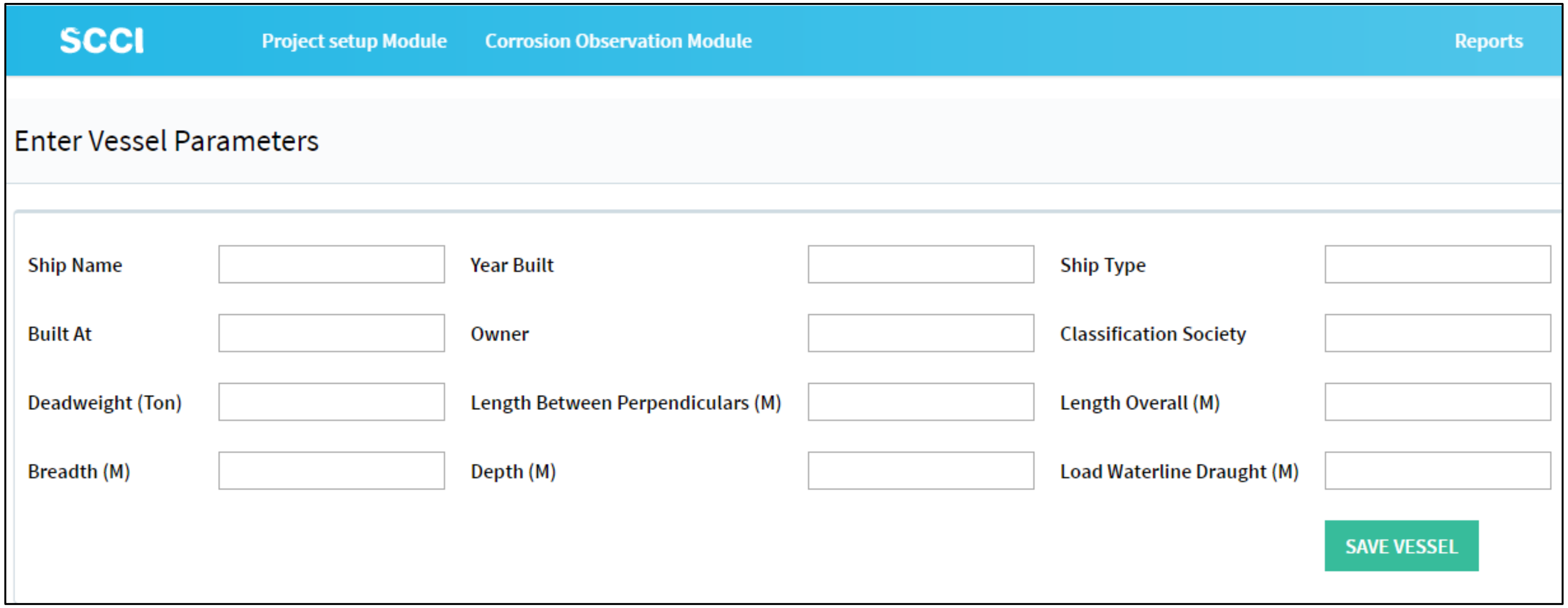
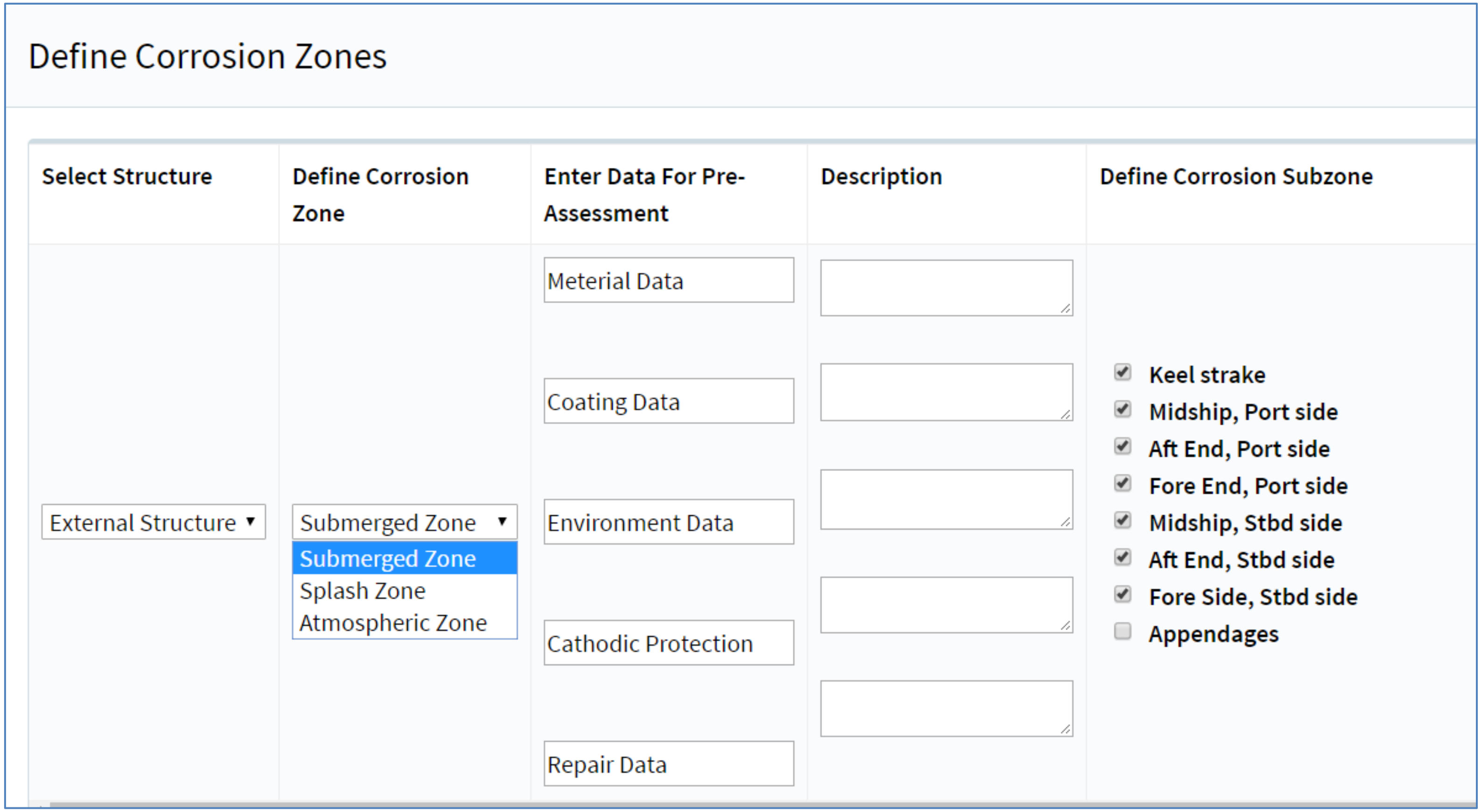


Fig 3.11 Screenshot of page for entering new vessel parameters



Define Corrosion Zones

Select Structure	Define Corrosion Zone	Enter Data For Pre-Assessment	Description	Define Corrosion Subzone
External Structure ▾	Submerged Zone ▾ Submerged Zone Splash Zone Atmospheric Zone	Meterial Data Coating Data Environment Data Cathodic Protection Repair Data		☑ Keel strake ☑ Midship, Port side ☑ Aft End, Port side ☑ Fore End, Port side ☑ Midship, Stbd side ☑ Aft End, Stbd side ☑ Fore Side, Stbd side ☐ Appendages

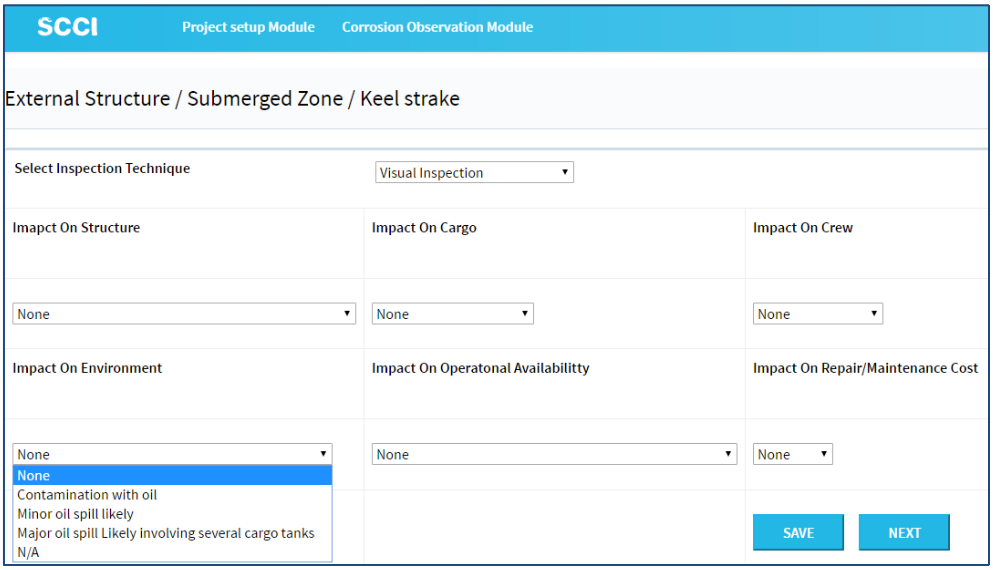
Fig 3.12 Screenshot of page for definition of corrosion zones and subzones

3.7.2 Module 2 - Corrosion Observation Module

This module has been designed for systematic input of corrosion observations at the corrosion subzone level, which has been defined in the project setup module and as per the schematic diagram presented in Fig. 3.4. On selecting a subzone, the first step is to input the necessary data for assigning the Corrosion weightage (CW). With the help of drop down menu options, the user will be guided to select the inspection technique as per KB-4 (Section 2.7) and consequence of observed corrosion on six different factors identified (impact on structure, impact on cargo, impact on passengers/ crew, impact on environment, impact on operational availability or impact on repair/ maintenance cost) as per the Knowledge Base Groups KB-5 (Table 2.2) and KB-6 (Table 2.3). A sample input page for calculation of CW is presented in Fig. 3.13.

The software will then guide the user to select corrosion assessment criteria from the list of six major assessment criteria (Fig. 3.14), which will contribute towards the overall corrosion condition assessment of ship structures, as compiled in KB-7 (Table 2.6). Depending on the user selection, the software will assign the Assessment Level (AL) values to each of the above criteria as illustrated in Knowledge Base Groups KB-8, KB-9, KB-10, KB-11, KB-12 and KB-13 (Tables 2.7, 2.8, 2.9, 2.10, 2.11(a) & (b) and 2.12 respectively). Various options are presented in a tabular form along with reference images to enable error free reporting by the user. Screenshots of user interfaces for entering the options for the above functions are shown in Figures 3.15, 3.16, 3.17, 3.18, 3.19, 3.20 and 3.21.

Once all input for a particular subzone has been completed, the user can move on to other subzones of the given corrosion zone. Similarly the input for all other subzones/ zones can be completed in a step by step manner. Since the number of inputs for a large vessel will be very high and user may not be able to complete the task in one sitting, provision has been made to save data and logout at any time. User can login later, select the vessel and continue updating the input data in future. Provision has also been provided to update or amend the existing data based on future corrosion inspections to facilitate monitoring of corrosion condition during ship’s operational phase.



External Structure / Submerged Zone / Keel strake

Select Inspection Technique: Visual Inspection

Imapct On Structure: None

Impact On Cargo: None

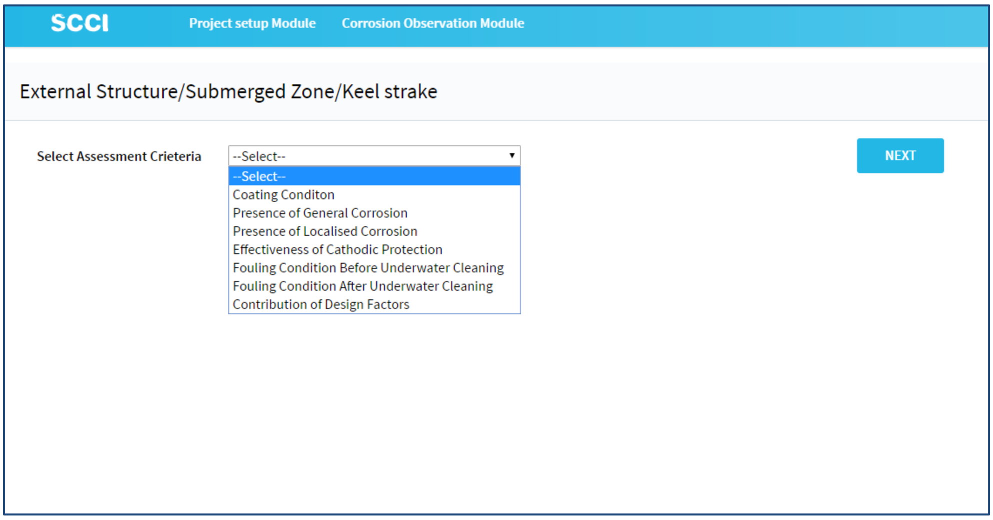
Impact On Crew: None

Impact On Environment: None

Impact On Operatonal Availabilitty: None

Impact On Repair/Maintenance Cost: None

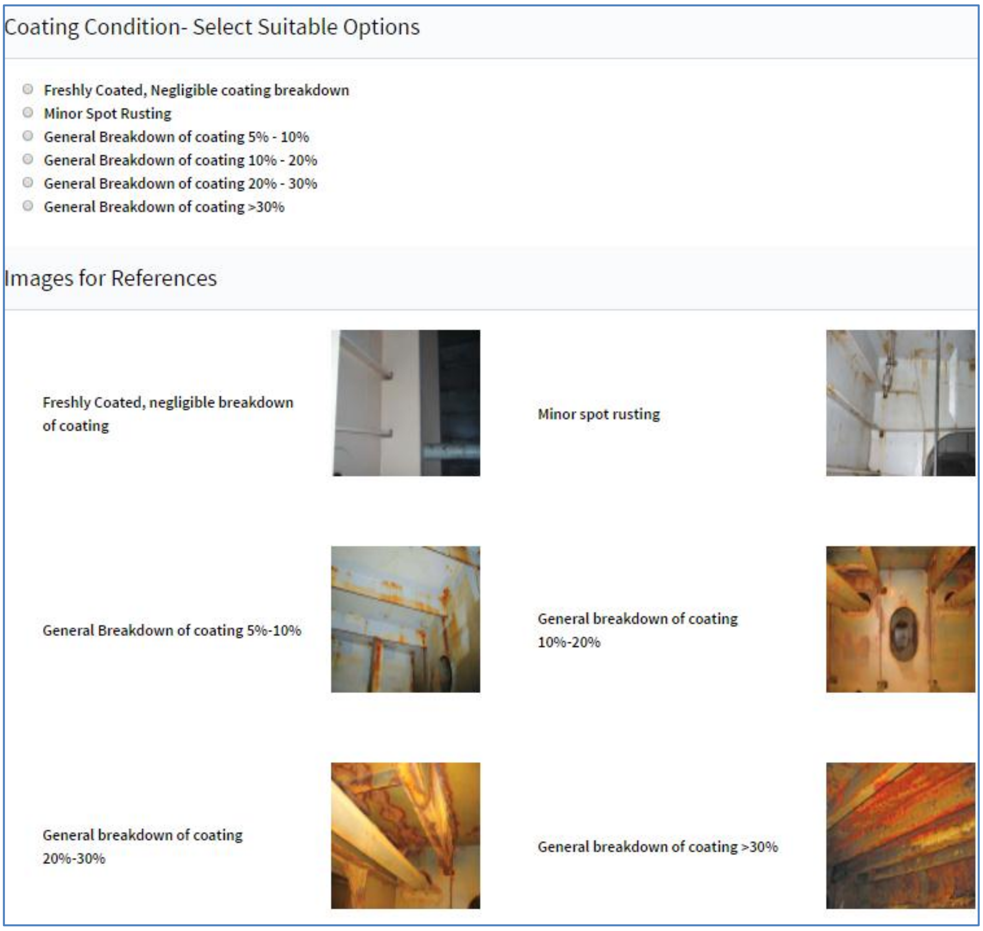
Fig 3.13 Screenshot of sample page for assigning of corrosion weightage



External Structure/Submerged Zone/Keel strake

Select Assessment Crieteria: --Select--

Fig 3.14 Screenshot of page for selection of assessment criteria



Coating Condition- Select Suitable Options

- ○ Freshly Coated, Negligible coating breakdown
- ○ Minor Spot Rusting
- ○ General Breakdown of coating 5% - 10%
- ○ General Breakdown of coating 10% - 20%
- ○ General Breakdown of coating 20% - 30%
- ○ General Breakdown of coating >30%

