Middlesex University Research Repository:

an open access repository of

Middlesex University research

http://eprints.mdx.ac.uk

Kloudas, Stamatios G., 2012. Reliability of the piping systems of a modern submarine. Available from Middlesex University's Research Repository.

Copyright:

Middlesex University Research Repository makes the University's research available electronically.

Copyright and moral rights to this thesis/research project are retained by the author and/or other copyright owners. The work is supplied on the understanding that any use for commercial gain is strictly forbidden. A copy may be downloaded for personal, non-commercial, research or study without prior permission and without charge. Any use of the thesis/research project for private study or research must be properly acknowledged with reference to the work's full bibliographic details.

This thesis/research project may not be reproduced in any format or medium, or extensive quotations taken from it, or its content changed in any way, without first obtaining permission in writing from the copyright holder(s).

If you believe that any material held in the repository infringes copyright law, please contact the Repository Team at Middlesex University via the following email address:

eprints@mdx.ac.uk

The item will be removed from the repository while any claim is being investigated.

Middlesex
University
London

"RELIABILITY OF THE PIPING SYSTEMS OF A MODERN SUBMARINE"

A project submitted to Middlesex University in partial fulfillment of the requirements for the degree of DOCTOR of Professional Studies

STAMATIOS G. KLOUDAS

B.Sc Naval Engineering Hellenic Naval Academy (1967)
M.Sc Naval Architecture and Marine Engineering MIT (1978)
M.Sc Mechanical Engineering MIT (1978)
Advanced Professional Degree of Ocean Engineer MIT (1978)

Institute for Work Based Learning Middlesex University, London

OCTOBER 2012

TABLE OF CONTENTS

SUMMARY

CHAPTER ONE : INTRODUCTION

CHAPTER TWO : TERMS OF REFERENCES / OBJECTIVES AND REVIEW OF RELEVANT LITERATURE AND OTHER INFORMATION

CHAPTER THREE : METHODOLOGY OF THE PROJECT

CHAPTER TEN : ANALYSIS OF OUTCOMES AND POTENTIAL SUGGESTIONS

SUMMARY

RELIABILITY OF THE PIPING SYSTEMS OF A MODERN SUBMARINE

by

Stamatios G. Kloudas

It is a common knowledge that safety is of importance for every sailing vessel but becomes unquestionable for a submarine for obvious reasons. Prerequisite for the safety of a submarine is that all its structural parts “working” on the diving pressure when the submarine is underneath, can withstand successfully the exercised enormous pressure and consequently the developed high stresses imposed on them. Piping of the submarine is one major part under diving pressure. The best way to assure these prerequisites, is to inspect piping frequently and using destructive and non destructive methods to get the necessary level of assurance or confirmation of safety. This is not always an easy task particularly in a submarine where the space is very “crowdy” and the major part of the piping is practically

inaccessible. Therefore, a more rational way has to be established, a way that would allow verifying the condition of inaccessible parts by making certain that piping retains the necessary reliability that allows the submarine to be further safely used.

This is the scope of the present study namely by using a “rational approach” to assess accurately and objectively the reliability of the piping. Having achieved that, one can proceed further and determine the probability of a certain deterioration for a specific time frame and/or the time frame in which you anticipate the deterioration of a piping to exceed a predetermined “threshold”.

Last but not least, in the development of this study the accuracy of the mathematical models used have been compared to actual measurements (data) taken in a later stage. Very much to our satisfaction all these comparisons turned to be very close in a surprisingly matching way. This coincidence holds promise for further and more extensive applicability of the models used.

ACKNOWLEDGEMENTS

This thesis is dedicated to my family for providing me with the necessary moral support and tolerating the stolen from them hours.

I would also like to express my appreciation to my advisor Dr. Stavros Drossos for his continuous encouragement and guidance.

Further appreciation to my thesis consultant Professor Dr. Th. Boufounos, for all his invaluable remarks.

My thanks go to all these people who have contributed during the years directly or indirectly, more or less significantly, to transform an originally vague concept to a workable rationalized method.

Last but not least my thanks to the Ladies who undertook the difficult task to transform my terrible manuscript to a readable document.

CHAPTER ONE

1. INTRODUCTION

During the Long Term Maintenance (LTM), of the four “Glafkos” type submarines in a Naval Base, extensive works were done on the sea piping networks of the submarines in addition to the standard LTM works. These works consisted of the inspection, repair and/or replacement of parts of the piping networks according to specific criteria, referred to in detail in the following study. During the works it was ascertained that the inspection of all sea piping networks was impossible without extensive dismantling works. This would extensively prolongate the time required for the completion of the LTM and consequently decrease submarine availability. Therefore efforts were focused towards the inspection of as much as possible of the accessible network parts within the determined time frame of the LTM. According to acquired experience, inspected parts of piping are growing, in both number and length, from the first to the fourth LTM. For the “Triton” submarine, which was the last having a LTM, it can be said that practically all possibilities concerning inspection, repair and replacement of the sea piping networks were exhausted. The aforesaid piping networks are schematically shown in the attached as APPENDIX FOUR network drawing.

During the second LTM of the “Glafkos” type submarine in the Naval Base, a strong similarity of condition of the inspected piping networks was observed to that of the previous one, as anticipated. Therefore the inspection of the piping of one submarine can lead to a general conclusion for the condition of the piping of all other submarines of the same type, operating more or less under the same circumstances.

The crucial question needed to be answered is whether the assessment of the condition of the **inspected** network piping parts can lead to reliable conclusions for the condition of remaining, but **non inspected** parts.

CHAPTER TWO

TERMS OF REFERENCES / OBJECTIVES AND REVIEW OF RELEVANT LITERATURE AND OTHER INFORMATION

2.1 PREFACE

When we faced the situation to “assess the condition of non-accessible parts of piping based on the condition of similar but accessible parts” our first thought was to examine how Navies or institutions of other countries have coped with similar issues. To our surprise and despite our systematic efforts nothing of substance was found!! The explanation for this practically non existence of similar cases in the literature was attributed either that different approaches have been taken in similar situations or that the sensitive data used prevent people who might have dealt with similar issues to publicize their efforts and works.

This lack of relevant “material” in the literature obliged us to start our own basic research which turned to be a very interesting exercise.

By definition research is the human activity that provides reliable ways to find out and deepen our understanding on a variety of phenomena in a planned and systematic way.

In this part of the research portfolio will be included:

a. Literature searches
b. Notes on books and articles
c. Relevant reports
d. Answers to activities
e. Glossary (preliminary)

having always in mind the main objectives of the project which can be summarized as follows:

“Finding ways that will provide the necessary assurance for the reliability of the piping network of the submarine that cannot be physically inspected.”

Without going into details, we can now state that when a submarine dives, her structural parts are under pressure that exceeds thirty (30) times the atmospheric one (depending of course on the depth).

This very high pressure creates enormous forces that have to be coped successfully. Even one “weak” point is enough to create a detrimental collapse like a domino effect to the whole ship. It is therefore imperative to exclude even the slightest probability that such a “weak spot” cannot be found, or even better cannot be foreseen.

2.2 LITERATURE SEARCHES

Submarines have been used more than one hundred years almost the very same way they are used today and there is no doubt that today’s technological achievements in shipbuilding are the derivatives of the “old primitive” submarines. Of course, huge changes have occurred meanwhile, like changes in technology, in human behaviour towards nation’s sovereignty, relations between countries and the requirements from a submarine’s mission. To be more specific, the first diving vessel for military purposes was built 156 years ago and submarines have been a traditional part of world’s Navies for more than a century. Even in a time when the worldwide political situation gives a general impression of détente, unobtrusive vigilance the protection of a country’s own territory still remain the prime concern of a sovereign state. But during such periods, the will to provide the financial means to guarantee the defence capabilities and safeguard national security is at its lowest. When every dime in the defence budget gets turned over twice, the defence concept has to be based on ships and equipment with the lowest building, operating and running costs but at the same time, these must achieve and maintain the highest standard of operational readiness, flexibility and SAFETY. This technical goal is very high and can be achieved in close cooperation between the operators, the industry and the scientists partners.