Images for References

Freshly Coated, negligible breakdown of coating

Minor spot rusting

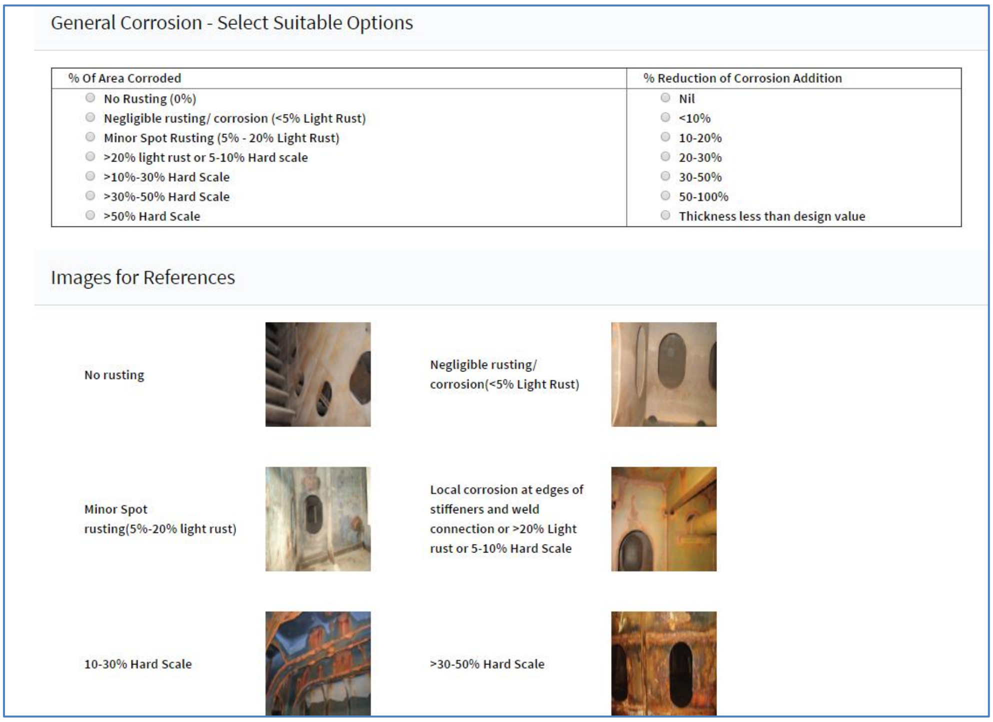
General Breakdown of coating 5%-10%

General breakdown of coating 10%-20%

General breakdown of coating 20%-30%

General breakdown of coating >30%

Fig 3.15 Screenshot of page for selection of assessment level for coating condition



General Corrosion - Select Suitable Options

% Of Area Corroded	% Reduction of Corrosion Addition
○ No Rusting (0%)	○ Nil
○ Negligible rusting/ corrosion (<5% Light Rust)	○ <10%
○ Minor Spot Rusting (5% - 20% Light Rust)	○ 10-20%
○ >20% light rust or 5-10% Hard scale	○ 20-30%
○ >10%-30% Hard Scale	○ 30-50%
○ >30%-50% Hard Scale	○ 50-100%
○ >50% Hard Scale	○ Thickness less than design value

Images for References

No rusting

Negligible rusting/ corrosion(<5% Light Rust)

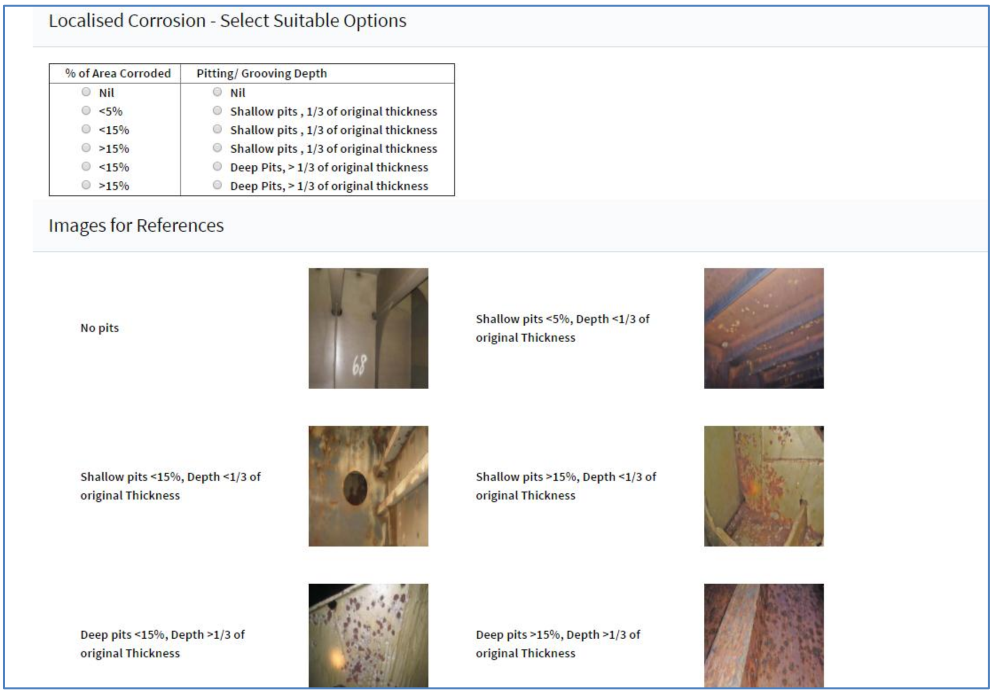
Minor Spot rusting(5%-20% light rust)

Local corrosion at edges of stiffeners and weld connection or >20% Light rust or 5-10% Hard Scale

10-30% Hard Scale

>30-50% Hard Scale

Fig 3.16 Screenshot of page for selection of assessment level for general corrosion



Localised Corrosion - Select Suitable Options

% of Area Corroded	Pitting/ Grooving Depth
○ Nil	○ Nil
○ <5%	○ Shallow pits , 1/3 of original thickness
○ <15%	○ Shallow pits , 1/3 of original thickness
○ >15%	○ Shallow pits , 1/3 of original thickness
○ <15%	○ Deep Pits, > 1/3 of original thickness
○ >15%	○ Deep Pits, > 1/3 of original thickness

Images for References

No pits

Shallow pits <5%, Depth <1/3 of original Thickness

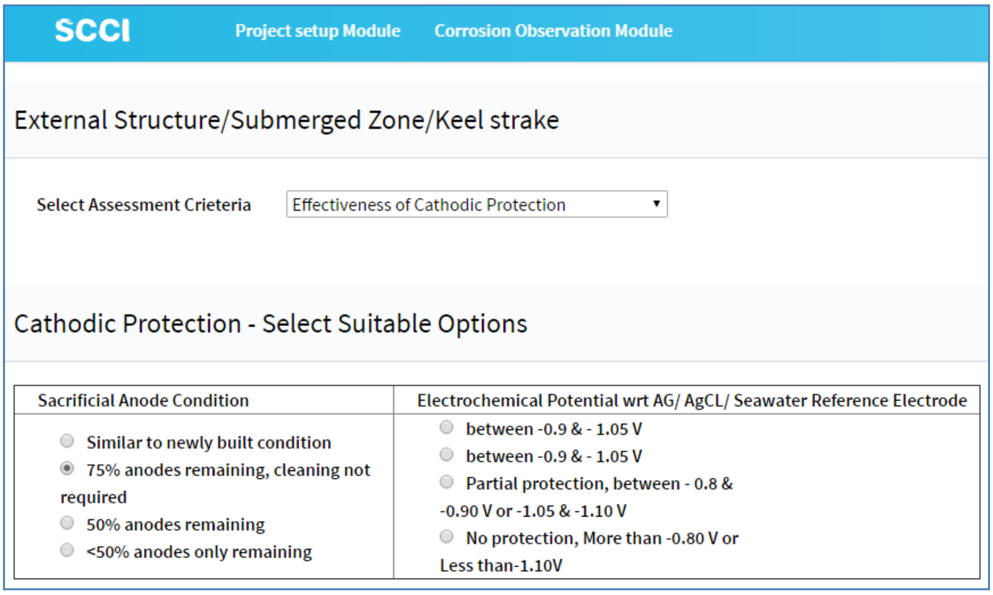
Shallow pits <15%, Depth <1/3 of original Thickness

Shallow pits >15%, Depth <1/3 of original Thickness

Deep pits <15%, Depth >1/3 of original Thickness

Deep pits >15%, Depth >1/3 of original Thickness

Fig 3.17 Screenshot of page for selection of assessment level for localised corrosion



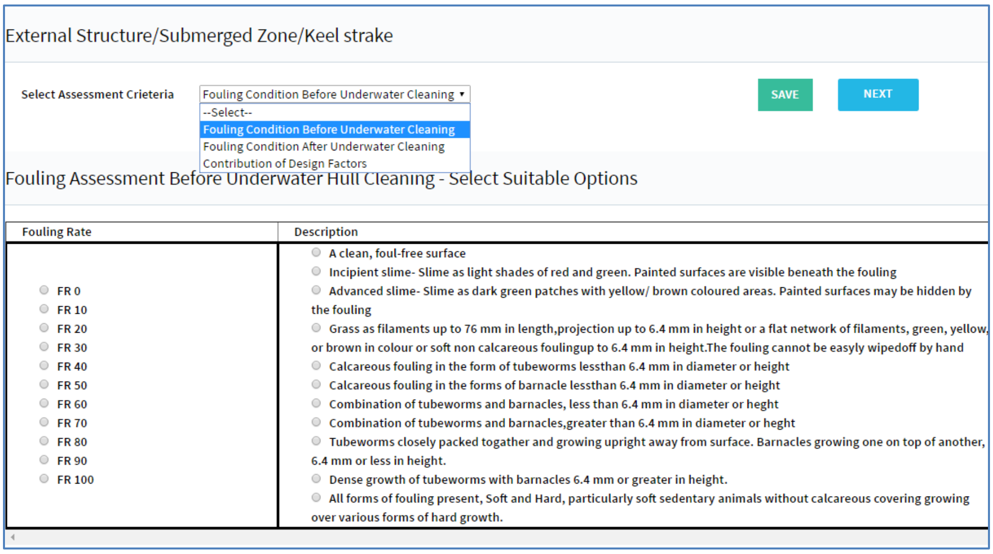
External Structure/Submerged Zone/Keel strake

Select Assessment Crieteria: Effectiveness of Cathodic Protection ▾

Cathodic Protection - Select Suitable Options

Sacrificial Anode Condition	Electrochemical Potential wrt AG/ AgCL/ Seawater Reference Electrode
○ Similar to newly built condition ● 75% anodes remaining, cleaning not required ○ 50% anodes remaining ○ <50% anodes only remaining	○ between -0.9 & - 1.05 V ○ between -0.9 & - 1.05 V ○ Partial protection, between - 0.8 & -0.90 V or -1.05 & -1.10 V ○ No protection, More than -0.80 V or Less than-1.10V

Fig 3.18 Screenshot of page for selection of assessment level for cathodic protection



External Structure/Submerged Zone/Keel strake

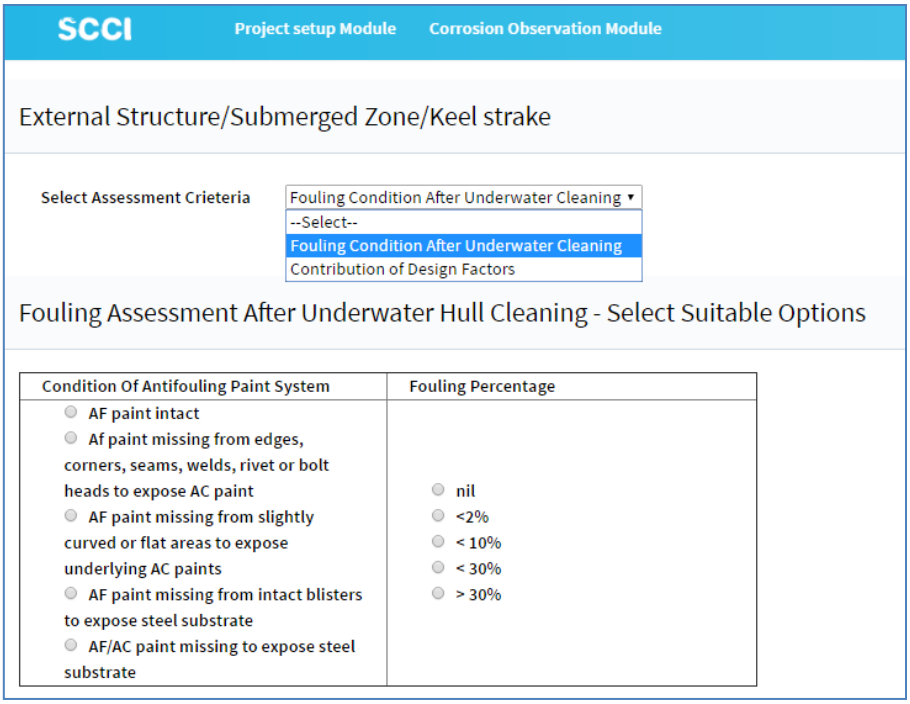
Select Assessment Crieteria: Fouling Condition Before Underwater Cleaning ▾

--Select--
Fouling Condition Before Underwater Cleaning
Fouling Condition After Underwater Cleaning
Contribution of Design Factors

Fouling Assessment Before Underwater Hull Cleaning - Select Suitable Options

Fouling Rate	Description
○ FR 0 ○ FR 10 ○ FR 20 ○ FR 30 ○ FR 40 ○ FR 50 ○ FR 60 ○ FR 70 ○ FR 80 ○ FR 90 ○ FR 100	○ A clean, foul-free surface ○ Incipient slime- Slime as light shades of red and green. Painted surfaces are visible beneath the fouling ○ Advanced slime- Slime as dark green patches with yellow/ brown coloured areas. Painted surfaces may be hidden by the fouling ○ Grass as filaments up to 76 mm in length,projection up to 6.4 mm in height or a flat network of filaments, green, yellow, or brown in colour or soft non calcareous foulingup to 6.4 mm in height.The fouling cannot be easyly wipedoff by hand ○ Calcareous fouling in the form of tubeworms lessthan 6.4 mm in diameter or height ○ Calcareous fouling in the forms of barnacle lessthan 6.4 mm in diameter or height ○ Combination of tubeworms and barnacles, less than 6.4 mm in diameter or heght ○ Combination of tubeworms and barnacles,greater than 6.4 mm in diameter or heght ○ Tubeworms closely packed togather and growing upright away from surface. Barnacles growing one on top of another, 6.4 mm or less in height. ○ Dense growth of tubeworms with barnacles 6.4 mm or greater in height. ○ All forms of fouling present, Soft and Hard, particularly soft sedentary animals without calcareous covering growing over various forms of hard growth.