As we have already stated, the specific object of this project are German built submarines. This implies that part of the literature refers to this type of submarines specifically, but of course there is relevant literature more generic. Part of the literature is in English and part of it in German. Another important fact is that as we are dealing with naval vessels, secrecy is involved. For example, the maximum diving depth of a submarine is not publicly disclosed. A big effort has to be paid to “circumvent” this situation by respecting “secrecy” on one hand and on the other to retain the necessary “clarity” and “transparency” as much as possible. Anyway, confidentiality does NOT have an impact on the research outcomes or on the level of quality of this work.

In this aspect, classified information or extracts will not be explicitly stated in details.

2.3 AN UPDATED REVIEW OF LITERATURE ON RELIABILITY – SAFETY – MAINTENANCE – COST OPTIMIZATION – CORROSION MECHANISM RELATED TO DIFFERENT OTHER DOMAINS

In several occasions are explained in this study the reasons why there is no specific literature on the subject “Reliability of piping network of Submarines”. When the whole study was completed and before present it officially, was decided to examine how other relative engineering domains are coping with similar requirements. In this aspect the following scientific documents were examined belonging mainly to the thematic areas of Maintenance Modelling and Optimization with references to Reliability, Safety, Corrosion and Risk of systems, pipings and others in oil industry, offshore platforms, nuclear installations and power production.

They are mentioned again with the order they have been used (No Harvard reference). The editors are: a. TAYLOR & FRANCIS Group LONDON year 2010 ISBN 978-0-415-60427-7 & 55509-8 b. SCHUELLER & KAFKA ROTTERDAM year 1999 ISBN 9058091090

1. The use of maintenance optimization models – An empirical study from the Norwegian oil and gas industry by J.I. Selvik, R. Flange, T. Aven

   Maintenance optimization is the development of mathematical models aimed at finding the appropriate time for maintenance by balancing cost and benefit.

2. Application of a Reliability Centered Maintenance model by V. Zille, C. Bérengues, A. Grall

   The application of a global framework to assess the performances of complex maintenance policies on a study case of a nuclear power plant. The modelling approach of a system maintained by Reliability Centered Maintenance based strategies are applied.

3. Multicriteria Analysis of the consequences established by the RCM (Reliability Centered Maintenance) methodology by M.H. Alencar and A.T. de Almeido

   The rise of a global competition and the growth of automation in manufacturing have required maintenance managers to pay special attention to reliability and availability. A multicriteria decision model provides a better assessment of the consequences of failures.

4. A new maintenance management model expressed in Unified Modeling Language (UML) by M.A. Lopez Campas, J.F. Gomez Fernandez et all.

   It deals with the process of designing and modelling a new maintenance management model aligned to the quality management standard ISO 9001:2008 and expressed using UML.

5. Employing Key Performance Indicators (KPIs) for improving processes within maintenance by O. Meland.

   Another management model based on Terry Wireman' s approach that "To manage you must have controls, to have controls you must have measurements, to have measurements you must have information, to have information you must have data”.

6. Interest of a global optimization tool for reliability models adjustment and systems optimization by A. Gabarbaye, J. Faure and R. Laulheret.

   A global optimization tool is used for the adjustment of complex probabilistic model from feedback operational data.

7. On line condition-based maintenance for time dependent deteriorating systems by M. Fouladirad and A. Grall.

   Examines a system beginning to deteriorate with a slow deterioration rate and at an unknown time the system’ s deterioration rate changes as a time dependent function. The objective is to choose a maintenance system with minimum maintenance cost.

8. The effective iterative algorithm to solve a maintenance optimization problem of a highly reliable system by R. Bris.

   Is examined how systems can be made as reliable as possible under certain constrains imposed. Reliability optimization is accomplished through preventive and corrective maintenance. Measures of system performance are reliability, availability, meantime to failure. For the systems redundancy is in parallel examined.

9. Optimal Routing, Design and Maintenance of main pipelines considering Internal Corrosion by E. Marcoulaki, A. Tsoutsias and I. Papazoglou.

   The work builds upon research on the optimal pipeline routing and design in order to avoid corrosion phenomena at the early stages of pipeline design. Criteria used are amongst others the initial investment and maintenance costs.

10. Multistate model for loss of Containment owing to corrosion by I. Papazoglou and A. Aneziris.

    A multistate markov model is presented for modelling the physical phenomenon of loss of containment in ammonia storage tanks owing to corrosion. It takes into consideration inspection, maintenance and repair of the tank.

2.4 MAIN RESEARCH QUESTIONS OR OBJECTIVES

The questions that have to be answered in our research project are numerous, difficult and of diversified nature. Furthermore, the questions and their relevant answers are not standing alone but they are very much interrelated. The main research questions or more accurately the research questions / objectives can be summarized as follows:

a. Identify the parts of piping systems of the submarine that in the given budget and time constraints cannot be inspected in a reliable way assuring their structural adequacy.
b. Try to find more rational way(s) than the simple assessment by using reliability's principles can achieve.
c. If a mathematical model is used for simulation of the non inspectable parts, make sure that the model represents or at least is very close to the actual condition of those parts.
d. To proceed further, the solution of the mathematical model has to be found either with analytical or at least with numerical methods.
e. The accuracy of the mathematical model to the actual working conditions and performance of the non inspectable parts has to be verified.

f. An outcome of major interest should be the calculation of reliability of the non inspectable parts. A simple answer (yes, it can be further used, or no, has to be replaced immediately) cannot be considered as an acceptable research outcome. Last, but not least, we have to convince beyond any logical doubt all parties involved (Authorities in the Navy, the submarines community, individuals, researchers, etc.) about the applicability, validity and correctness of our outcomes. Prerequisite for that is first to convince ourselves!

It seems rather easy to identify the objectives (and I prefer this term instead of questions to be answered) of the research, but I don’t anticipate their implementation equally smooth. Apart from that I wonder if, for any reason, one of the objectives cannot be met in a satisfactory way, how this can have an impact for further proceeding. Lastly the sequence to meet the objectives has to be properly managed.

A last notice: Due to the engineering nature of the project, we don’t anticipate to be faced with any conflicting issues raised by the literature, although minor discrepancies in the theory and consequently in the calculations cannot be excluded. If for example, we calculate the necessary thickness of a piping using the theory of shells, we can end with different results by calculating the same variable using the theory of solid body. Furthermore, we have different outcomes depending on the type of function used as e.g. time to failure.

CHAPTER THREE

METHODOLOGY OF THE PROJECT

3.1 PREFACE

Research is a planned and systematic activity which provides reliable ways of finding out and deepening our knowledge. The type of research we are concerned with is described as work based i.e. it has relevance, usually by direct application to work, and hence it is often referred as research and development (R&D). Our project is a typical example of such a work that focus on improving current practice and/or seeking a tangible outcome in terms of how we can assess the condition (and consequently the use) of non accessible parts of piping of a submarine.

Methodology describes and justifies the choice of research approach and data collection techniques. Obviously the research approaches to be used in any research project are very much related to certain factors amongst them the crucial ones are:

a. The nature of the research

b. The objectives of the project

c. The Sources of information available

d. The experience of the researcher
e. The position/involvement of the researcher

Furthermore, for work based projects the following categories of research approaches seem to be the most appropriate as well as the ones more accepted by the scientific community:

a. Case study
b. Experiments
c. Survey
d. Action research
e. Ethnography
f. Other soft systems

We are of the opinion that very rarely just one research approach is purely needed in a project as in most of the cases rather more than one are necessary, not of course all of them to the same extent. In our case, our main research approach will be SURVEY in conjunction with EXPERIMENT and CASE STUDIES as the development of the research project shows us to be appropriate and necessary. The combination of these approaches, we believe, has as result:

a. One approach to act supplementary to the others
b. To enable us achieving our objectives by forming a model susceptible to reliable results.

3.2 WHY THESE METHODS

The rationale behind this preference is a logical consequence of the nature of the research project, its available data, its objectives and its “environment” in general.

It is common knowledge that by survey most of us understand something like public opinion i.e. associated with the idea of asking groups of people questions. Of course in a broader sense, subjects being questioned by the researcher can in fact be objects, materials rather than people as it will be in our project.

The main reason of using the SURVEY approach in our case comes out of the necessity and simultaneous ability to gather and assess data from a broad range of representative samples of the “population” of interest.

To be more specific:

SURVEY APPROACH will allow us first to assess then estimate and finally calculate the structural behaviour of a big representative sample of piping that are accessible (and/or can be accessible) and based on the outcome of calculations to elaborate further on the probability to sustain the hydrostatic pressure, under given conditions, for a certain period of time. The final conclusion will be the calculation of their constructual reliability namely if these piping have to be replaced and when.

As defined, experimentation can be in the form of a simulation. Quasi-experiments are used in work based learning research projects mostly in the sense to change one variable in a naturally occurring situation in order to assess the consequences (effects).

Obviously for the accessible piping all aforementioned procedures are easier implemented compared to the non accessible piping. But in both cases the use of a quasi-experiment method is necessary. By this quasi-experiment method we will simulate the actual conditions of operation of a certain piping in a "model" that corresponds to the actual conditions “as close as possible”. The model has the enormous advantage that the unknown parameters of its operation can be mathematically calculated and consequently the unknown parameters of the actual physical phenomenon can be found as well.

The other two research approaches will be used in conjunction with the main one.

The advantage of the quasi-experiment research method is that it allows the creation of an artificial situation namely a model. Modelling with diversification of subjects, variables, dependent and independent allows the assessment of the results through quantifiable and systematic ways.

Case study is in general very well suited to the resources and environment of a work based research like ours, as it allows the researcher to focus on so many examples of the investigation as we wish and we deem appropriate.

In conclusion we can state that our work is a prototype examination of an existing situation for which the objective is to define and calculate all its operating and forming parameters in such a way that will enable us to seek and assess the ultimate reliability of the whole structure.

3.3 WHY OTHER METHODS ARE NOT USED

In the beginning we considered all theoretically possible research approaches which were discarded for the following reasons each:

a. Action research

Not applicable. Relies on “good will” of a group of people.

b. Soft systems Methodology

Not applicable at all in engineering problems.

c. Ethnography

Not applicable. It is more suitable when the researcher can become a participant observer of a group being studied. It refers mostly to social behaviour of ethnology group.

3.4 DATA COLLECTION TECHNIQUES

As far as data collection techniques are concerned the most applicable one in our research project seems to be "reviewing and analyzing documents / literature and undertaking observations". The analysis of data will constitute the basis of our research as it is obvious from the nature of our project. Without data availability and data analysis the project cannot be implemented. One very basic parameter in data collecting is the accuracy of them. The correlation between data collecting and project research objectives is very high. Specifically referring to previous Chapter Two and mainly in paragraph 2.4 (main research questions and objectives) we can hardly find even one of the objectives which is not related to reviewing, analyzing documents, literature and undertaking observations. As it turned out, data collected have been in very good conformity with the model used. The other two data collection techniques (conducting interviews and designing and administrative questions) can be used supplementary and will be used if need arises and to the necessary extent each.

3.5 PURPOSES OF THE STUDY

1. The purposes of the present study are:
    a. Evaluation of the inspection results of the sea water piping networks during the LTM of “Glafkos” type submarines.
    b. In depth analysis of the corrosion procedure mechanism of the piping and the formulation of applicable measures for its restriction.
    c. Selection of rational criteria for the assessment of the condition of the piping networks and consequently for the necessity of their replacement and/or repair.
    d. Correlation of the reliability theory and actual data from the on site piping inspection enabling the estimation of it’s mean lifetime or of the probability for a piping network to be out of operation after a specific time frame (i.e 6 or 12 years).
2. From the aforementioned purposes of the study, the following are expected:
    a. The determination of objective criteria leading to the decision for the necessity of inspection of the complete sea network piping and for the frequency of such an inspection.

   b. The necessity to take corrective measures of major extend (i.e. replacement of network materials) or measures of minor importance (improvement of maintenance, installation of zinc, etc).

3. Decision concerning the inspection of all networks piping of the submarine will result in extensive works that would greatly exceed the available time frame for the LTM, as mentioned above.

3.6 PROJECT FEASIBILITY, REPORT AND PRODUCT

The action plan of our research – project can be summarized in titles as follows:

a. Identification of non easily inspectable parts of the piping of submarine hereafter to be called (NISP).
b. Examine and quantify the necessary efforts to have the (NISP) inspectable.
c. Examine how similar problems in different environments and circumstances may have been examined.
d. Modelling of (NISP) in as such as possible accurate way reassembling the actual conditions of operation.

e. Validate the accuracy of the model either comparatively and/or directly.
f. Find the appropriate solution(s) for the model used, either strictly mathematically or numerically.
g. The least acceptable outcome is the quantification of reliability of (NISP).
h. Provided that (g) above is done, further step forward was to determine the existing margin of reliability, positive or negative and to express it in a convenient tangible way, e.g. time to elapse till certain deterioration is reached.
i. Verification of modelling, calculations, simulations and hypotheses involved, in the real scale and conditions of the submarine.
j. Extrapolation of the methodology used to similar cases but of non inspectable conditions.

Ethical issues of this work have been examined from the very beginning. Ethical problems usually arise when there is a conflict of interests as for example between the demands of confidentiality or anonymity and those of legality or professionalism. In our research this was used for negotiation of a route between a.m. interests. Our objective was beneficial to the whole community of the Navy. Of course, when you deal with issues having a sensitive impact on matters of National Defence one must be careful up to which extent can proceed without creating, implicitly or explicitly on purpose or by mistake undesirable repercussions. Existing guidelines in the Navy turned to be a very helpful tool.

In this aspect were no ethical considerations for the project because existing rules and regulations for appropriate use of data, as confidentiality is concerned, were not be violated. The most important parameter prevailing was secrecy of the operational characteristics of submarines. Therefore, we had to deal with everything very cautiously but without sacrificing the clarity and the transparency of our methods, procedures and outcome.

As we succeeded to implement promptly all aforementioned steps and objectives then we can claim that our endeavours and expectations have been fulfilled.

The Project’s Report / Product is a process that enable us the calculation of Reliability of (NISP) of the piping of a submarine as a matter of its working conditions, time elapsed, materials used and existing geometry. The knowledge of reliability allow us the proper use of the submarine i.e. without any operational restrictions, the extent of them, if any, the necessary measures for their remedy, how to plan and when the general overhaul aiming in two objectives namely:

a. Saving effort, money and time.
b. Much more important avoid to put at risk the physical integrity of the submarine and consequently human lives.

3.7 STRENGTH AND POTENTIAL WEAKNESS OF THE PROJECT

As major potential weakness of our research project we can identify, the fact that we felt as pioneers. We felt very much obliged to open paths, roads, highways. We were running the danger to pay an enormous effort and not be in a position to conclude tangible outcomes proportional to this effort. This ambiguity was present all over until the very end.