Fig 3.19 Screenshot of page for selection of fouling assessment level before underwater cleaning



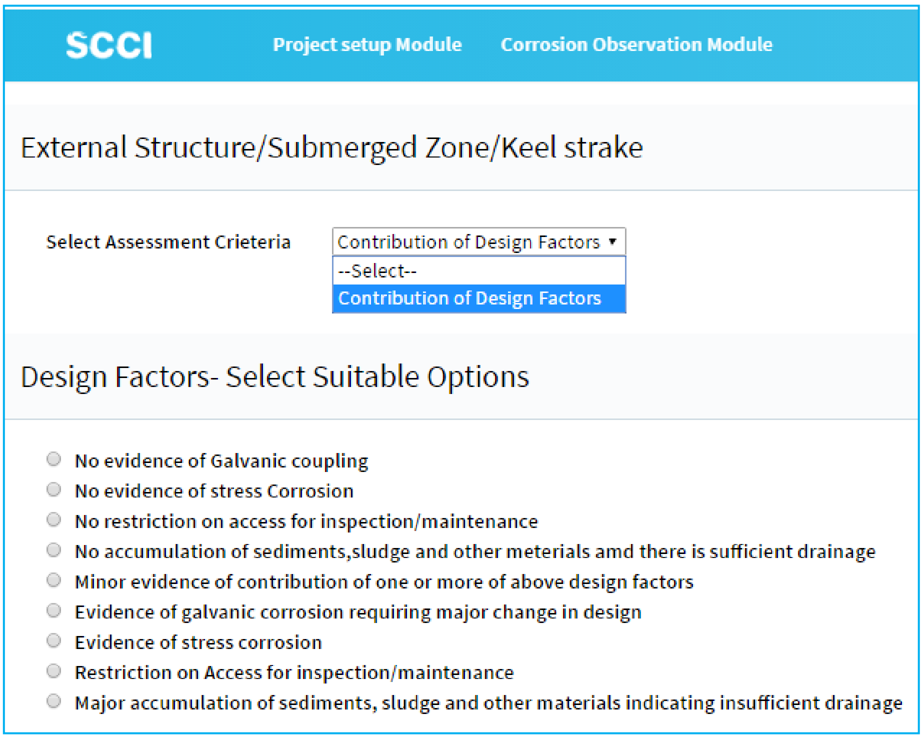
External Structure/Submerged Zone/Keel strake

Select Assessment Crieteria: Fouling Condition After Underwater Cleaning

Fouling Assessment After Underwater Hull Cleaning - Select Suitable Options

Condition Of Antifouling Paint System	Fouling Percentage
○ AF paint intact ○ Af paint missing from edges, corners, seams, welds, rivet or bolt heads to expose AC paint ○ AF paint missing from slightly curved or flat areas to expose underlying AC paints ○ AF paint missing from intact blisters to expose steel substrate ○ AF/AC paint missing to expose steel substrate	○ nil ○ <2% ○ < 10% ○ < 30% ○ > 30%

Fig 3.20 Screenshot of page for selection of fouling assessment level after underwater cleaning



External Structure/Submerged Zone/Keel strake

Select Assessment Crieteria: Contribution of Design Factors

Design Factors- Select Suitable Options

- ○ No evidence of Galvanic coupling
- ○ No evidence of stress Corrosion
- ○ No restriction on access for inspection/maintenance
- ○ No accumulation of sediments,sludge and other meterials amd there is sufficient drainage
- ○ Minor evidence of contribution of one or more of above design factors
- ○ Evidence of galvanic corrosion requiring major change in design
- ○ Evidence of stress corrosion
- ○ Restriction on Access for inspection/maintenance
- ○ Major accumulation of sediments, sludge and other materials indicating insufficient drainage

Fig 3.21 Screenshot of page for selection of assessment level for contribution of design factors

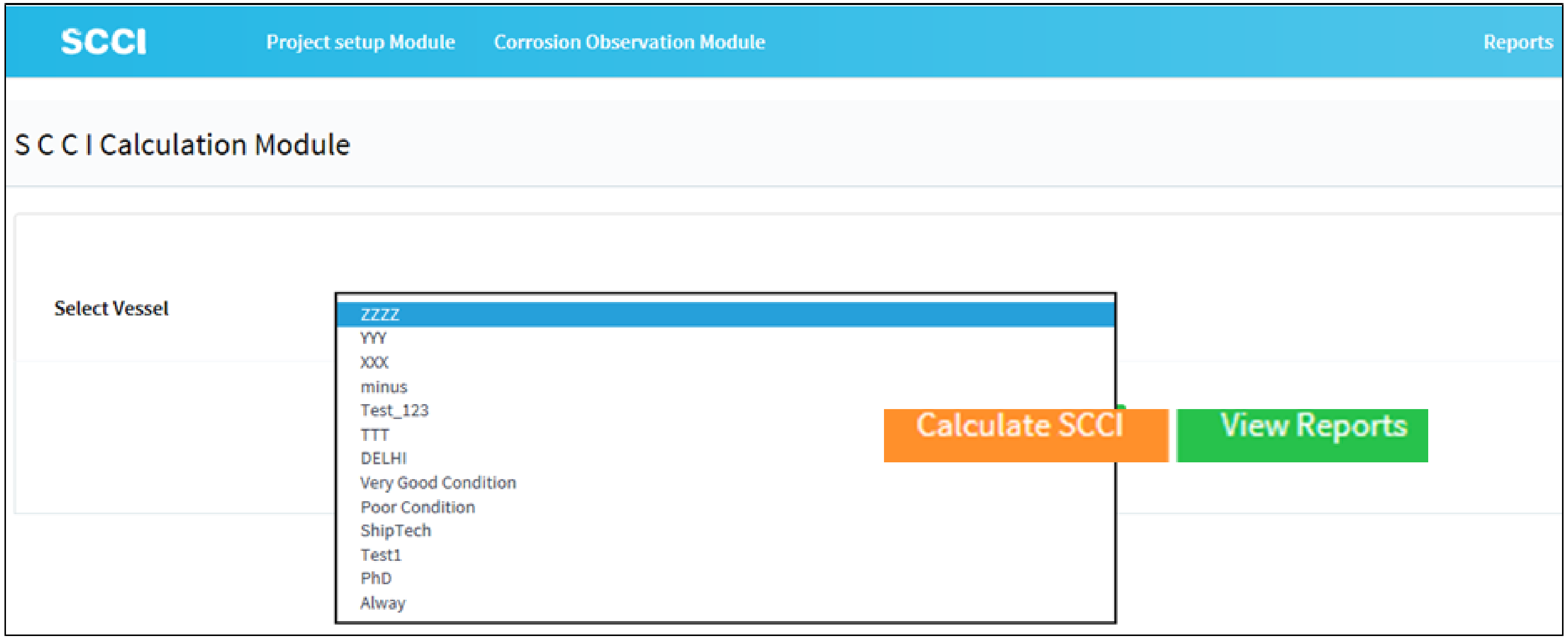


Fig. 3.22 Screenshot of page for the SCCI calculation module

3.7.3 Module 3 - SCCI Calculation Module and Reports

Function of this module is to perform the C.C.I calculations based on the input data in the project setup module as well as the corrosion observation module. The user can login, enter the SCCI calculation module, select the vessel and click the "Calculate SCCI" button. The software will use the formulae compiled under Knowledge Group KB-14 (Table 2.13, Section 2.9 and 2.10) to do the calculations and generate output reports. Another salient feature of this module is the reporting of critical areas and generation of recommendations based on the C.C.I values calculated, as per the Knowledge Base, KB-15. The screenshot of the SCCI calculation module page is shown in Fig. 3.22.

3.8 Implementation of the Software

The SCCI Software has been developed as a web based tool for larger purpose of utilisation by the shipping community, involving all stakeholders. The aim has been to make the tool available to all through internet (*www.scci.minusbugs.com*) with password protection. The software may be accessed by the user through the user name and password selected during registration of the vessel. The sample vessel data and reports may be accessed with username (babu) and password (123). The 'administrator' functions may be accessed using user name (admin) and password (admin).

3.9 Case Studies for Validation of the SCCI Software

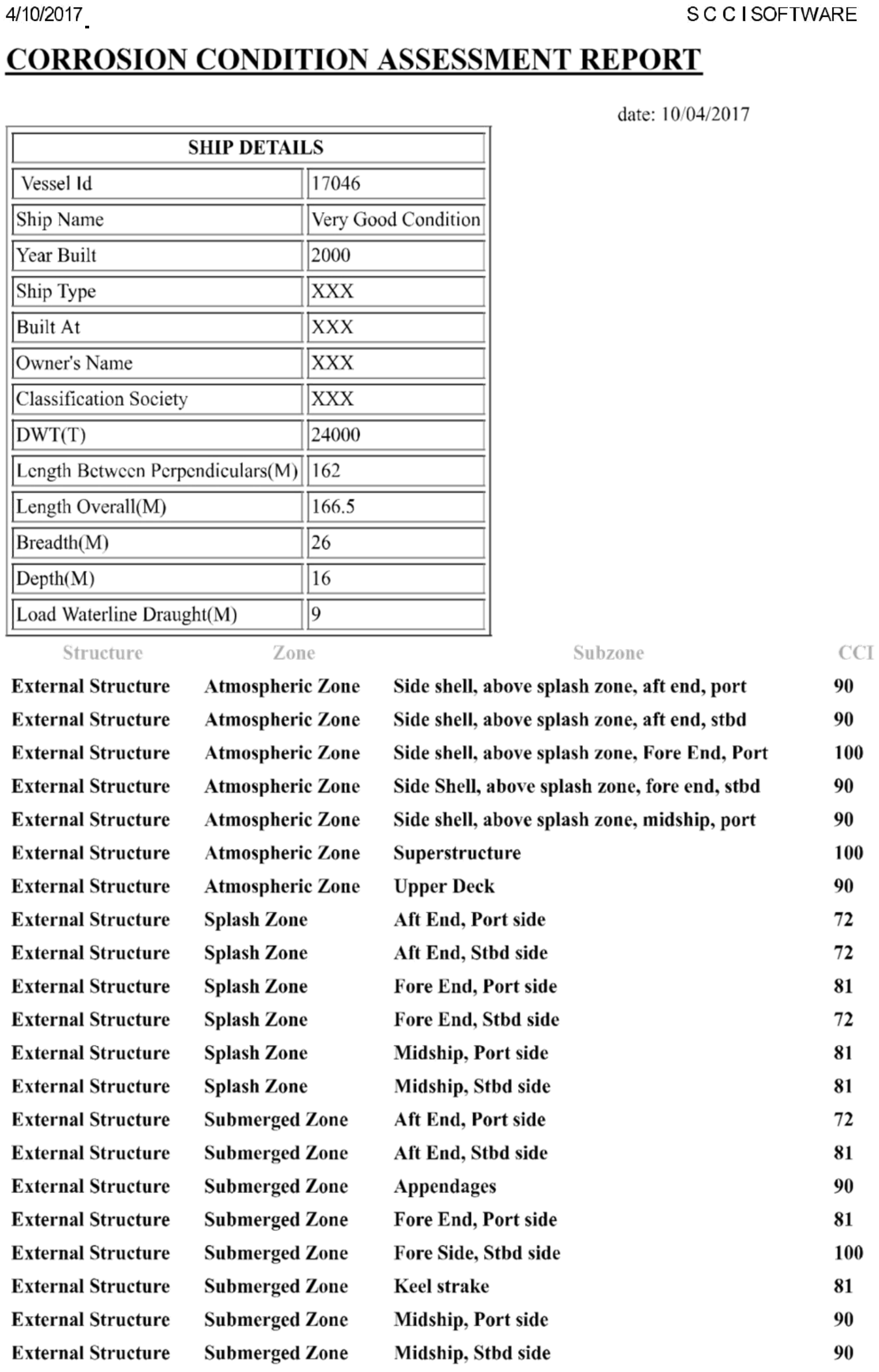
Validation is an integral part of the KB-DSS (SCCI Software) development process to ensure that the right data are accessed, right calculation method is used and the right assessment of corrosion condition is predicted by the application. Three case studies have been carried out to validate the C.C.I formulation method as discussed at Section 2.13. Three corrosion conditions corresponding to "very good condition", "satisfactory condition" and "poor condition" were simulated as indicated in the proposed C.C.I rating system presented at Tables 2.16 to 2.19. The calculations for the same three cases were repeated using the SCCI software to compare the results and thereby to validate the software. The details of input parameters for three cases are summarized in Table 3.3.

Table 3.3 Details of Input Parameters for Validation of SCCI Software

Sl. No	Description of Input to SCCI Software	Source
a)	Main particulars of a ship selected for case studies for validation of SCCI software	Table 2.17
b)	Definition of corrosion zones and subzones	Table 2.18
c)	Details of corrosion conditions and Corrosion Weightage (CW) for the case studies	Table 2.19
d)	Input parameters for Case-1 (Very Good Corrosion Condition)	Table 2.20
e)	Input parameters for Case -2 (Satisfactory Corrosion Condition)	Table 2.21
f)	Input parameters, Case -3 (Poor Corrosion Condition)	Table 2.22

Table 3.4 Summary of Corrosion Condition Assessment Calculations by the SCCI Software

	Case - 1	**Case - 2**	**Case - 3**
Corrosion Zone	**C.C.I**	**C.C.I**	**C.C.I**
Submerged zone	72.0	56.0	42.0
Splash zone	72.0	72.0	72.0
Atmospheric zone	90.0	72.0	72.0
Ballast tanks zone	72.0	56.0	42.0
Cargo hold zone	72.0	72.0	49.0
Other internal structures zone	72.0	72.0	72.0
External structure C.C.I$_{\mathbf{Ext}}$	72.0	56.0	42.0
Internal structure C.C.I$_{\mathbf{Int}}$	72.0	56.0	42.0
Overall C.C.I$_{\mathbf{Ship}}$	72.0	56.0	42.0
Remarks	**Conforms to Very Good condition**	**Conforms to Satisfactory condition**	**Conforms to Poor condition**



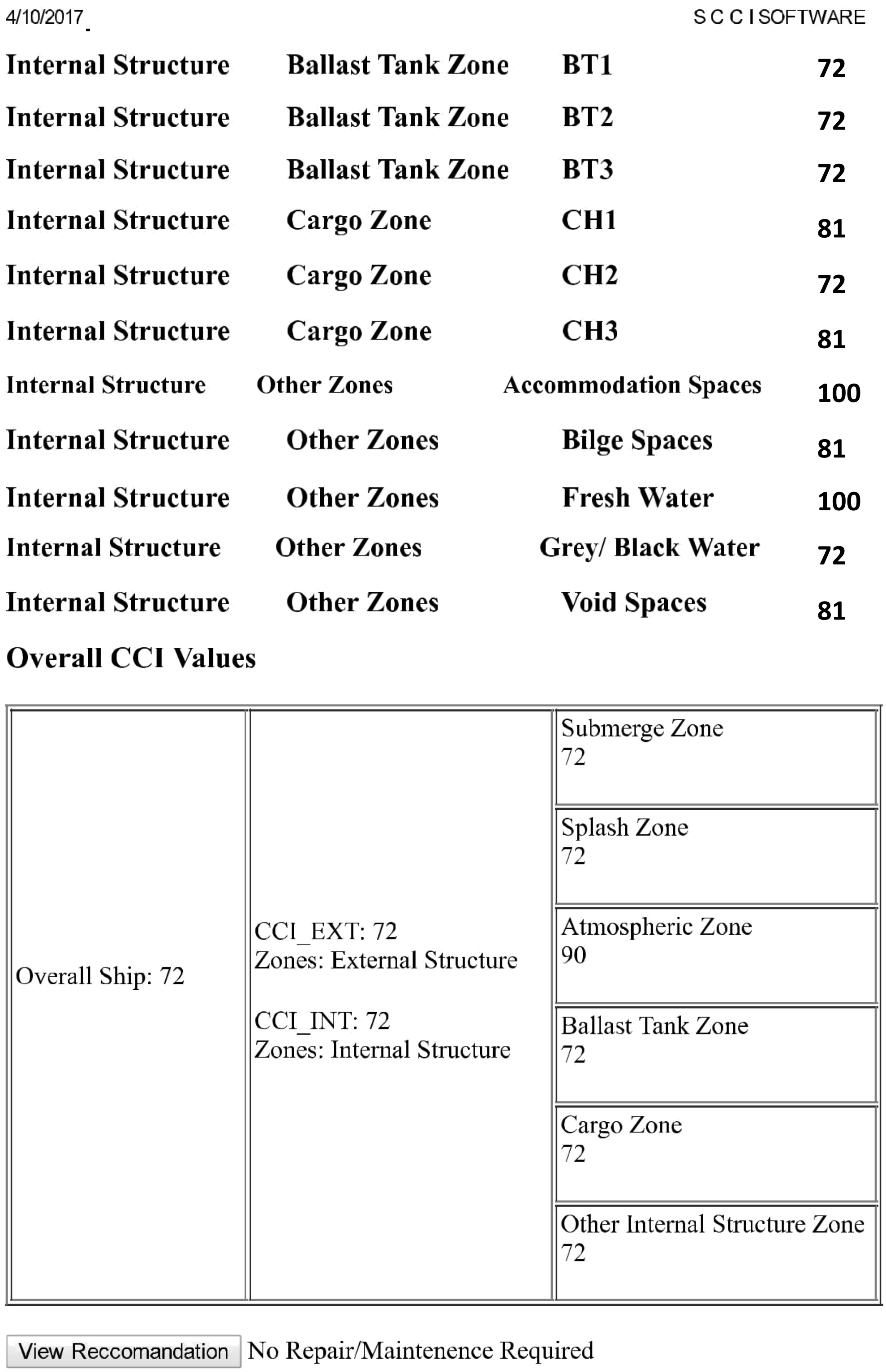
4/10/2017 S C C I SOFTWARE

CORROSION CONDITION ASSESSMENT REPORT

date: 10/04/2017

SHIP DETAILS	
Vessel Id	17046
Ship Name	Very Good Condition
Year Built	2000
Ship Type	XXX
Built At	XXX
Owner's Name	XXX
Classification Society	XXX
DWT(T)	24000
Length Between Perpendiculars(M)	162
Length Overall(M)	166.5
Breadth(M)	26
Depth(M)	16
Load Waterline Draught(M)	9

Structure	Zone	Subzone	CCI
External Structure	**Atmospheric Zone**	**Side shell, above splash zone, aft end, port**	**90**
External Structure	**Atmospheric Zone**	**Side shell, above splash zone, aft end, stbd**	**90**
External Structure	**Atmospheric Zone**	**Side shell, above splash zone, Fore End, Port**	**100**
External Structure	**Atmospheric Zone**	**Side Shell, above splash zone, fore end, stbd**	**90**
External Structure	**Atmospheric Zone**	**Side shell, above splash zone, midship, port**	**90**
External Structure	**Atmospheric Zone**	**Superstructure**	**100**
External Structure	**Atmospheric Zone**	**Upper Deck**	**90**
External Structure	**Splash Zone**	**Aft End, Port side**	**72**
External Structure	**Splash Zone**	**Aft End, Stbd side**	**72**
External Structure	**Splash Zone**	**Fore End, Port side**	**81**
External Structure	**Splash Zone**	**Fore End, Stbd side**	**72**
External Structure	**Splash Zone**	**Midship, Port side**	**81**
External Structure	**Splash Zone**	**Midship, Stbd side**	**81**
External Structure	**Submerged Zone**	**Aft End, Port side**	**72**
External Structure	**Submerged Zone**	**Aft End, Stbd side**	**81**
External Structure	**Submerged Zone**	**Appendages**	**90**
External Structure	**Submerged Zone**	**Fore End, Port side**	**81**
External Structure	**Submerged Zone**	**Fore Side, Stbd side**	**100**
External Structure	**Submerged Zone**	**Keel strake**	**81**
External Structure	**Submerged Zone**	**Midship, Port side**	**90**
External Structure	**Submerged Zone**	**Midship, Stbd side**	**90**



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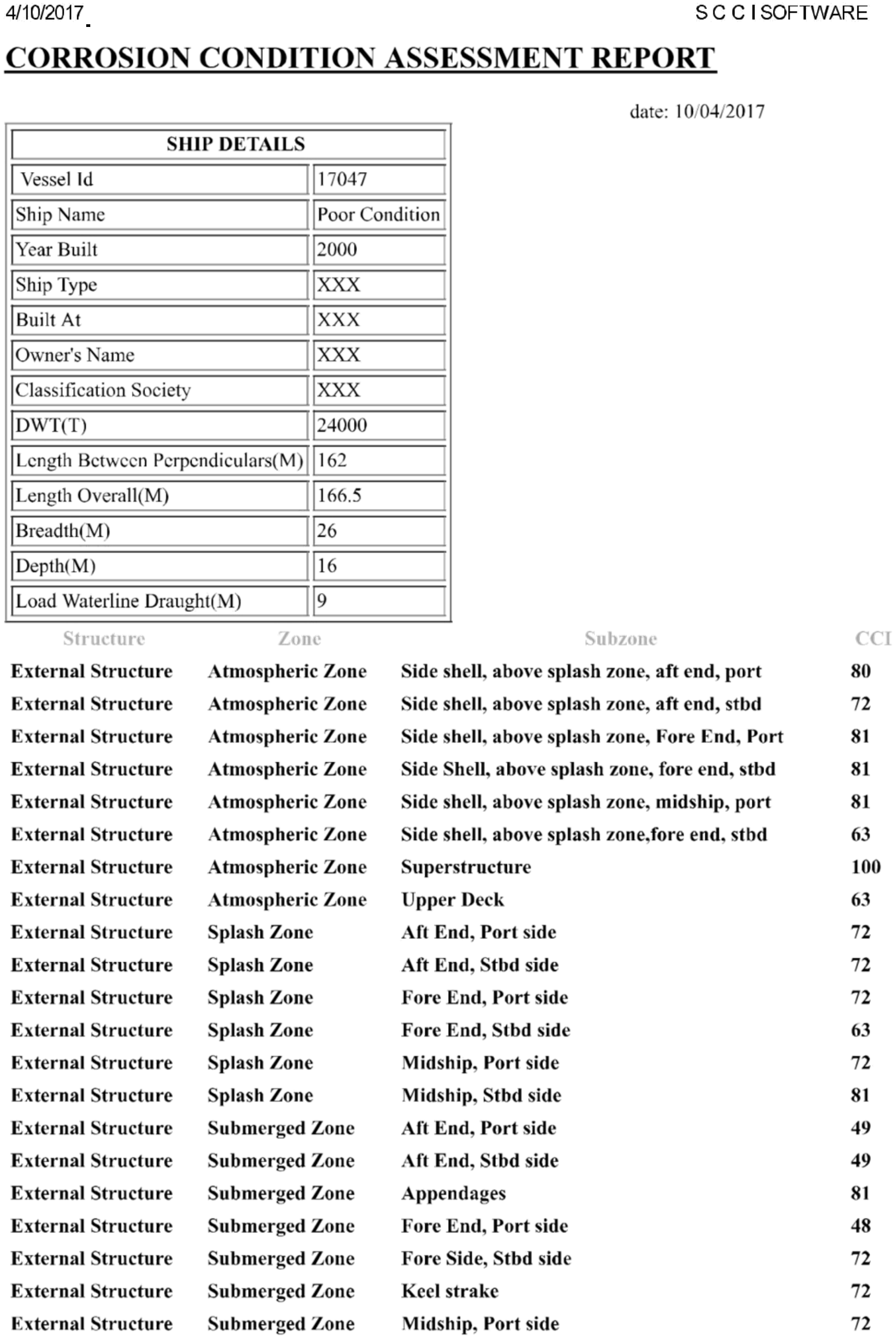
Internal Structure	**Ballast Tank Zone**	**BT1**	**72**
Internal Structure	**Ballast Tank Zone**	**BT2**	**72**
Internal Structure	**Ballast Tank Zone**	**BT3**	**72**
Internal Structure	**Cargo Zone**	**CH1**	**81**
Internal Structure	**Cargo Zone**	**CH2**	**72**
Internal Structure	**Cargo Zone**	**CH3**	**81**
Internal Structure	**Other Zones**	**Accommodation Spaces**	**100**
Internal Structure	**Other Zones**	**Bilge Spaces**	**81**
Internal Structure	**Other Zones**	**Fresh Water**	**100**
Internal Structure	**Other Zones**	**Grey/ Black Water**	**72**
Internal Structure	**Other Zones**	**Void Spaces**	**81**

Overall CCI Values

Overall Ship: 72	CCI_EXT: 72 Zones: External Structure CCI_INT: 72 Zones: Internal Structure	Submerge Zone 72
		Splash Zone 72
		Atmospheric Zone 90
		Ballast Tank Zone 72
		Cargo Zone 72
		Other Internal Structure Zone 72

No Repair/Maintenence Required

Fig 3.23 Output of the KBDSS for "Very Good" Corrosion Condition



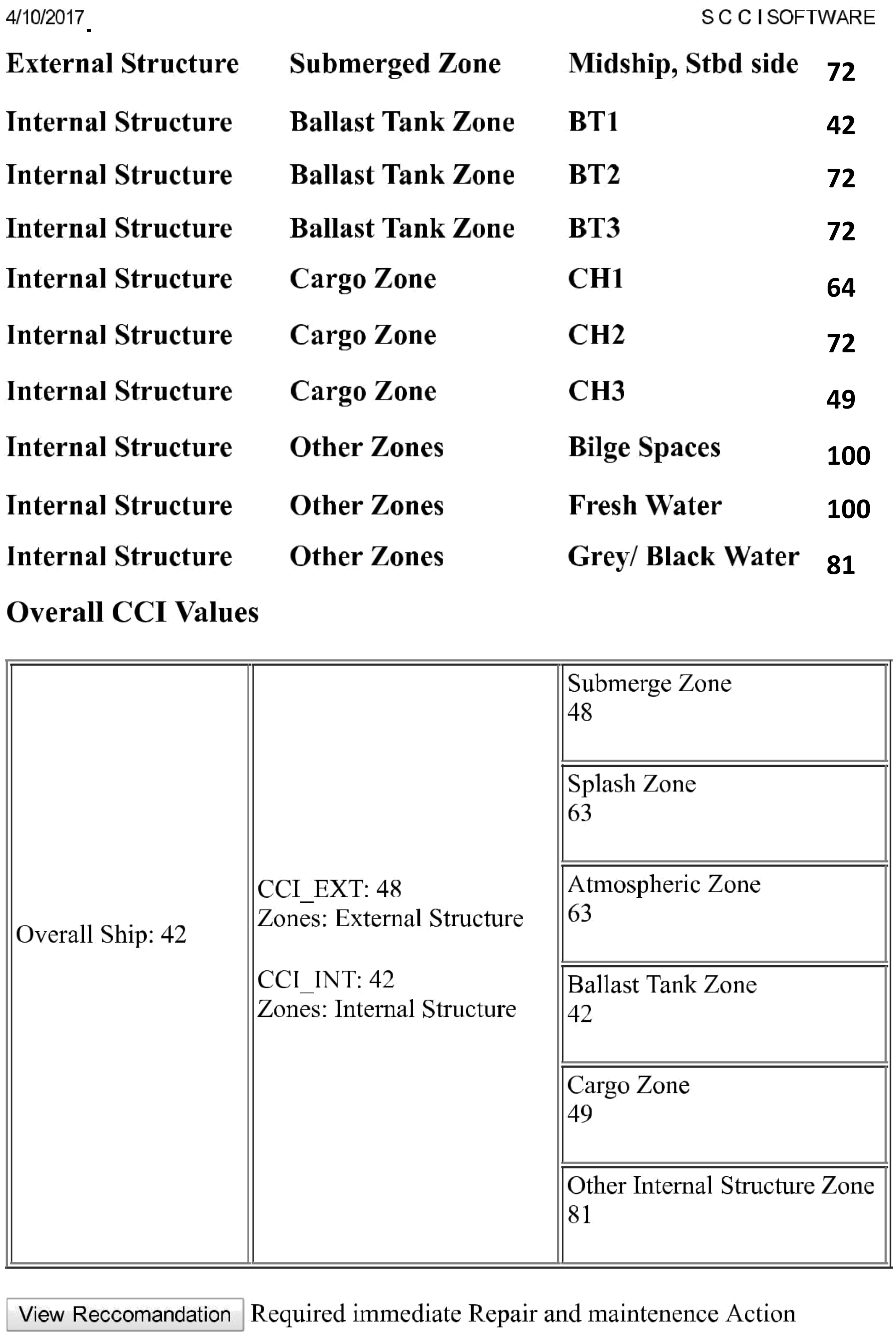
4/10/2017 S C C I SOFTWARE

CORROSION CONDITION ASSESSMENT REPORT

date: 10/04/2017

SHIP DETAILS	
Vessel Id	17047
Ship Name	Poor Condition
Year Built	2000
Ship Type	XXX
Built At	XXX
Owner's Name	XXX
Classification Society	XXX
DWT(T)	24000
Length Between Perpendiculars(M)	162
Length Overall(M)	166.5
Breadth(M)	26
Depth(M)	16
Load Waterline Draught(M)	9

Structure	Zone	Subzone	CCI
External Structure	**Atmospheric Zone**	**Side shell, above splash zone, aft end, port**	**80**
External Structure	**Atmospheric Zone**	**Side shell, above splash zone, aft end, stbd**	**72**
External Structure	**Atmospheric Zone**	**Side shell, above splash zone, Fore End, Port**	**81**
External Structure	**Atmospheric Zone**	**Side Shell, above splash zone, fore end, stbd**	**81**
External Structure	**Atmospheric Zone**	**Side shell, above splash zone, midship, port**	**81**
External Structure	**Atmospheric Zone**	**Side shell, above splash zone,fore end, stbd**	**63**
External Structure	**Atmospheric Zone**	**Superstructure**	**100**
External Structure	**Atmospheric Zone**	**Upper Deck**	**63**
External Structure	**Splash Zone**	**Aft End, Port side**	**72**
External Structure	**Splash Zone**	**Aft End, Stbd side**	**72**
External Structure	**Splash Zone**	**Fore End, Port side**	**72**
External Structure	**Splash Zone**	**Fore End, Stbd side**	**63**
External Structure	**Splash Zone**	**Midship, Port side**	**72**
External Structure	**Splash Zone**	**Midship, Stbd side**	**81**
External Structure	**Submerged Zone**	**Aft End, Port side**	**49**
External Structure	**Submerged Zone**	**Aft End, Stbd side**	**49**
External Structure	**Submerged Zone**	**Appendages**	**81**
External Structure	**Submerged Zone**	**Fore End, Port side**	**48**
External Structure	**Submerged Zone**	**Fore Side, Stbd side**	**72**
External Structure	**Submerged Zone**	**Keel strake**	**72**
External Structure	**Submerged Zone**	**Midship, Port side**	**72**



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External Structure	**Submerged Zone**	**Midship, Stbd side**	**72**
Internal Structure	**Ballast Tank Zone**	**BT1**	**42**
Internal Structure	**Ballast Tank Zone**	**BT2**	**72**
Internal Structure	**Ballast Tank Zone**	**BT3**	**72**
Internal Structure	**Cargo Zone**	**CH1**	**64**
Internal Structure	**Cargo Zone**	**CH2**	**72**
Internal Structure	**Cargo Zone**	**CH3**	**49**
Internal Structure	**Other Zones**	**Bilge Spaces**	**100**
Internal Structure	**Other Zones**	**Fresh Water**	**100**
Internal Structure	**Other Zones**	**Grey/ Black Water**	**81**

Overall CCI Values

Overall Ship: 42	CCI_EXT: 48 Zones: External Structure CCI_INT: 42 Zones: Internal Structure	Submerge Zone 48
		Splash Zone 63
		Atmospheric Zone 63
		Ballast Tank Zone 42
		Cargo Zone 49
		Other Internal Structure Zone 81

Required immediate Repair and maintenence Action

Fig 3.24 Output of KBDSS for the “Poor” Corrosion Condition

The input data in Tables 2.17 and 2.18 have been entered using the project setup module. The details of the three different corrosion conditions (very good, satisfactory and poor conditions as shown in Tables 2.20, 2.21 and 2.22 respectively) were entered using the corrosion observation module with the help of user interface. The C.C.I for each of the corrosion conditions were then calculated using the SCCI calculation module. Summary of results from the SCCI software for the three corrosion conditions are presented in Table 3.4, which shows the C.C.I values of all corrosion zones as well as for the overall ship structure. It may be noted from Table 3.4 that the SCCI software has returned the same C.C.I values compared to the results of the three case studies presented in Table 2.26. The development of the SCCI software is thus validated and can be implemented for use by the stakeholders in the shipping industry for corrosion assessment of steel ship structures at any point in her operational life. The results of SCCI calculations for the 'very good' and 'poor' corrosion conditions are given in Fig 3.23 and 3.24 respectively as examples.

3.10 Applications of Database

As the database for various type/ class of ships get built up as a result of wide use of DSS, following trends or inferences can be arrived at which can be made useful in the design, building and operational stages.-

(a) Recurrent corrosion problems, if any, at a given subzone for a given class of ships can be identified.

(b) The design deficiencies (causing corrosion) observed in any subzone with respect to the material selection (structural and coating), improper drainage from tanks, evidence of stress corrosion etc. can be corrected for the future designs. In case of operational ships, such corrections are to be carried out during ship's repair periods wherever possible.

(c) Areas which are inaccessible for corrosion inspection, repairs, coating etc. can be identified for modification during repair periods or in the general arrangement design of future ships.

(d) The database can help in evolving better operational practices onboard ships without adversely affecting the integrity of corrosion control systems.

(e) Requirement of improving the production technology with respect to welding, coating application and installation of cathodic protection systems can be suggested to the shipyards.

The DSS is useful for new vessels as well as existing vessels. For existing vessels, the present data can be captured during the maintenance period (preferably during dry-docking) and fed into the database. Only constraint is that the corrosion monitoring aspect will commence from the current level. The corrosion condition information on current vessels is usually kept confidential by the owners/ repair yards/ classification societies. Unless there is a clear directive from regulatory bodies to undertake this exercise or make the data accessible to public, it will be difficult to obtain this abundant data. However, the monitoring system proposed in the present work is highly useful for ship owners and fleet managers since they can easily access the corrosion data of their vessels.

3.11 Conclusions

Though there are several Decision Support Systems (DSS) in existence for corrosion management in various industries, it was identified that there is no reported development of DSS in the field of corrosion assessment and monitoring of ship structures. The advantages of developing a Knowledge Based DSS for corrosion condition assessment of ship structures can be judged by the large number of input data required from the designated user for a typical ocean going vessel and the regular changes in the corrosion condition during ship's service life. The KB-DSS has been named as SCCI (Ship's Corrosion Condition Index) Software since the most important output of the software is the Corrosion Condition Index (C.C.I) of the ship structure as well as its corrosion zones.

The domain knowledge has been compiled in 15 KB groups and integrated in the software. The KB-DSS has been developed in the form of four functional modules viz. Project setup module, Corrosion observation module, SCCI Calculation module and Administrative functions module. The users need to only select answers to the pre-defined questions. The software can improve decision making performance by enhancing the quality of services by having an expert readily available and can also assist to make decisions more consistently. The codes of the SCCI software were validated with the help of case studies corresponding to three corrosion conditions viz. very good, satisfactory and poor conditions.

The SCCI software has been implemented on the web for corrosion condition assessment and will enable all stakeholders in the shipping industry to access the software similar to any other website. The ship owners/ shipping agencies can therefore contract local expertise to assess the corrosion condition of ship structures. The SCCI software will provide necessary user interface, supporting knowledge base, historic information, calculations etc. It will also free the user from multiple documentations and the stakeholders can view the reports from distant locations. The web based SCCI software will be highly useful when the owners/ shipping agencies have to manage a large fleet of ships, operating at multiple routes and are of varying age, type etc.