On the other hand, as strengths of our research proposal can be seen the extreme importance it has for a big organization like the Hellenic Navy, the availability of resources for data gathering (and not only!) the involvement of real professionals and dedicated people and above all determination to believe in success and not considering at all failure as an option!

3.8 MODEL OF THE PROJECT TO BE USED

1. In order to accomplish the purposes of this study, the implemented procedures are as follows:
    a. Full description of the cooling system and its subsystems.
    b. The corrosion mechanism of the piping and the factors related to this mechanism are examined.
    c. Quantitative calculations based on the reliability theory are implemented and the normal distribution of the deterioration coefficient or time to failure is selected.
    d. Basic calculations of the strength concepts of the piping are provided and the condition of piping of “Glafkos” submarine is assessed, according to these strength calculation concepts.

e. The piping expected mean time life is calculated.

f. The probability that the useful time life of a piping to be less than an arbitrary defined period, is calculated using the following clarifications:

   (1) Two periods were examined (i.e. 6 and 12 years) corresponding to the 1st and 2nd LTM of the submarine.

   (2) Two criteria were used for the definition of the useful time life:

      (a) The criterion for acceptance or replacement of the network during the LTM is the deterioration of the examined piping, not to exceed the 15% of the initial pipe thickness.

      (b) The nullification of the excess redundant thickness of the piping, defined as the difference of the initially manufactured thickness from the thickness required for its strength resistance in the test pressure. As it will be shown this second criterion is more rational than the first one.

        (3) Two cases of failures were examined i.e.

            (a) General corrosion

            (b) Local corrosion

    g. Following the examination of the above sub cases, a real comparison between the theoretical models and the actual ones is implemented. As it will be shown the correlation of the theoretical and actual values was very high.

2. The proposed model is functionally linked to the data model and furthermore to the research question by a simple comparison of the measurements taken on data collected and the relevant predictions of the model.

3. Finally, the conclusions of the study are summarized and specific proposals are presented, bearing in mind on one hand the consequences of the proposals on the cost and availability and on the other hand the required sense of safety for the personnel, which is very sensitive for the case of a submarine.

CHAPTER FOUR

DESCRIPTION OF THE SEA COOLING PIPING NETWORK

The sea cooling piping network's purpose is to provide a cooling medium to the ship's systems. In the "Glafkos" type submarine the cooling system provides cooling to four diesel engines, to one electrical propulsion motor, air pumps, air conditioning system, exhaust piping, thrust bearings and to the propeller shaft. The drawings of the cooling system of "Glafkos" submarine are shown in figures 1 (see APPENDIX FOUR) and 2. The full description of the system is given in [Ref. 6]. The entire system can be divided into subsystems that are branched around the main cooling piping network. The aforementioned subsystems are shown in the following figures.

4.1 MAIN COOLING PIPING NETWORK

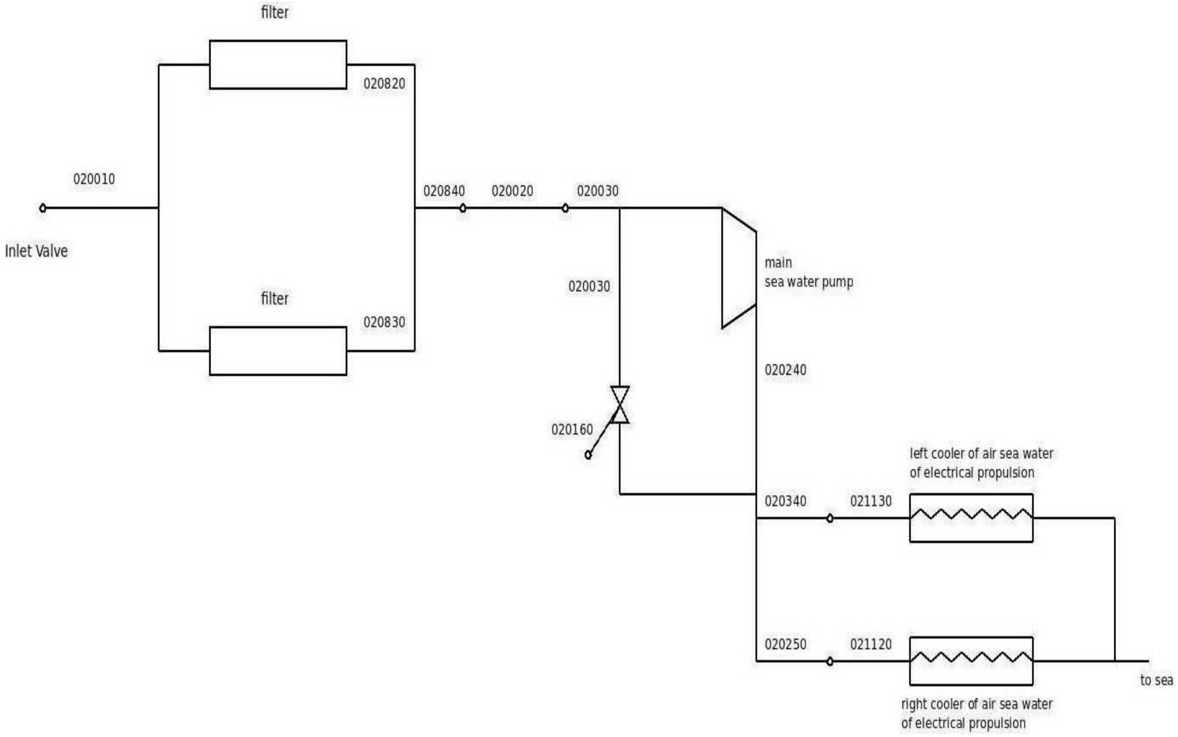


FIGURE 2

MAIN COOLING PIPING NETWORK

pipe number	Nominal diameter (mm)	External diameter (mm)	Nominal thickness (mm)	material	Test pressure (atm)
020010	250	267	8	ST 35.8 II gal	40
020020	200	219.1	7.1	‘’	40
020030	125	133	4.5	‘’	40
020160	125	133	4.5	‘’	40
020170	80	88.9	3.6	‘’	40
020180	80	88.9	3.6	‘’	40
020190	125	133	4.5	‘’	40
020220	125	133	4.5	‘’	40
020240	125	133	4.5	‘’	40
020250	80	88.9	3.6	‘’	40
020340	80	88.9	3.6	‘’	40
020820	200	219.1	7.1	‘’	40
020830	200	219.1	7.1	‘’	40
020840	250	267	8	‘’	40
021110	80	88.9	3.2	1.4571	40
021120	80	88.9	3.2	1.4571	40
021130	80	88.9	3.2	1.4571	40
021140	80	88.9	3.2	1.4571	40