*****

Chapter 4

RECOMMENDATIONS FOR BEST PRACTICES: CORROSION CONTROL OF SHIP STRUCTURES DURING LIFE CYCLE

Contents

4.1 General

Long term corrosion protection of any metallic structure when exposed to an aggressive environment is difficult and this is particularly true for vessels in a marine environment. Corrosion is prevalent throughout a steel ship structure and it tends to manifest itself in a variety of commonly recognised degradation forms. Statistics for ship hulls show that 90 % of ship failures are attributed to corrosion (Melchers, 1999). Depending upon the structure to be protected and its exposed environment, there is a wide range of anti-corrosion strategies that may be used. In a modern business environment, successful ship owners cannot afford major corrosion failures involving injuries, fatalities, unscheduled maintenance and environmental contamination. Ship owners and operators recognize that combating corrosion impacts significantly upon vessels' availability, reliability, through life costs and budget availability for future projects. Considerable efforts are therefore necessary on corrosion control during various stages of ship's life cycle.

The cost of corrosion in India has been estimated as approximately 2 Lakh Crore Rupees per year (The Times of India, 2012). Corrosion represents one of the largest through life cost component of ships. The annual cost of corrosion in shipping industry in various countries is also significantly high as brought out in Chapter 1. These costs include coating, corrosion resistant materials, cathodic protection, additional plate thickness, etc. and manpower costs. Long periods in service with short maintenance periods are necessary for economical operation of ships and for this an effective corrosion assessment and monitoring system must be in place.

Irrespective of the age of the ship or trading areas, ship owners/ operators have now begun to see the benefits of preserving the outer hull and internals in terms of repair costs and downtime. The shipping industry is very complex with the presence of large number of stakeholders. The adverse effect of corrosion on cost, safety of cargo and employees, environment, and operational availability makes almost all stakeholders concerned about corrosion in some way or other. The massive cost of corrosion provides many opportunities to various stakeholders in the industry to reduce corrosion and risks of failure as well as to develop new mitigation strategies.

The persistent and hidden effect of corrosion has negative impact on structure, equipment and environment of ships and is therefore a source of major concern to ship owners and platform managers. In the absence of a stipulated corrosion prevention programme that would guarantee continuity of initiatives, ship owners are often forced to trade off corrosion resistance as a cost saving measure especially when under financial constraints. Design of a ship and its systems with built-in corrosion resistance would result in less planned and unplanned maintenance and thereby substantial saving in through life costs. The unpredictability of the cost and extent of corrosion necessitates active consideration of corrosion right from the initial stages of ship design.

The life cycle of ships can be broadly divided into three stages viz. ship design, shipbuilding and ship operation. Major considerations that contribute to the corrosion condition have been identified, based on the domain knowledge base collated as part of this research work, for all stages and recommendations for best practices are presented in this chapter for minimising the adverse effect of corrosion. Though corrosion of ship's structures cannot be prevented fully, the total life cycle cost can be reduced substantially by adopting the recommended practices. The best practices will constitute a set of broad guidelines/ instructions to be followed by the involved persons. While prediction of definite return on investment resulting from focussed attention to corrosion prevention and control is difficult, there will be a range of potential benefits such as lower maintenance, increased reliability, safety, performance and service life and reduced life cycle cost.

4.2 Key Stakeholders in the Shipping Industry

A large number of stakeholders participate in various capacities during the life cycle of ships. Linda et al. (2013) have presented an overview of key stakeholders whose action may directly or indirectly influence the shipping sector. All stakeholders have a common interest, which is the safe operation of ship and her proper maintenance. Considering the risk of corrosion and huge cost of corrosion control during the life cycle of ships, there is a definite need to coordinate the actions of all stakeholders. There is a realisation that corrosion is a major factor and cumulative involvement of all stakeholders will go a long way in minimising the cost attributed to corrosion of ship structures, which will in turn improve the profitability of operations. The key stakeholders participating in the shipping industry in some way or the other have been identified as listed below and are also pictorially represented at Fig 4.1. All stakeholders can contribute positively towards improving the corrosion condition of ship structures during the life cycle.

(a) Ship owners, Charters and Operators

(b) Ship designers

(c) Shipbuilders

(d) Suppliers of material and equipment

(e) Classification Societies

(f) Maritime sector associations

(g) Investors, banks and insurers

(h) Customers

(i) Employees and unions

(j) Government and regulators

(k) General public

(l) Ship recyclers

(m) Academia and research organisations

(n) Media

There is a need for reliable and regular exchange of information among various stakeholders to promote an effective corrosion control culture in this industry. The responsibility of initiating this new culture rests with owner or shipping companies, who take all the financial risks. They need to be aware of this responsibility and should allocate sufficient budgetary provision to incorporate corrosion control measures at various stages of ship’s life cycle.

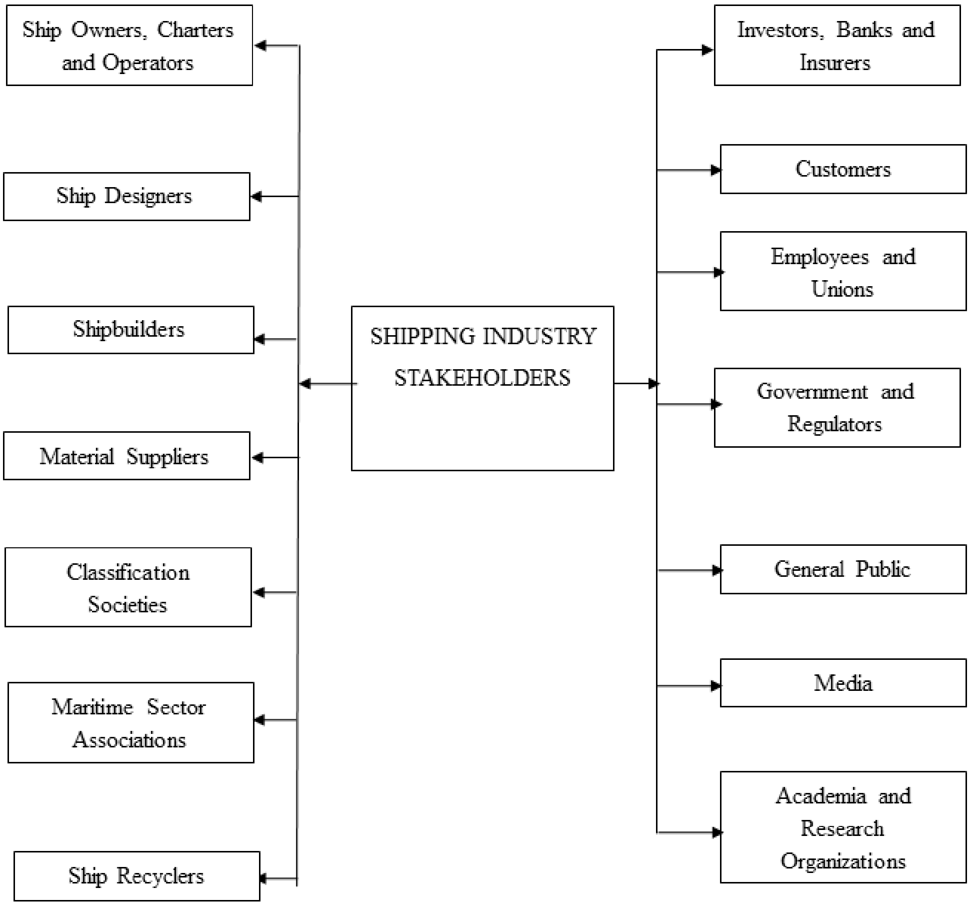

Fig 4.1 Key stakeholders in the shipping industry

Ship designer always strives to design a ship that will carry certain deadweight of cargo in a seaworthy vessel at a pre-determined speed on a given radius of action as cheaply as possible (Barass, 2004). The designer shall also give equal consideration for corrosion aspects along with stability, strength, seakeeping, powering, general arrangement etc. from the concept design stage itself and has to be progressed through the preliminary and detailed design stage. The shipbuilder shall translate the design into a ship without compromising the corrosion control measures incorporated in the design. Corrosion aspects shall be one of the major factors during production stages such as material ordering, reception, storage, prefabrication, fabrication, erection and sea trials. The various considerations during life cycle of a ship from the point of view of corrosion have been identified and are presented at Section 4.3.

The suppliers have the responsibility to maintain the prescribed chemical compositions and material homogeneity of their product, which have an impact on corrosion resistance of the material. Also care is to be taken during transportation of materials from supplier to the shipyards to minimise surface damages. The Classification Societies, Government and other Regulators are to strictly assess and monitor the status of corrosion from time to time during the service life of the vessel through timely inspections. The investors/ banks/ insurers are another set of affected stakeholders who have high financial stake in the shipping business and they will be keen to get a feedback on the corrosion condition of the ship. The employees and their unions must demand timely repair and maintenance actions for the safe and reliable use of the vessel. They must also undergo regular training on the corrosion control during ship’s operational phase.

The customers can also contribute by chartering only those ships that are in good corrosion condition and follows requisite safety standards. The media can actively report the incidents as well as various developments and can spread the awareness among the maritime community and the public in general. The academia as well as R&D organisations can be key partners in this process by offering advanced courses in corrosion engineering and helping to develop new materials/ technologies for corrosion control. Ship recycling involves breaking up of ships either for parts, which can be sold for re-use, or for the extraction of raw materials, chiefly scrap. The recycling would come into play when the ship becomes uneconomical to run due to uncontrolled corrosion, fatigue or non-availability of parts.

All stakeholders in the shipping industry shall together form a corrosion community network with an aim to reduce the overall cost of corrosion. Their representatives may continually participate in conferences, seminars, and symposia to exchange information and update the broad knowledge base of corrosion prevention and mitigation strategies. Corrosion as a major factor must be considered by all the stakeholders right from the stage of conceiving a new ship.

4.3 Life Cycle Phases of Ships

25 to 30 years is the lifetime of a modern ocean going ship once the construction is completed and is handed over to ship owner. From the inception of idea to order a new ship, a number of steps are followed by personnel from various stakeholders (Section 4.2) till the end of service life. The life cycle of a ship can be broadly classified into three stages, viz. **Ship design, Shipbuilding and Operational phases** from the point of view of corrosion and its control. Though these are distinct stages, they are sometimes concurrent. For example the production activities may begin before the design is frozen to save project completion time. Methods and procedures for controlling corrosion of ship’s structural members need to be adopted during all the three phases. For effective corrosion control, considerations of corrosion and its control must be integrated with activities in the life cycle of ships right from the design stage, and be practiced during the building and operational phases.

4.3.1 Considerations in Ship Design Phase: Corrosion Point of View

Ship design is a complex process which involves optimisation of a large number of requirements of geometric, structural, operational, arrangement of machinery and systems, etc. Ship design is often a compromise between several constraints. The various stages in a typical ship design process have been reported by Rawson and Tupper (2001). They have also presented a design spiral describing the iterative nature of design process. A concept of integrated ship design and its role in enhancing ship production has been presented by Ross (1995). The benefits of such an integrated ship design program are decreased design hours, reduced lead time, improved productivity, early detection of interferences, ease in making changes, a drastic reduction of information errors, and the availability of production oriented data.

The ship design is an iterative process which culminates in production of large number of documents/ drawings that are to be submitted to the Classification Societies for plan approval. Typical list of such documents and their general requirements are presented by DNV (2012). The ship design documents are organised into 14 disciplines such as Stability, watertight and weather tight integrity, Mechanical, Electrical, Safety, Hull and structure, Instrumentation, Materials, Navigation, Process, Quality management, Piping, Telecommunications, Geotechnical engineering and Multidiscipline.

It is necessary that considerations of corrosion and its prevention be given due importance right from the early stages of ship design. The application of sound design principles can eliminate many future corrosion problems and reduce the cost and time attributable to corrosion maintenance and repair. The ship designer must give equal consideration for corrosion aspects along with considerations of stability, strength, seakeeping, powering, general arrangement etc. from the concept design stage itself. This will facilitate better implementation of corrosion control plans in the shipbuilding phase and maintenance/ repair plans during the operational phase. Correcting unanticipated corrosion when the vessel is in operation may be time consuming and very costly.

While it is difficult to quantify the financial benefit resulting from increased attention to corrosion prevention and control during vessel design, one can appreciate the range of potential benefits that will result in efficient ship operations and reduced life-cycle cost. The designers should gain a firm understanding of all the environmental factors that will influence corrosion of the ship before determining the corrosion prevention strategy. Rather than considering the corrosion engineering as a reactive discipline, it should figure at the concept design stage of a project when decisions are made that will have a significant impact upon the structures (BMT Defence Services, 2009).

Adoption of best practices to ensure that corrosion resistance is built in 'up front' is the only way to guarantee that a vessel will have the desired corrosion resistance during the subsequent phases of its life cycle. Major design considerations that will mitigate the risk of unexpected corrosion of vessels and significantly lessen their through life cost have been presented in Fig. 4.2 and are described in the subsequent sections.

(a) Material Selection

Proper selection of materials used in shipbuilding will play an important role towards achieving good degree of corrosion control during the life cycle of ships. The selected material must withstand the aggressive nature of the environment, must be compatible with the adjacent materials and also compatible with selected corrosion control methods. Non-corrosive materials such as GRP may be used wherever it is economically and practically feasible. If metallic materials dissimilar to steel are used, dielectric barrier materials should be provided to isolate the dissimilar materials and avoid galvanic corrosion. Also, the relative positions of the metals in the galvanic series and the area ratio to the steel structure must be considered to prevent either metal becoming a sacrificial anode to the other *(*Parente et al. 1996). Selection of correct welding consumable is essential to avoid localised galvanic corrosion due to difference between the compositions of the parent and weld metals.

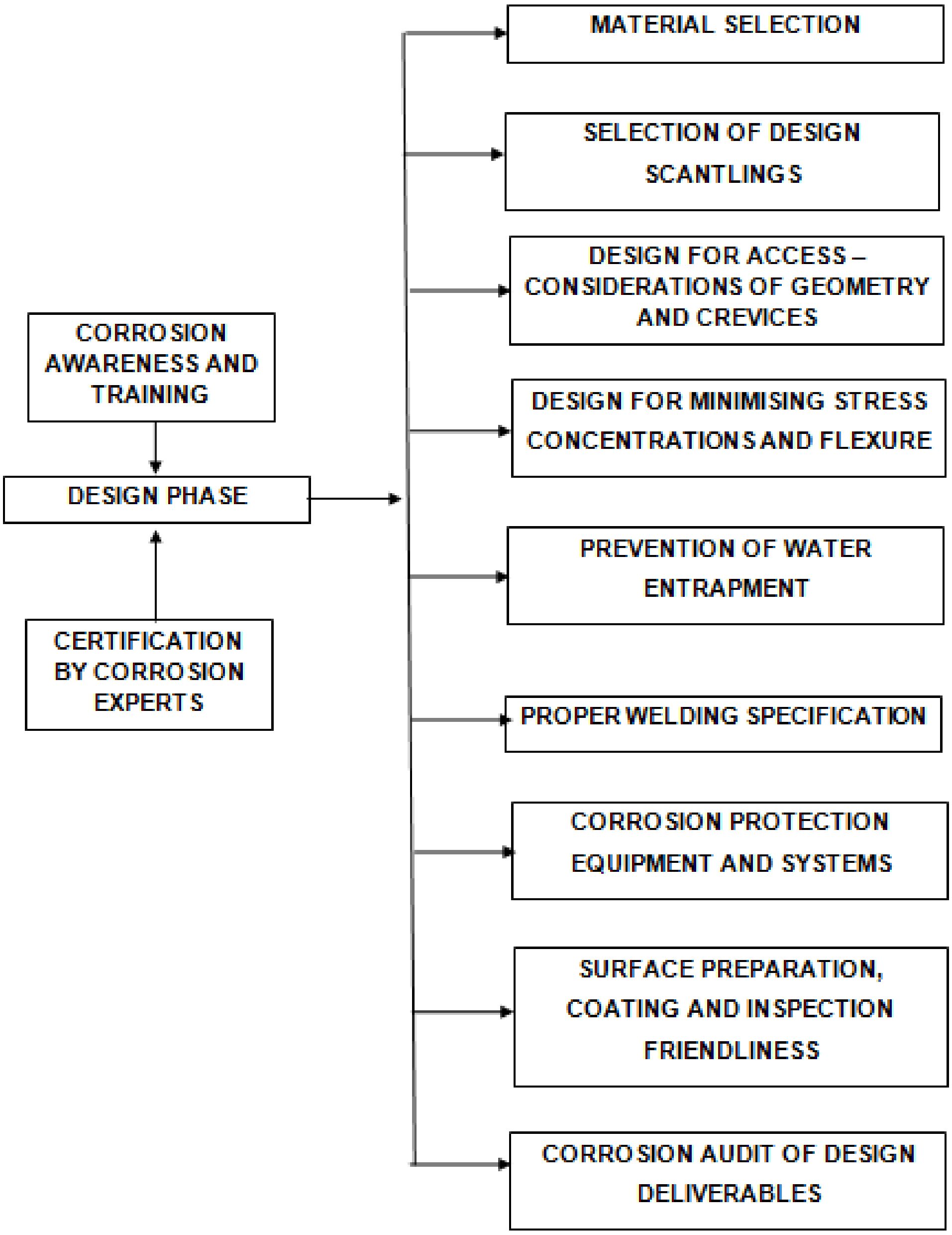

Fig 4.2 Considerations in ship design phase: corrosion point of view

(b) Selection of Design Scantlings

In order to maximise the load carrying capacity for a given displacement, there is a tendency to design structures with lighter scantlings with the help of improved analysis techniques for prediction of design stresses and failures. There is also a constant effort to reduce the production and operational cost with the help of lighter scantlings. Stipulated corrosion additions and allowances must be added to the design scantlings as per the common structural rules published by the classification societies. A deliberate attempt may be given to increase the scantlings more than the minimum calculated as per the classification rules, at locations with higher chances of corrosion, inaccessible area etc.