Table 1

4.2 COOLING PIPING NETWORK OF DIESEL ENGINES

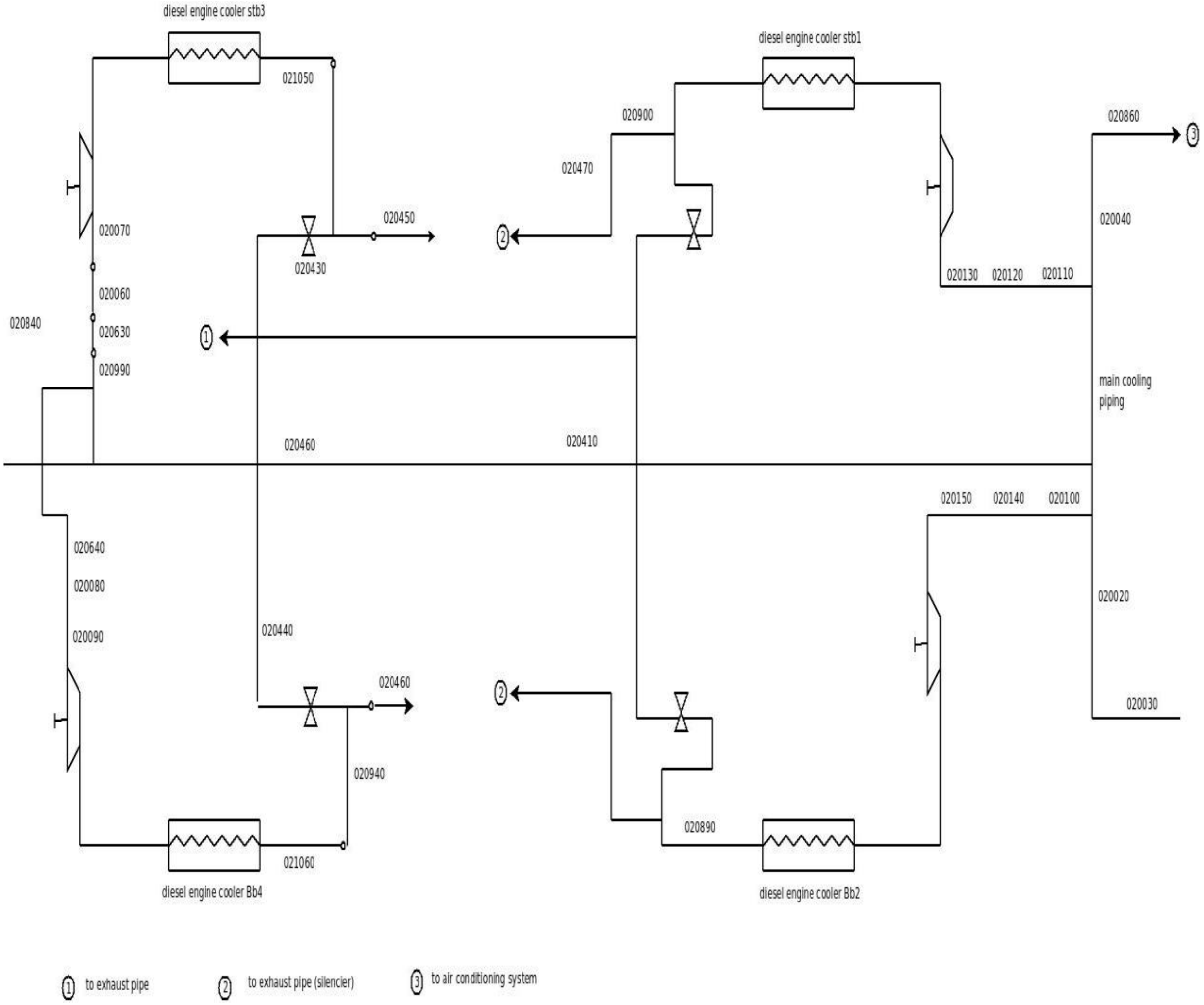


FIGURE 3

COOLING PIPING NETWORK OF THE DIESEL ENGINES

pipe number	Nominal diameter (mm)	External diameter (mm)	Nominal thickness (mm)	material	Test pressure (atm)
020040	125	133	4.5	ST 35.8 gal	40
020060	80	88.9	3.2	ST 35.8 gal	6
020070	70	76	2.5	CuNi 10Fe	6
020080	80	88.9	3.2	ST 35.8 gal	6
020090	70	76	2.5	CuNi 10Fe	6
020100	100	108	4	ST 35.8 gal	40
020110	100	108	4	ST 35.8 gal	40
020120	80	88.9	3.2	ST 35.8 gal	6
020130	70	76	2.5	CuNi 10Fe	6
020140	80	88.9	3.2	ST 35.8 gal	6
020150	70	76	2.5	CuNi 10Fe	6
020390	80	88.9	3.2	ST 35.8 gal	6
020400	80	88.9	3.2	ST 35.8 gal	6
020410	125	133	4	ST 35.8 gal	6
020420	150	159	4.5	ST 35.8 gal	6
020430	80	88.9	3.2	ST 35.8 gal	6
020440	80	88.9	3.2	ST 35.8 gal	6
020450	70	76.1	2.9	ST 35.8 gal	6
020460	70	76.1	2.9	ST 35.8 gal	6
020470	70	76.1	2.9	ST 35.8 gal	6
020480	70	76.1	2.9	ST 35.8 gal	6
020630	100	108	4	ST 35.8 gal	40
020640	100	108	4	ST 35.8 gal	40
020860	70	76.1	3.2	ST 35.8 gal	40
020890	70	76.1	2.9	1.4571	6
020900	70	76.1	2.9	1.4571	6
020940	70	76.1	2.9	ST 35.8 gal	6
020950	70	76.1	2.9	ST 35.8 gal	6
020990	125	133	4.5	ST 35.8 gal	40
021050	70	76.1	2.9	1.4571	6
021060	70	76.1	2.9	1.4571	6

Table 2

4.3 COOLING PIPING NETWORK OF DIESEL ENGINES EXHAUST

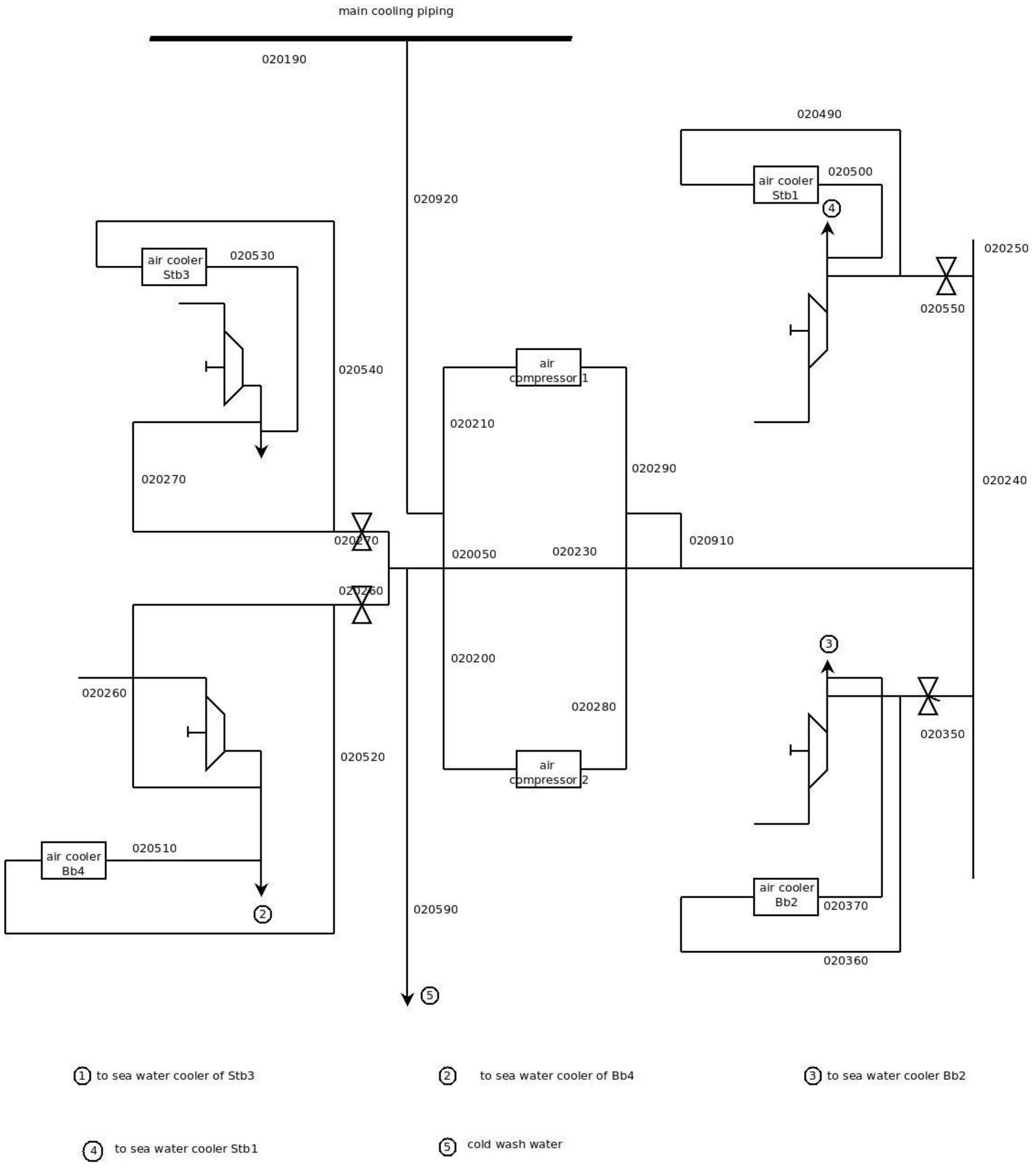


FIGURE 4

COOLING PIPING NETWORK OF DIESEL ENGINES EXHAUST

pipe number	Nominal diameter (mm)	External diameter (mm)	Nominal thickness (mm)	material	Test pressure (atm)
020390	80	88.9	3.2	ST 35.8 gal	6
020400	80	88.9	3.2	ST 35.8 gal	6
020410	125	133	4	ST 35.8 gal	6
020420	150	159	4.5	ST 35.8 gal	6
020430	80	88.9	3.2	ST 35.8 gal	6
020440	80	88.9	3.2	ST 35.8 gal	6
020450	70	76.1	2.9	ST 35.8 gal	6
020460	70	76.1	2.9	ST 35.8 gal	6
020470	70	76.1	2.9	ST 35.8 gal	6
020480	70	76.1	2.9	ST 35.8 gal	6
020650	80	88.9	3.2	1.4571	6
020660	80	88.9	3.2	1.4571	6
020670	80	88.9	3.2	ST 35.8 gal	6
020680	80	88.9	3.2	ST 35.8 gal	6
020790	200	219.1	5.9	ST 35.8 gal	6
020880	50	57	2.9	ST 35.8 gal	6
021160	70	76.1	2.9	1.4571	6
021170	70	76.1	2.9	1.4571	6
021180	70	76.1	2.9	1.4571	6
021190	70	76.1	2.9	1.4571	6
050680	50	57	2.9	ST 35.8 gal	6

Table 3

4.4 COOLING PIPING NETWORK OF AIR CONDITIONING SYSTEM

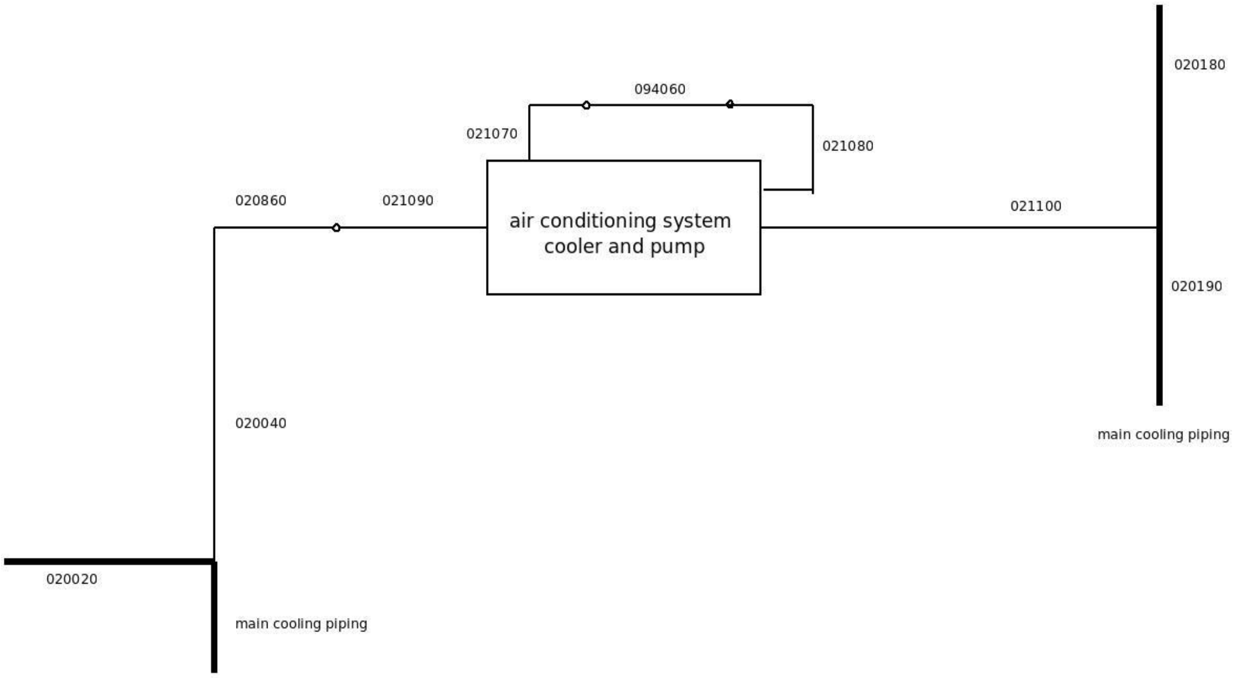


FIGURE 5

COOLING PIPING NETWORK OF AIR CONDITIONING SYSTEM

pipe number	Nominal diameter (mm)	External diameter (mm)	Nominal thickness (mm)	material	Test pressure (atm)
020040	125	133	4.5	ST 35.8 gal	40
020860	70	76.1	3.2	ST 35.8 gal	40
020870	70	76.1	3.2	ST 35.8 gal	40
021070	70	76.1	2.9	1.4571	40
021080	70	76.1	2.9	1.4571	40
021090	70	76.1	2.9	1.4571	40
021100	70	76.1	2.9	1.4571	40
094060	70	76	2.5	ST 42.2 gal	40