(c) Design for Access (Considerations of Geometry and Crevices)

Corrosion often occurs in crevices or inaccessible spaces where the corrosive medium becomes more aggressive. These areas need to be eliminated or minimized in the design process. All joints need care in design and are to be examined with a view to avoid crevice corrosion. Safe accessibility to all parts of the structure must be ensured while developing the structural configurations and the general arrangement of all spaces. This will facilitate proper application, inspection and maintenance of protective coating systems. Adequate manholes and safe accesses are to be provided and they must be located based on efficient access routes through the vessel for corrosion inspection. The geometric considerations to minimise erosion corrosion are also necessary during the design stage.

(d) Design for Minimising Stress Concentrations and Flexure

Stress Corrosion Cracking (SCC) is the conjoint action of stress and the corrosive environment which results in formation of a corrosion crack. At locations where there is a possibility of stress corrosion cracking, the components may be designed to operate at stress levels below the threshold stress for cracking (ASM International, 2000). Insufficient stiffness of structural panels would result in excessive flexure due to vibrations or cyclic loading, which may cause premature breakdown of protective coatings. An earnest attempt to reduce the stress concentrations and/ or residual stresses which will adversely affect the coating life and thereby increasing the possibility of corrosion inception shall be made. The structural details, notches and discontinuities are to be specifically considered in the design stage to reduce stress concentration. Corrosion may enhance the stress and strain and may lead to catastrophic failure. The cyclic loads acting on the structure also need to be considered from the point of view of corrosion fatigue.

(e) Prevention of Water Entrapment

Insufficient drainage is a contributing factor towards localised corrosion. The structural design and general arrangement plans shall be critically reviewed from the point of view of provisions made for proper drainage of water and dispersal of contaminants from horizontal surfaces. Provision of corrugated bulkheads instead of stiffened plate bulkheads, scallops, drain cut-outs, slopes for horizontal surfaces, etc. shall be considered to improve the drainage facilities without compromising the structural strength.

(f) Weld Specifications

Corrosion failures of welds may occur in spite of the fact that the proper base metal and filler metal have been selected. Major factors that influence corrosion of welds are weldment design, fabrication technique, welding practice, welding sequence, moisture contamination, oxide film, weld slag and spatter, incomplete weld penetration or fusion, porosity, crevices, high residual stresses, improper choice of filler metal and surface finish (ASM International, 2006). The causes of weldment corrosion are linked to material (both base and filler) composition and welding procedures. Differences in composition between the weld metal and the base metal can generate a potential difference in certain environments, thus setting up a galvanic cell, leading to corrosion. Microstructural differences between the base metal and in the as-welded microstructure or as-welded heat affected zones can lead to localised corrosion attack (Lee et al. 2004). Further, requirements of preheating and post heating of the weld zone may be considered to minimise the temperature effects. Apart from these, specifying continuous welds rather than intermittent or spot welding and avoiding lapped joints may be followed for better corrosion control. The designer shall develop optimum weld joint design considering the above factors and specify guidelines for the production stage.

(g) Surface Preparation, Coating and Inspection Friendliness

Protective coatings are the primary line of defence against corrosion. The selection of suitable painting scheme, surface preparation, application and maintenance will go a long way towards corrosion control of ships during life cycle and are to be addressed right at the beginning of the design stage. Available options are to be considered and the best painting scheme is to be selected for construction as well as operational phases. An excellent coating system will not give desired results if applied on a poorly prepared surface or the prescribed application conditions such as environmental, curing time, coating thickness etc. are not adhered to. The access openings on the structure must be of sufficient size to allow personnel to pass with tools, protective clothing and breathing apparatus. The ladders and walkways must be of sufficient width and inspection platforms are to be provided as required. It is often far more economical to apply a very good coating on to a well-prepared surface when that surface is easily accessible than to effect repairs when the surface has been covered by insulation, wiring or pipe work *(*Parente et al. 1996).

(h) Corrosion Protection Equipment and Systems

In addition to protective coatings, the ship designer shall actively consider and provide cathodic protection system (sacrificial anode or ICCP systems) for the submerged and ballast tank corrosion zones. The cathodic protection system would control the corrosion in case of any damage to the coating system. Recommended practice for design of a cathodic protection system, its associated components and installation have been presented by DNV (2010).

(i) Corrosion Awareness and Training

In several cases, corrosion occurs due to inadequate knowledge of the importance and causes of corrosion among the design team members and therefore cannot take the relevant factors into consideration. Imparting quality training and improving the awareness among the design personnel on corrosion of ship structures and its control is the key factor in developing a ship design that has the potential to reduce the life cycle cost of ships. Strengthening of the ship design team with experience in the field of corrosion engineering may also be considered.

(j) Corrosion Audit and Certification by Qualified Corrosion Engineers

In order to ensure that the corrosion control aspects have been incorporated in the ship design, all design deliverables related to corrosion (documents, drawing and specifications) shall be certified by a qualified corrosion engineer. The certification may be carried out by internal experts within the design team or by the classification agency, as decided by the owner. These corrosion specifications are to be compulsorily followed during the building as well as operation phases. Corrosion audit of design deliverables shall be a mandatory exercise for ensuring the compliance to the recommended best practices (presented at Section 4.5.1) during the design stage.

4.3.2 Considerations in Shipbuilding Phase: Corrosion Point of View

The condition most favourable for installing corrosion control measures (especially for coating application) is during the new construction stage. Practices followed during the shipbuilding phase have a long lasting impact upon the long term integrity of corrosion protection systems. Before commencement of shipbuilding, it is essential that all involved stakeholders agree on a quality control programme incorporating corrosion control practices. The Quality Control (QC) department of the shipyard shall be strengthened by appointing persons adequately trained in the field of corrosion engineering. Further, various production centres of the shipyard shall strictly adhere to the procedures and guidelines for corrosion control promulgated by the design team.

All necessary records shall be maintained by the QC department to facilitate corrosion audit as well as for future references. Clear planning of the construction process in order to minimise all forms of coating damage due to mechanical abrasion is essential to give good through life performance without inconvenient and expensive repairs at a later stage (BMT Defence Services, 2009). The initial stresses and strains may be introduced at the time of rolling of plates in the steel plants. Each successive step of operations such as cutting, forming, welding etc. may introduce further stresses and strains. The residual stress and strains induced during the construction process must be kept as low as possible to improve the corrosion resistance of structures.

Though, the shipbuilding process may vary among different shipyards and/or different countries, it can be generally represented as shown in Fig 4.3 from the point of view of corrosion. Successive stages from incoming raw materials to trials and final fitting out are represented in the form of a flow diagram. A number of personnel from the production team (such as fabrication shop, marine equipment, electrical systems, communication equipment etc.) participate during these processes and a good understanding corrosion is essential among them.

Every process shown in Fig 4.3 presents its own corrosion challenge and the major considerations during these processes are summarised in Table 4.1. The installation of corrosion protection systems should be a well-planned and coordinated activity, integrated in the shipyard's production plans during this phase. Care must be taken to avoid conflicts with other yard operations which are progressing concurrently, mainly the piping installations and welding to avoid damage to protective coatings. The entire shipbuilding process may take several years depending on the size and complexity of the ship. Extensive operations such as cutting, welding, bending, machining, lifting, transportation, etc. are involved at every stage and corrosion inspections are necessary at every stage to effectively monitor the activities. The corrosion control activities during the shipbuilding stage shall have the support and commitment from the top management and the same need to be insisted by the ship owner. A set of general recommendations for corrosion control during the shipbuilding process have been presented in Section 4.5.2. These recommendations can form a set of guidelines for inspection by the QC department as well as documentation for facilitating the corrosion audit.

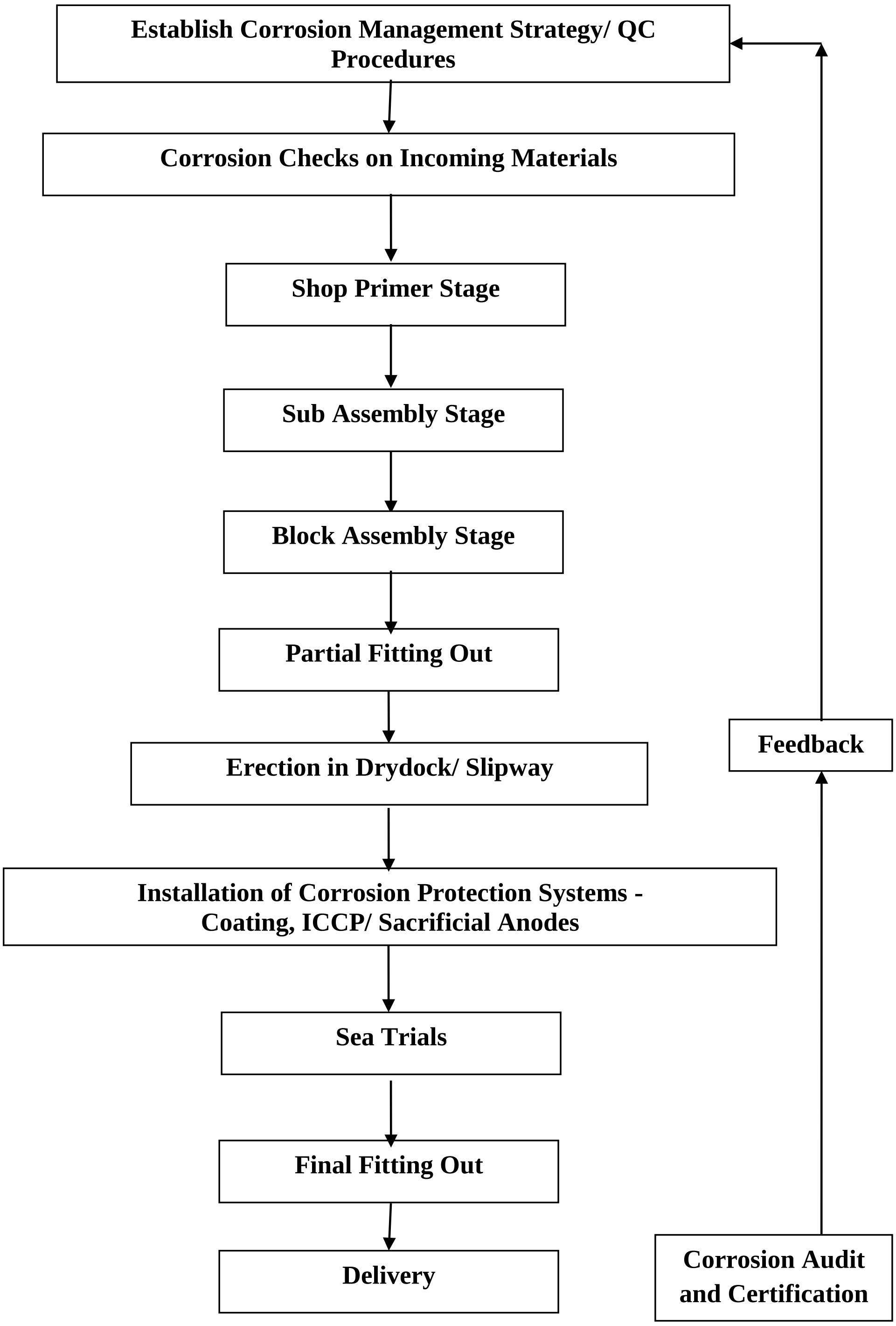

Fig 4.3 Typical shipbuilding process: corrosion point of view

Table 4.1 Corrosion Considerations: Shipbuilding Phase

Sl No	Shipbuilding Process	Corrosion Considerations
(a)	Establishing of Corrosion Management Strategy	The strategy shall address the following aspects:- a) Strengthen the Quality Control (QC) department with corrosion engineers or conduct training for the existing persons for effective monitoring of construction processes. b) Establish QC procedures for all shipbuilding processes that may affect the corrosion condition. c) Establish QC procedures for repair or replacement of components that may become damaged during construction. d) Establish standards for surface preparation for coating during the contract stage itself. e) Specify the welding procedures in accordance with design specifications. f) Avoid the tendency to meet the production schedule by compromising or bypassing corrosion aspects.
(b)	Corrosion checks on incoming raw materials (Necessary since corrosion problems often arise with the raw materials supplied to the shipyard)	Following corrosion QC checks are necessary:- a) Examine the surface contaminants on the raw materials that might have picked up during their manufacture, transportation and storage. b) Examine chemical composition of incoming structural materials. c) Examine the plates/ sections arrived in a pitted condition.
(c)	Shop Primer Stage (Surface preparation and primary corrosion protection using shop primer is carried out at this stage).	It is necessary for corrosion protection before the final coating is applied. Quality of coating will be severely affected if shop primer is applied on material with incorrect surface preparation or contamination. Corrosion inspection of steel plates as they emerge from the automated blasting/ painting process and quality of the applied shop primer is necessary.

Sl No	Shipbuilding Process	Corrosion Considerations
(d)	Sub Assembly and Block Assembly Stages (The shipbuilding progresses by joining plates and sections to form sub-assemblies which are joined together to form assemblies in this stage)	Each process shall undergo corrosion QC checks before progressing to the next stage. Careful attention shall be given to the following with respect to corrosion control:- a) Welds/ joints as well as the joining techniques are as per the approved design specifications to minimise potential locations for onset of corrosion. b) Minimise surface contaminations due to welding and cutting processes. c) Minimise the residual stresses from cutting, welding and fitting operations and undertake stress relieving if necessary. d) Minimise the oil contamination due to the use of overhead cranes and hand held tools.
(e)	Erection and Fitting out stages (The individual blocks that make up the structure are welded together at this stage. There is a possibility of substantial coating damage due to welding of scaffolding and other fixtures)	Careful attention shall be given to the following:- a) Special attention to the welds since they are hard to execute and to paint during this stage. Often the work is carried out under poor conditions of lighting and cleanliness. b) Minimise modifications to the already completed fabrication works to reduce the extent of damage to the coatings.
(f)	Installation of Corrosion Protection Systems (Protective coating and Cathodic protection systems)	Careful attention shall be given to the following:- a) Composition of painting system is as per the specification. b) Specified surface preparation standards and painting scheme for various corrosion zones. c) Environmental conditions are within the prescribed limits.

Sl No	Shipbuilding Process	Corrosion Considerations
		d) The tendency to deviate/ shorten the coating schedule to comply with an overall schedule to be avoided. Such practice may lead to significantly increased maintenance time and costs in the future. e) The size, type and distribution of sacrificial anodes are as per the design specification and the anodes are installed properly. f) The number, size, and distribution of ICCP anodes and reference electrodes are as specified and are installed properly.
(g)	Sea Trials (Sea trials are conducted to measure a vessel's seaworthiness at the end of construction)	Corrosion expert shall be present and the performance of corrosion control systems shall be evaluated during sea trials as follows:- • The hull potential measurements are within the protection range. • The ICCP system is working satisfactorily. • The drainage system is working satisfactorily.
(h)	General	In addition to the above, following general guidelines shall be followed during the shipbuilding stage:- • Contact of dissimilar metals shall be prevented to avoid galvanic corrosion. • All sharp edges shall be ground smooth and stripe coated to minimise corrosion. • Prevent the stray current corrosion due to incorrect usage of welding equipment. • Complete maximum welding prior to surface preparation and coating application to preserve coating integrity.

4.3.3 Considerations in the Operation Phase: Corrosion Point of View

Modern ship operation is a complex and sophisticated process involving a number of specialised agencies/ organisations. Details of key stakeholders directly or indirectly involved with ship's operation phase have been brought out at Section 4.2. During this phase, the ship is expected to generate income for the owner and help to get return on the investment. The corrosion control measures built-in during the design and incorporated in the building phase will succeed only if the importance of corrosion is understood by the crew members and timely mitigating actions are performed during the operational phase. Continuous assessment and monitoring of corrosion condition is therefore important in this phase. This is one of the critical functions to be performed by the ship's crew to ensure the structural integrity and seaworthiness of their ships.

Any material system when subjected to an aggressive environment will degrade over a period of time due to corrosion and therefore, maintenance will be necessary. Almost all structural components of ships are susceptible to corrosion in marine environment. Maintenance and upkeep of corrosion protection systems as well as repair costs represent a significant portion of operational budgets of ships, especially as the age of the vessel increases. Maintenance of protective coating and cathodic protection system is the primary corrosion control task in the operational phase of ships and consequences of poor maintenance practices could lead to major operational limitations in the future. Proactive actions to detect/ mitigate corrosion and to repair/ replace the unusable structural members are necessary while the ship is in operation.

Ship's crew as well as repair organisations need to perform corrosion inspections while the ship is at sea as well as during her maintenance periods. The knowledge and competence of a ship's crew to inspect and report the corrosion on critical structural members is highly important. The ship owner may adopt the preventive maintenance approach to avoid major failures in the future. Besides this, mandatory inspections and surveys are carried out by many agencies such as Classification Societies, insurers, vetting agencies, cargo surveyors, Port State, Coastal State and Flag State authorities in accordance with the international regulations. All agencies have a common objective of safe operation of the ship and its proper maintenance (Kalghatgi et al. 2009). Usually the corrosion problems resulting from the shortcomings in the shipbuilding processes would occur relatively early in the service life of the ships. Also the coatings problems such as delamination and blistering often show up within a few months of the structure coming into contact with environment. Therefore thorough corrosion inspections within the first year of service are highly essential. Damaged areas of coatings, together with cracks showing through coatings may often be observed easily because of the rust staining coming through defects (BMT Defence Services, 2009).

Dry-docking of ships during operation phase is an expensive process due to cost of docking, labour, loss of service time and other costs related to inspection, repair and renewal activities. However regular dry-docking is unavoidable, for mandatory corrosion inspections and maintenance designed to ensure the safety of the vessel, crew and passengers, which are an essential part of sea travel and transportation (Hydrex, 2011). Also, certain repairs such as renewal of underwater structure/ system components can only be carried out with the ship out of water.

4.4 Corrosion Management

Corrosion management is that part of the overall management system, which is concerned with the development, implementation, review and maintenance of the corrosion policy (Capcis, 2001). The goal of corrosion management is to achieve the desired level of ship operation at least cost. An overall corrosion management system is necessary to manage not only technical corrosion issues but also human response and actions. To ensure continued operation of marine structures at minimum cost, corrosion has to be actively managed from the early stages of design until it is taken out of service. Corrosion audit is a corrosion management tool, which should be in place if effective corrosion management is to be achieved (Mathiazhagan and Babu, 2012). The requirement of an overall corrosion prevention and mitigation culture that considers the long-term effects of corrosion, sets boundaries on the cost of corrosion, implements sound corrosion prevention and mitigation policies for both equipment and infrastructure, and establishes realistic metrics to evaluate the effectiveness of these policies and resulting programs has been articulated by Department of Defence, (2004).

Adequate budgeting to cater for the cost of built-in corrosion resistance, construction methods, inspections, maintenance/ repairs, timely renewal of structural members and coating systems, cleaning etc. are mandatory elements of a successful corrosion management programme. Strategies for the inspection, maintenance and repair of the parts that can corrode and their protections systems, should be planned and implemented. Permanent means of access should also be carefully maintained as they are crucial to the corrosion protection regime (Babu et al. 2014). Corrosion audit is necessary during the life cycle of ships to verify that the established corrosion control programme is performing as originally designed, incorporated during the building stage and practiced during the operational stage. The audit needs to be performed by independent corrosion experts appointed by owner, who will have unrestricted access to all activities. The aim of auditing may not be to find faults but to ensure compliance to the corrosion management guidelines. Further, they should provide valuable feedback that can be implemented for the future projects.

4.5 Recommendations for Best Practices

Considering the complex nature of the shipping industry, extremely high financial commitments, social and environmental repercussions, a definite need was felt for a long term strategy to oversee corrosion prevention and mitigation programme, throughout the life cycle of ships. In that direction, following recommendations have been proposed as best practices as elaborated in the following sections:-

4.5.1 Recommendation 1: Corrosion Control Booklet (C.C.B) - Deliverables from the Design phase

Based on the knowledge base collated as part of the research work (Section 3.4) and the design considerations from the point of view of corrosion (Section 4.3.1), a set of major design deliverables have been identified that may directly influence the future corrosion condition of the ship structures. These documents are proposed to be compiled as a "**Corrosion Control Booklet (C.C.B)**" and certified mandatorily by corrosion experts representing the Classification Societies or appointed by the owners prior to finalising the design. These documents will contain all corrosion control measures incorporated by the ship design team. The ship owners shall maintain the Corrosion Control Booklet, as it forms the basis for subsequent corrosion inspections during the ship production and operation stages, till the end of ship's service life. The documents have been given a code CC (Corrosion Control) indicating that they represent corrosion control measures incorporated in the ship design. List of 11 documents forming part of the Corrosion Control Booklet and the information to be specified in each document are explained in the Table 4.2.

Table 4.2 Contents of Corrosion Control Booklet

Document No	Description	Information to be Specified
CC-01	Structural material specifications	Material specifications for identification, delivery condition, chemical composition, dimensions and tolerances, surface protection, certification and marking.
CC-02	Design scantlings	Thickness of major structural members (plating and stiffeners) including the corrosion allowance catered in the design.
CC-03	Structural connections	Specifications for structural connections, weld joint design and filler materials.
CC-04	Welding procedures	Specifications for welding inspection such as edge preparation, preheating, method of welding, post-weld heat treatment and necessary equipment to be used.
CC-05	Coating system Specifications	a) Coating system (what type of coating to be applied and where) including surface preparation standards, number of coats, colours, dry film thickness (total and individual layers) etc. b) Method of application and environmental conditions during surface preparation and application. c) Inspection procedures, acceptance criteria and tests. d) Procedures for repair of coating system during shipbuilding and operation phases.
CC-06	Cathodic protection systems	a) Details of corrosion zones to be protected, protective current density demand for coated and un-coated surfaces, total current demand in initial condition and at the end of the design life. b) Sacrificial anodes - Target design life, type, number and distribution, target protective

Document No	Description	Information to be Specified
		potential to be obtained in initial condition and at the end of the design life. c) Impressed current system – anodes, reference electrodes, system control and monitoring arrangement, cabling, and procedures for renewal of components.
CC-07	Joints with dissimilar metals	Specifications for joints with dissimilar metals highlighting the precautions taken to prevent galvanic corrosion.
CC-08	General Arrangement plan - Access arrangements	Descriptions and drawings arrangements for access (to and within the space) to carry out overall and close-up inspections and thickness measurements, including portable means of access.
CC-09	General Arrangement plan: Drainage system	Descriptions and drawings of arrangements to avoid accumulation/ entrapment of water in the compartments or on the decks.
CC-10	Corrosion protection of piping/ valves/ flanges/ fittings	Specification for the corrosion protection measures for the piping, valves and fittings.
CC-11	Cargo List	Specification of the cargoes intended to be carried in each cargo hold.

4.5.2 Recommendation 2: Shipbuilding Practice for Corrosion Control

Shipbuilding being a complex and costly process, adherence to certain best practices is the best way to achieve the desired results. The major considerations from the point of view of corrosion during this phase were presented in Section 4.3.2. Seven general recommendations are proposed as part of this research as “shipbuilding practice for corrosion control” for the production yards to combat corrosion, as follows:-

a) **Establishing of Corrosion Management Strategy**. The prospective owner along with the shipyard management shall establish an efficient corrosion management strategy for progressing the shipbuilding process and inspections to minimise the adverse effects of corrosion, in the beginning stage itself.

b) **Role of Top Management**. The corrosion control programme shall have the commitment and support from the top management during construction period.

c) **Quality Control Team.** Establish a qualified QC team to monitor and ensure that the corrosion aspects incorporated during the design phase are effectively implemented by the shipbuilding yard. The QC inspections shall cover all production processes (brought out at Section 4.3.2) commencing from incoming materials to the sea trials.

d) **Joining Techniques**. The established welding procedures shall be followed without deviation to minimise the distortion as well as residual stress and strain.

e) **Corrosion Protection Systems**. Special attention shall be given for the installation and maintenance of corrosion protection systems during the building period.

f) **Sea Trials.** Corrosion expert shall be an integral member of the sea trials team to verify the performance of corrosion control systems.

g) **Corrosion Audit.** Corrosion audit by an independent team authorised by the ship owner shall be conducted to ensure the progress of the corrosion control programme as well as to provide a feedback for the future projects. There shall be an established system for recording the production activities to facilitate this process.

4.5.3 Recommendation 3: Corrosion Assessment and Monitoring During the Operation Phase

The ship owners shall promulgate a suitable corrosion management strategy for their ships and allocate trained manpower and financial resources considering the overall benefits. A new concept of Corrosion Condition Index (C.C.I) for systematic assessment of corrosion condition of steel ship structures during service life was developed and discussed in Chapter 2 taking into account all major influencing parameters. A web based Decision Support System (DSS) was developed as a tool for calculation of C.C.I and effective corrosion monitoring of ship structures and the same has been presented in Chapter 3. Incorporating this new concept of C.C.I, certain best practices are recommended towards corrosion assessment and monitoring during the operational phase of ship's life cycle. The recommended corrosion monitoring system is pictorially represented in Fig 4.4 and is amplified in the subsequent sections.

a) Definition of Corrosion Zones and Subzones

The ship structure as a whole is too large to be considered as a single component for inspection and corrosion condition assessment. Accordingly the ship structure may be divided into number of corrosion zones as proposed at Section 2.5. The corrosion zones may be further subdivided in to subzones depending on the size and complexity of the zone being considered.

b) Corrosion Inspections

Conduct of regular corrosion inspections during the service period is the first and foremost component of the corrosion management programme. Ships undergo large number of inspections by various agencies during the operation phase and same was summarised at Table 1.2. Various corrosion inspections and major assessment criteria are presented at Chapter 2. The owner may capture the corrosion data from the inspections conducted by external agencies such as Classification Societies or conduct his own inspections by employing experienced crew/ contracted corrosion experts at regular intervals. The inspections need to focus on the corrosion probable areas such as crevices, inaccessible spaces, etc. In addition, the owner has to plan and conduct targeted inspections at critical locations which were identified earlier, for corrosion monitoring.

c) Corrosion Condition Assessment and Prediction of Corrosion Condition Index (C.C.I)

C.C.I is a useful tool for assessment and monitoring of corrosion condition during a steel ship’s operational phase. Procedure for formulation of C.C.I and development of a web based Decision Support System (SCCI Software) was presented at Chapters 2 and 3 respectively. The C.C.I may be calculated for the corrosion zones individually as well as for the whole ship structure. Based on the recommended C.C.I rating system (Section 2.12), the owner can ascertain the repair/ maintenance actions to be undertaken as well as the criticality of such actions. It is recommended to maintain a minimum C.C.I of 70 (corresponding to very good condition) throughout ship’s operational life. Ships with C.C.I below 50 (corresponding to poor condition) must undergo immediate remedial actions/ extensive repairs to improve the C.C.I rating.

d) Dry-docking and Coating Renewals

The ship’s owner shall take maximum advantage of opportunities by scheduling activities for improving the corrosion condition of the hull during the dry-docking period. Activities such as underwater hull cleaning, survey/ inspection, plate thickness measurements, repairs/ renewal of structures corroded beyond acceptable limits, repair/ renewal of coating system (anti-corrosive and anti-fouling paints), repairs/ renewal of cathodic protection systems etc. may be planned and executed during this period.

e) Maintenance of Corrosion Protection Systems

Proactive actions to detect, mitigate corrosion and repair/ replace unusable structural members by the ship's crew are necessary during the operational phase and following actions are recommended:-

i). All corrosion observations and remedial actions taken are to be recorded in the form of a **"Corrosion Logbook"** and the outstanding observations may be included in the defect list for repair by external agencies.

ii). The proposed web based DSS shall be implemented for corrosion assessment and expert opinion be sought from the software.

iii). Continuous monitoring of hull potential at various locations is to be carried out for assessment of corrosion condition.

iv). Focussed attention is to be given to the critical areas identified.

v). Maintenance coating shall be applied only after surface preparation using ship husbandry tools and no coating over rust is permitted.

vi). The crew members shall never try to apply paint over the corroded surfaces or attach doubler plates on top of corroded plates.

vii). The exposed surfaces are to be washed with fresh water to remove salt accumulation after every sailing programme.

viii). Probable locations of occurring erosion corrosion such as pipes, tank boundaries (due to partially filled tanks) etc. need to be closely monitored.

ix). Carryout frequent checks on the drainage system and possibility of water entrapment.

f) Corrosion Monitoring of Ballast Water Tanks

Corrosion of ballast tanks generally pose the highest threat due to reasons brought out at Section 2.5.1 and are therefore to be monitored separately as per the following guidelines:-

i). Coating system is to be maintained in Good condition as per the guidelines stipulated by IACS (2015).

ii). Maintenance coating should be carried out before breakthrough of rust reaches 1 % of the surface area (DNV, 2000).

iii). Accumulated salt, mud, sludge etc. in the bottom of ballast tanks should be removed regularly in order to prevent pitting corrosion and bacterial growth.

iv). Closely monitor the condition of installed cathodic protection system in the tanks.

v). Thickness measurement may be resorted to in case of extremely high corrosion to assess the extent of material loss.

g) Training

Imparting corrosion awareness among the ship’s crew would significantly improve the corrosion control activities while the ship is at sea. The crew shall be trained on conducting corrosion inspections to identify the probable corrosion sites. The crew need to be competent on use of ship husbandry tools, primary maintenance of corrosion protection systems, hull potential measurements and monitoring of ICCP systems. They may also be trained on the use of Knowledge Based Decision Support System (SCCI software) to obtain expert advice from time to time for corrosion monitoring.

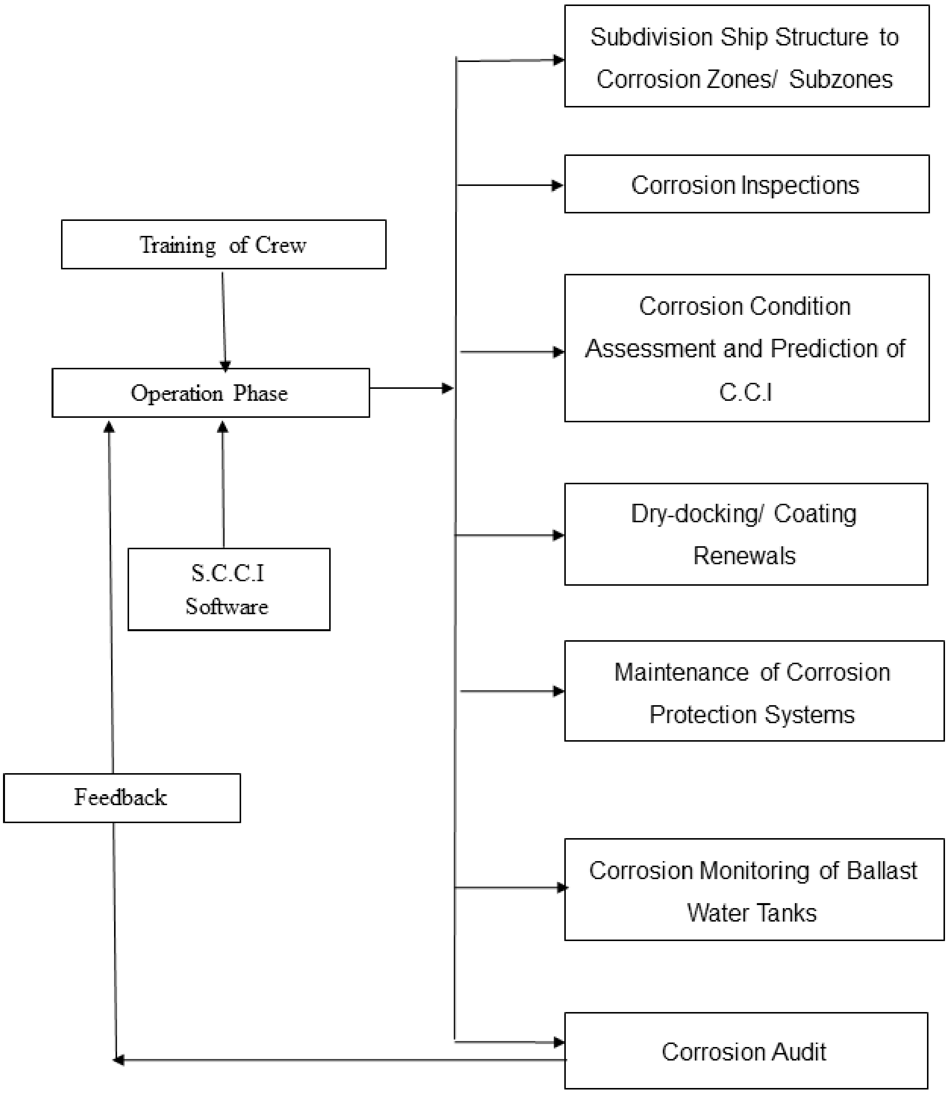

Fig 4.4 Corrosion assessment and monitoring system for ships during operational phase

h) Corrosion Audit

The ship’s owner shall organise an audit of the corrosion observations recorded, corrosion condition assessment process and remedial actions carried out to verify that the recommended practices are followed during the service life of a ship. The audit may be carried out by corrosion experts contracted by the owner. They may monitor the C.C.I values with the help of SCCI software to see that the C.C.I values are maintained above 70 as recommended at Section 2.12. The audit report will give valuable feedback to stakeholders with regard to the efforts being undertaken to maintain the ship structure and provide input for necessary future changes in the corrosion management programme.