Table 4

4.5 COOLING PIPING NETWORK OF AIR PUMPS AND GENERATORS

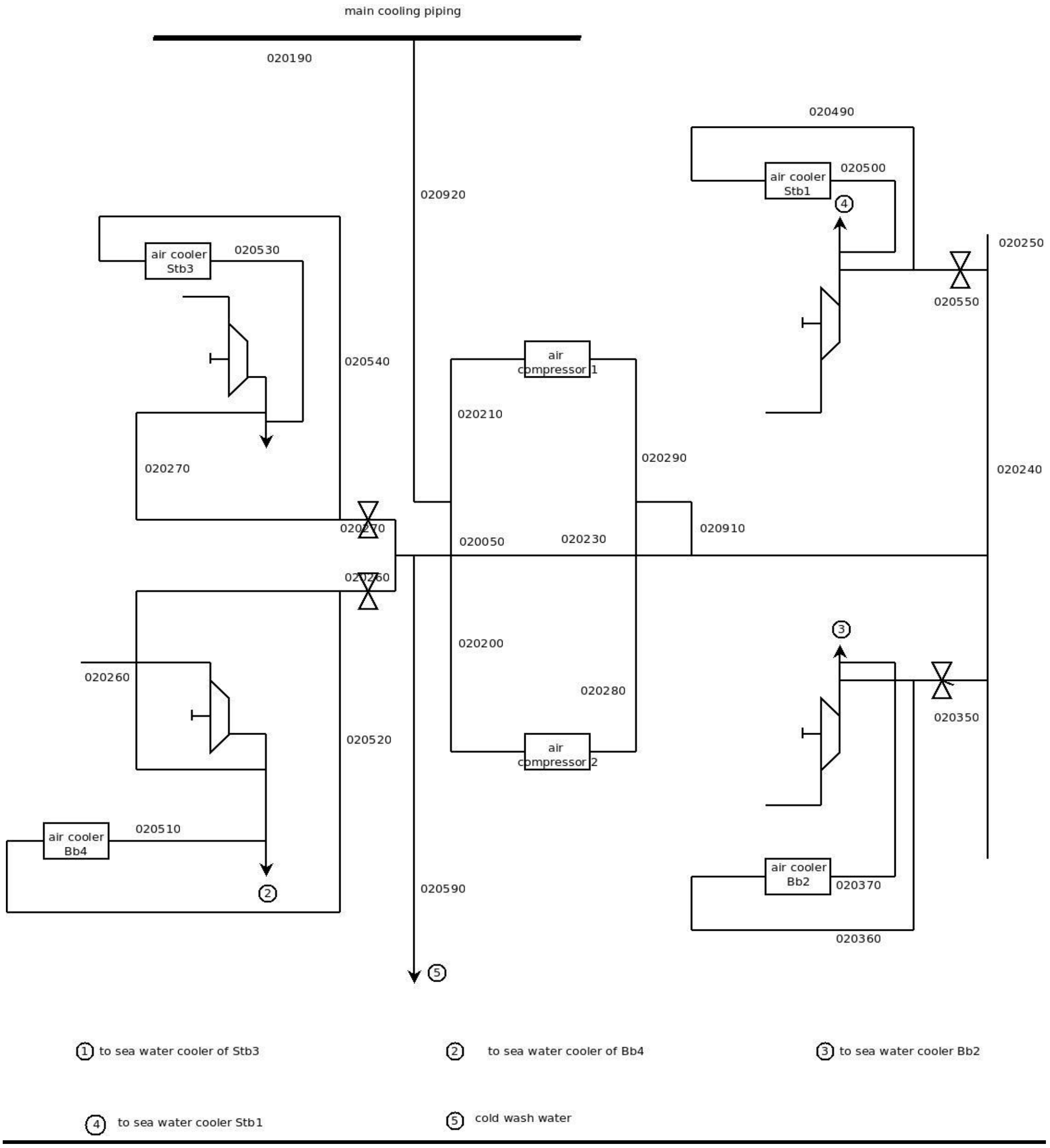


FIGURE 6

COOLING PIPING NETWORK OF

AIR COMPRESSORS AND GENERATORS

pipe number	Nominal diameter (mm)	External diameter (mm)	Nominal thickness (mm)	material	Test pressure (atm)
020050	100	108	4	ST 35.8 gal	40
020200	25	30	2.6	ST 35.8 gal	40
020210	25	30	2.6	ST 35.8 gal	40
020230	125	133	4.5	ST 35.8 gal	40
020260	70	76.1	3.2	ST 35.8 gal	40
020270	70	76.1	3.2	ST 35.8 gal	40
020280	25	30	2.6	ST 35.8 gal	40
020290	25	30	2.6	ST 35.8 gal	40
020350	70	76.1	3.2	ST 35.8 gal	40
020360	50	57	2.9	ST 35.8 gal	6
020370	50	57	2.9	ST 35.8 gal	6
020490	50	57	2.9	ST 35.8 gal	6
020500	50	57	2.9	ST 35.8 gal	6
020510	50	57	2.9	ST 35.8 gal	6
020520	50	57	2.9	ST 35.8 gal	6
020530	50	57	2.9	ST 35.8 gal	6
020540	50	57	2.9	ST 35.8 gal	6
020550	70	76.1	3.2	ST 35.8 gal	40
020590	25	30	2.6	ST 35.8 gal	40
020910	32	38	2.6	ST 35.8 gal	40
020920	32	38	2.6	ST 35.8 gal	40

Table 5

4.6 COOLING PIPING NETWORK OF THRUST BEARING AND PROPELLER SHAFT

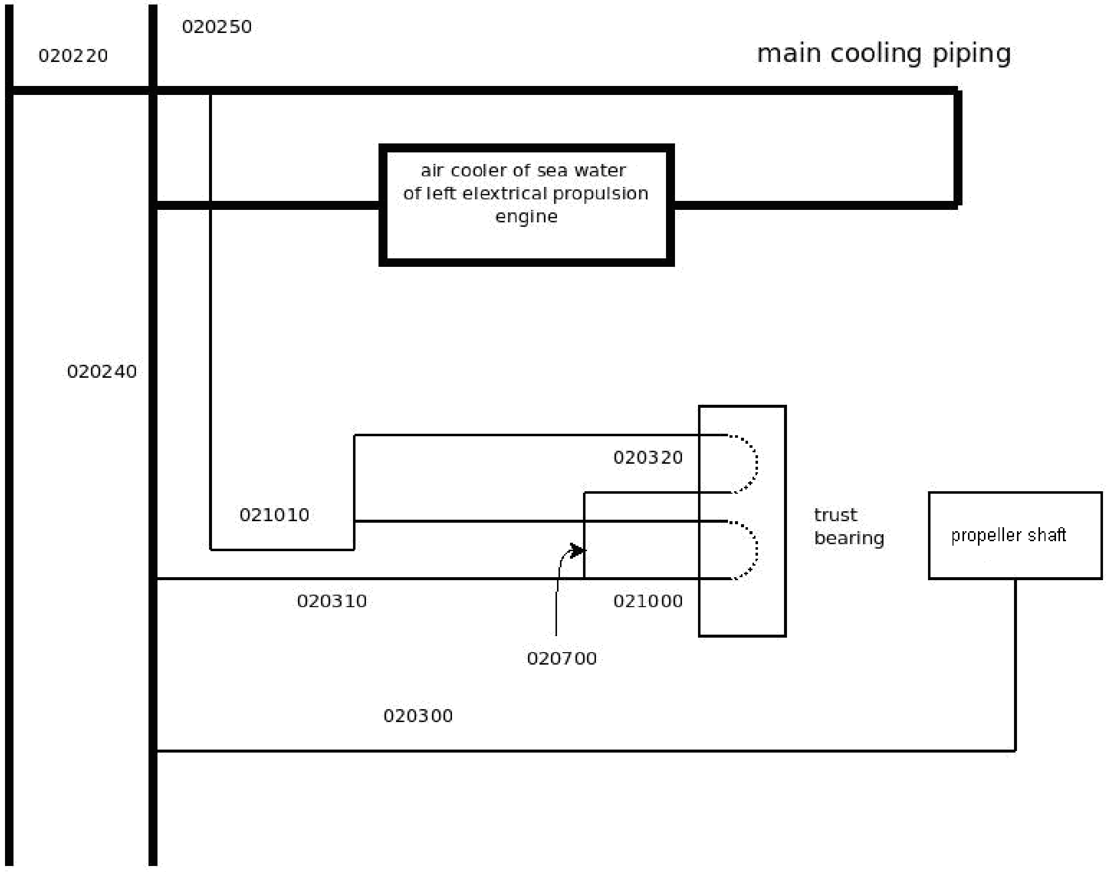


FIGURE 7

COOLING PIPING NETWORK OF THRUST BEARING AND PROPELLER SHAFT COVER

pipe number	Nominal diameter (mm)	External diameter (mm)	Nominal thickness (mm)	material	Test pressure (atm)
020300	25	30	2.6	ST 35.8 gal	40
020310	20	25	2	ST 35.8 gal	40
020320	212	16	2	SBCu F25	40
020330	20	25	2	ST 35.8 gal	40
020700	12	16	2	SBCu F30	40
020810	12	16	2	SBCu F30	40
021000	20	25	2.5	SBCu F30	40
021010	20	25	2.5	SBCu F30	40