4.5.4 Recommendation 4: Corrosion Control Model (C.C.M)

Though the corrosion of steel ship structures in marine environment is inevitable, its detrimental effect can be reduced by adopting certain best practices during the vessel’s life cycle. Accordingly best practices have been recommended for every stage (Sections 4.5.1 to 4.5.3) in the life cycle which will constitute a set of broad guidelines/ instructions. It has been observed that there is no coordinated effort between various phases of ship’s life cycle to reduce the adverse effects of corrosion. Further, there is no established corrosion management system existing in the shipping industry. Corrosion as a major factor must be considered by all the stakeholders right from the stage of conceiving a new ship. Also, there is no feedback mechanism between various phases in order to make necessary corrections in the best practices or in the corrosion management strategy itself.

With an aim of reducing the overall impact of corrosion, a new **Corrosion Control Model (C.C.M)** has been proposed as shown in Fig 4.5. The model is in the form of a flow chart where the flow of information between ship’s life cycle phases is indicated. It stipulates a framework that defines interaction between various stakeholders in the shipping industry. Training of personnel as well as the corrosion audit are integral parts of the corrosion control model. The proposed C.C.M has the potential to provide a roadmap for coordination of corrosion control activities including Research and Development activities.

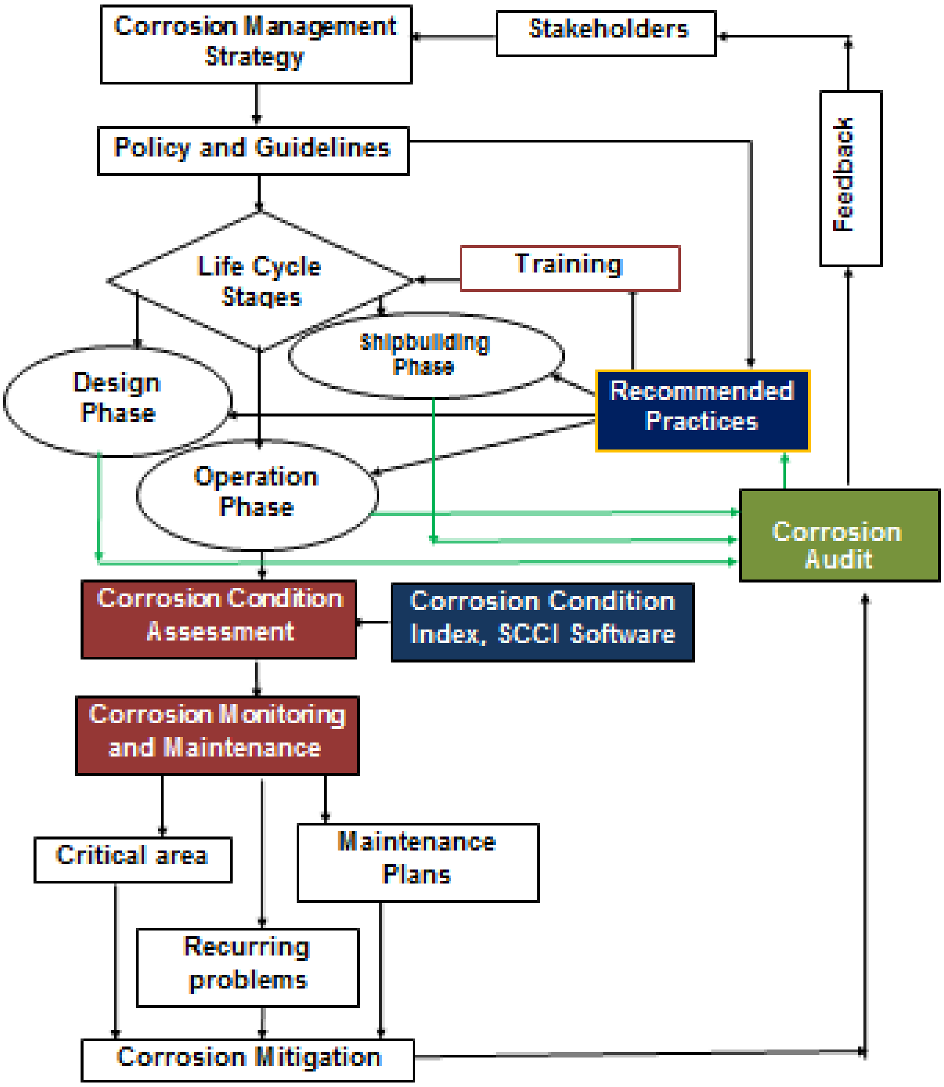

Fig 4.5 Corrosion Control Model (C.C.M) for the shipping industry

The C.C.M is being proposed as a voluntary system, which if implemented will have immense benefits in the overall corrosion condition of ship structures. Such a corrosion control model does not exist as on date in the shipping industry and is being proposed for compliance by all involved players. The responsibility of ensuring adherence to the Corrosion Control Model and the recommended practices rests on heads of the respective organisations. A well-defined quality control team, comprising corrosion engineers, are necessary to approve/ certify the actions before proceeding ahead in the life cycle.

4.5.5 Recommendation 5: Integration of Role of Stakeholders

14 key stakeholders who are participating in the shipping industry in some way or the other and their role in corrosion control have been identified and discussed in Section 4.2. The stakeholders can influence the technical, financial or social aspects due to the effects of corrosion. Corrosion as a major factor must be considered by all the stakeholders right from the stage of conceiving a new ship. There should be a smooth transfer of corrosion data from ship design to shipbuilding and then to the operation phases. Further, constant efforts to develop new materials/ technology to combat corrosion and to train the personnel involved should be made. Critical analysis corrosion incidents shall be carried out and the lessons learnt shall be implemented to avoid recurrence of similar events.

Considering the risk of corrosion and the huge cost of corrosion control during the life cycle of ships, there is a definite need to coordinate the actions of all stakeholders. They should together form a corrosion community network with the aim to reduce the overall cost of corrosion. Their representatives may continually participate in conferences, seminars, and symposia to exchange information and update the broad knowledge base of corrosion prevention and mitigation strategies.

4.6 Conclusions

Corrosion represents one of the largest through life cost component of ships. The cost of corrosion in shipping industry is substantial warranting its active consideration along with other operational factors. Ships need to be maintained for safe operation for almost 25 years to recover the investment and make it economically viable. Shipping is a rather complex industry with the presence of large number of stakeholders having financial as well as social interests. In spite of this, an effective mechanism to integrate activities of stakeholders with respect to corrosion and its control during the life cycle of ships, does not exist at present. There is a definite need for reliable and regular exchange of information among stakeholders to promote a new corrosion control culture in the shipping industry.

The life cycle of ships can be broadly divided into three stages viz. ship design, shipbuilding and ship operation. Major factors that contribute to the corrosion condition have been identified and **recommendations for best practices** are presented for minimising the adverse effect of corrosion in all stages. Though corrosion of ship’s structures cannot be prevented fully, by adopting the recommended practices the total ownership cost can be reduced substantially. The best practices will constitute a set of broad guidelines/ instructions based on the knowledge base collated as part of this research work.

The ship designer must give equal consideration for corrosion aspects along with considerations of stability, strength, seakeeping, powering, general arrangement etc. from the concept design stage itself. The ship designer must prepare and submit a **Corrosion Control Booklet**, comprising of 11 documents and drawings mentioned in Table 4.2, to the owner. The shipbuilder is to translate the design into a ship without compromising on corrosion control aspects during the material ordering, reception, storage, prefabrication, fabrication, erection and trials stages. Assessment of corrosion of ship structures using Corrosion Condition Index (C.C.I) (developed as part of this research and presented in Chapter 2) has been proposed as a best practice during the operation phase. The web based SCCI decision support system software (discussed at Chapter 3) is a handy tool for estimation of C.C.I as well as for monitoring of corrosion condition.

A new concept of **Corrosion Control Model** has been proposed as part of the present research (Fig 4.5) as a long term strategy to oversee the corrosion control programme through the life cycle of ships. A well-defined corrosion management strategy, the life cycle stages and the recommended best practices are integrated with this model. The model illustrates the flow of information between various ships' life cycle phases and stipulates a framework for interaction among various stakeholders in the shipping industry.

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Chapter 5

Summary and Conclusions

5.1 Summary

Shipping industry plays a major role for the economic prosperity of maritime countries. Corrosion has been a known factor since metal was first used in the construction of ships and it causes accelerated decline in the material state of structures. Corrosion also causes several concerns on the safety of cargo, crew as well as the environment. Apart from this, there are adverse effects on the ship’s resistance resulting in higher fuel cost and loss of operational time due to corrosion. Ships are very costly assets and safe operation for almost 25 years is necessary to make them economically viable.

The research efforts were initiated with extensive review of available literature. Visits to various ships, ship design offices and shipbuilding/ repair yards were carried out to understand the existing corrosion control practices during ship’s life cycle. Though there are well established methods such as coating, cathodic protection etc. for fighting against corrosion, it was observed that corrosion was generally treated as a reactive subject and was not getting the attention it deserves. The primary objective of the research has been to develop a comprehensive system to assess the corrosion condition of a ship at any point of ship’s service life and to assign a Corrosion Condition Index (C.C.I), which will be a measure of its susceptibility to corrosion.

The problem was approached from the perspective of a Naval Architect. A qualitative assessment of major parameters influencing corrosion of ship structure has been attempted based on the type, extent as well as the envisaged the severity of consequences. A C.C.I rating system has been recommended based on which decisions on future operations may be arrived. The C.C.I development method as well as the rating system has been validated with the help of three case studies corresponding to three corrosion conditions viz. Very good, Satisfactory and Poor conditions.

The corrosion assessment and monitoring of ships is an unavoidable continuous activity since the corrosion condition aggravates or improves depending on the incidents/ maintenance level during service. Different structural members in a ship are subjected to varying environment as well as levels of corrosion. A Knowledge Based Decision Support System (KBDSS) was developed as a corrosion assessment and monitoring tool which can be used for an existing vessel or for new vessels. The users of KBDSS would be able to access the built-in expert knowledge and input corrosion data by answering questions with a user interface. Further, the KBDSS would generate an easy to understand report and has been implemented as a web application to make it available for all stakeholders from any part of the world.

Though corrosion of steel structures cannot be fully prevented in the marine environment, their adverse effects can be minimized by following certain best practices during the life cycle. These best practices will constitute a set of broad guidelines/ instructions based on the knowledge base collated as part of the research work. As the databases for various type/ class of ships get built up, certain trends or inferences can be arrived at, which can be useful for identifying recurrent problems, deficiencies in design, areas which are inaccessible (for inspection, repairs, coating etc.)

and requirement for improving the production technology (welding, coating application, installation of cathodic protection systems etc.).

There are a large number of activities which happens simultaneously during the ship’s life cycle. This research has made an effort to highlight the importance of corrosion aspects during the design, building and operational stages from the perspective of a Naval Architect. The conclusions and salient contributions of the present work are given in the following sections.

5.2 Conclusions and Noticeable Contributions

a) Documentation of Knowledge Base on Corrosion and Corrosion Control of Ship Structures

Existing knowledge base on corrosion and corrosion control practices followed in the shipping industry has been documented. Various types of corrosion prevalent in the ship structures, major corrosion susceptible areas and corrosion prevention techniques being used have been summarised. The inspection regime by various classification societies and regulatory framework with respect to marine corrosion being in force are also briefly mentioned.

b) Corrosion Zone Approach to Corrosion Condition Assessment and Monitoring

The ship structure as a whole is too large and complex to be considered as a single component for the purpose of corrosion inspection and condition assessment. A system approach of dividing ship structure into corrosion zones and subzones based on their exposure conditions has been proposed. Six corrosion zones have been identified for a typical ocean going vessel, which are “submerged zone”, “splash zone”, “atmospheric zone”, “ballast tank zone”, “cargo hold zone” and “other internal structures zone”. The importance of protecting each zone towards overall corrosion condition is presented.

c) Development of the Concept of Corrosion Condition Index (C.C.I)

A new concept of C.C.I as a measure of corrosion condition of steel ship structures during ship's operation phase has been formulated. It is a comprehensive assessment considering the type/ extent of corrosion on the entire hull as well as its impact on safety of ships and environment. A set of six criteria which are important for assessing the corrosion condition and an Assessment Level (A.L) for each criterion developed. Also a method to account for the severity of corrosion was proposed through a concept of Corrosion Weightage (C.W). The C.C.I represents a qualitative assessment of corrosion condition for a given subzone/ zone/ whole structure with the help of ALs and CWs.

The suggested corrosion assessment method can facilitate targeted corrosion inspections at critical areas. The C.C.I may be used along with other shipping indices to promote safer ships and can also be used by shippers and ship owners as their own promotional instrument. It will be useful for all stakeholders and can be an indicator for the prospective buyers looking for second hand ships. It is being proposed as a voluntary system, helping to improve the environmental as well as operational performance of shipping industry.

d) Rating of Corrosion Condition of Steel Ship's Structure based on C.C.I

A rating system based on the C.C.I with recommendations for future operation of ships has been made. The C.C.I rating scale varies from 100 to 50 and below, indicating a corresponding deterioration in the corrosion condition. Higher the C.C.I, higher will be the integrity of corrosion protection systems. Based on the C.C.I, the ship's structure can be rated as "As built condition", "Excellent", "Very good", "Good", "Satisfactory" and "Poor". The effort of the ship owner shall be to maintain a minimum C.C.I of 70 (corresponding to very good condition) throughout ship's operational life. Ships with C.C.I value below 50 (corresponding to poor condition) must undergo immediate remedial actions/ extensive repairs to improve the C.C.I prior to further operations.

e) Implementation of Knowledge Based Decision Support System for Corrosion Condition Assessment and Monitoring of Steel Ship Structures

A user friendly Knowledge Based Decision Support System (KBDSS) has been developed as a web based application by integrating the domain Knowledge Base (KB) and the concept of C.C.I. knowledge base has been organized into 15 KB groups and used as expert knowledge for the DSS. A modular design approach was selected for DSS, comprising of four functional modules viz. "Project setup module" "Corrosion observation module", "CCI calculation module" and "Administrative functions Module". User friendly interface for selection of answers to the pre-defined questions with reference pictures has been provided for obtaining consistent results. The domain knowledge base is not static and provision has been made for regular updation. The application can be used for managing large database and effectively monitoring of corrosion condition of ships. The data base can also provide valuable inputs for the future ship designs.

f) Identification of Key Stakeholders in the Shipping Industry

The shipping industry is very complex with the presence of a large number of players and fourteen key stakeholders have been identified whose action may directly or indirectly influence aspects of corrosion. A realisation that corrosion is a major factor and cumulative involvement of all stakeholders will go a long way in minimising the cost attributed to corrosion of ship structures. Accordingly, the necessity of a new corrosion control culture and possible contribution of each stakeholder has been brought out.

g) Development of a Corrosion Control Model (C.C.M)

A concept of C.C.M for effective monitoring of corrosion control activities during ship's life cycle has been proposed in the form of a flow chart. The aspects of corrosion management, best practices in the life cycle phases, corrosion assessment using C.C.I methodology, application of KBDSS, training and corrosion audit have been integrated in the model. The model illustrates the flow of information between ship's life cycle phases and stipulates a framework for interaction among various stakeholders.

h) Recommendation for Best Practices During Ship's Life Cycle Stages for Corrosion Control

Major corrosion considerations to be adopted in the design, production as well as operation stages have been compiled. A set of 11 important design deliverables have been identified that may directly influence the future corrosion condition of the ship structures. These documents are proposed to be compiled as a "**Corrosion Control Booklet**" by the design team and certified mandatorily by corrosion experts. General guidelines for corrosion control by shipyards during production stage have been made. Further, best practices for corrosion monitoring during the operational phase have been recommended incorporating the concept of C.C.I developed as part of the research.

5.3 Limitations and Scope of Future Work

a) Corrosion of only structural steel components of a ship has been considered in the present work. However, the scope of C.C.I can be further extended to include corrosion of all equipment, piping, valves etc. onboard ships.

b) The scope of C.C.I can be further improved to take input from various corrosion sensors so that real time corrosion assessment and monitoring is possible and the KB-DSS can be accordingly modified.

c) Quantitative models for all parameters influencing corrosion of ship structures are not available at present. Development of such models which can be applied to ships of varying type, age, size etc. can be considered as a scope for further study.

d) The Corrosion Control Model (C.C.M) presented as part of the research can be further modified by documenting an exhaustive corrosion management programme for ships including strategy, policy and guidelines, corrosion audit, training curriculum etc. for the benefit of the shipping industry.

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