Table 6

4.7 PIPING ENDING TO OTHER NETWORKS (bilge, washwater system)

PIPING NETWORK ENDING TO OTHER NETWORKS

piping	number	Nominal diameter (mm)	External diameter (mm)	Nominal thickness (mm)	material	Test pressure (atm)
From and to bilge	010000	125	133	4.5	ST 35.8 gal	40
From bilge	010130	125	133	4.5	ST 35.8 gal	40
Washawater system	010840	50	57	2.9	ST 35.8 gal	6
Bilge (ventil)	020590	25	30	2.6	ST 35.8 gal	40
Bilge (ventil)	020600	40	44.5	2.6	ST 35.8 gal	25
Connection to 010000	020610	40	44.5	2.6	ST 35.8 gal	25
Bilge (ventil)	020620	125	133	4.5	ST 35.8 gal	40
Bilge (ventil)	020690	40	44.5	2.6	ST 35.8 gal	25
Bilge (ventil)	020850	40	44.5	2.6	ST 35.8 gal	25
Bilge (ventil)	020930	70	76.1	2.9	ST 35.8 gal	6
Bilge (ventil)	020960	70	76.1	2.9	ST 35.8 gal	6
Bilge (ventil)	020970	70	76.1	2.9	ST 35.8 gal	6
Pressure water	020980	70	76.1	2.9	ST 35.8 gal	6
for fuel system	050680	50	57	2.9	ST 35.8 gal	6

Table 7

4.8 CONNECTION OF MEASURING INSTRUMENTS

PIPING FOR THE CONNECTION OF MEASURING INSTRUMENTS

pipe	number	Nominal diameter (mm)	External diameter (mm)	Nominal thickness (mm)	material	Test pressure (atm)
Water pump pressure of motor Bb2	020380	6	10	1.5	SB-Cu F 30	6
Water pump pressure of motor stb 1	020560	6	10	1.5	SB-Cu F 30	6
Water pump pressure of motor Bb4	020570	6	10	1.5	SB-Cu F 30	6
Water pump pressure of motor stb 3	020580	6	10	1.5	SB-Cu F 30	6
Pressure after the main air pump	020710	6	10	1.5	SB-Cu F 30	40
Pressure before the main air pump	020720	6	10	1.5	SB-Cu F 30	40
Pressure system motor Bb2	020730	6	10	1.5	SB-Cu F 30	6
Pressure system motor stb1	020740	6	10	1.5	SB-Cu F 30	6
Pressure after air pump 1	020750	6	10	1.5	SB-Cu F 30	40
Pressure after air pump 2	020760	6	10	1.5	SB-Cu F 30	40

pipe	number	Nominal diameter (mm)	External diameter (mm)	Nominal thickness (mm)	material	Test pressure (atm)
Pressure system of motor Bb4	020770	6	10	1.5	SB-Cu F 30	6
pipe	number	Nominal diameter (mm)	External diameter (mm)	Nominal thickness (mm)	material	Test pressure (atm)
Pressure system of motor Stb3	020780	6	10	1.5	SB-Cu F 30	6
Water pump pressure of motor Bb4 (engine room)	021020	6	10	1.5	SB-Cu F 30	6
Water pump pressure of motor Stb3 (engine room)	021030	6	10	1.5	SB-Cu F 30	6
Water pump pressure of motor Bb2 (engine room)	021040	6	10	1.5	SB-Cu F 30	6
Water pump pressure of motor Stb1 (engine room)	021050	6	10	1.5	SB-Cu F 30	6

Table 8

4.9 SUMMARIZED OVERVIEW OF THE PIPE NETWORK AND OTHER SIGNIFICANT DATA

The piping of the sea cooling networks of the submarines “Glafkos” consisted mostly of zinc coated steel of type St 35.8 II as well as of steel of type 1.4571 (chrome-nickel coated steel). For the suction piping of the 4 pumps of the diesel engines, CuNi 10Fe material was used. For the connection of the measuring instruments and pressure gauges, piping SB Cu F30 with 6mm nominal diameter was used exclusively. The same material was used for the piping in the area of the thrust bearing. The standard piping of the sea water network of the “Glafkos” type submarines are as explicitly shown in the following table 9:

SUMMARY TABLE OF SEA WATER NETWORK PIPING

Nominal diameter (mm)	External diameter (mm)	Nominal thickness (mm)	Material	Test pressure (atm)	Number of pipes
250	267	8	St 35.8 II gal	40	020010,020840
200	219.1	7.1	St 35.8 II gal	40	020020, 020820, 020830
	219.1	5.9	St 35.8 II gal	6	020790
150	159	4.5	St 35.8 II gal	6	020420
125	133	4.5	St 35.8 II gal	40	
	133	4	St 35.8 II gal	60	020030, 020160, 020190, 020220, 020240, 020040, 020990, 020230, 010000, 010130, 020620
100	108	4	St 35.8 II gal	40	020100, 020110, 020630, 020640, 020050
80	88.9	3.6	St 35.8 II gal	40	020170, 020180, 020250, 020340
	88.9	3.2	St 35.8 II gal	6	020060, 020080, 020120, 020140, 020390, 020400, 020430, 020440, 020670, 020680
	88.9	3.2	1.4571	40	021110, 021120, 012130, 012140
	88.9	3.2	1.4571	6	020650, 020660
70	76.1	3.2	St 35.8 II gal	40	020860, 020870, 020260, 020270, 020350, 20550
	76.1	2.9	St 35.8 II gal	6	020450, 020460, 020470, 020480, 020940, 020950
	76.1	2.5	St 42.2 II gal	40	094060
	76.1	2.9	1.4571	40	021070, 021080, 021090, 021100
	76.1	2.9	1.4571	6	020890, 020900, 021050, 021060, 021160, 021170, 021180, 021190, 020930, 020960, 020970, 020980
	76	2.5	CuNi 10 Fe	6	020070, 020090, 020140, 020130

Nominal diameter (mm)	External diameter (mm)	Nominal thickness (mm)	Material	Test pressure (atm)	Number of pipes
50	57	2.9	St 35.8 II gal	6	050680, 020360, 020370, 020490, 020500, 020510, 020520, 020540, 010840
40	44.5	2.6	St 35.8 II gal	25	020600, 020610, 020690, 020850
32	38	2.6	St 35.8 II gal	40	020910, 20920
25	30	2.6	St 35.8 II gal	40	020200, 020210, 020280, 020290, 020590, 020300
20	25	2	St 35.8 II gal	40	020310, 020330
	25	2.5	SBCu F30	40	021000, 021010
12	16	2	SBCu F25	40	020320, 020700, 020810
6	10	1.5	SBCu F30	6	020380, 020560, 020510, 20580, 020330, 020740, 020770, 020780, 021020, 021030, 021040, 021150
	10	1.5	SBCu F30	40	020710, 020720, 020730, 020760

Table 9

CHAPTER FIVE

CORROSION MECHANISM AND DATA FOR CORROSION PROPAGATION

5.1 DEFINITION

According to the German standard DIN 50900 Part 1, corrosion is defined as the reaction of a metallic material with the environment that results in significant and measurable deterioration of the said material, affecting the operation of an engine component or of an entire system. In the present case the “environment” is the sea water and the “metallic material” is the material of the piping. Apart of explaining the phenomenon, outcomes and data of this chapter are used in the project unless otherwise mentioned.

5.2 FACTORS AFFECTING THE CORROSION PROPAGATION SPEED

Many factors influence the rate of corrosion propagation. The main factor is the content level of salt in the sea water as this content determines its conductivity. The level of salt in the water of Mediterranean Sea is between 37% and 39%. The specific resistance that determines the speed of electromechanical corrosion is inversely proportional to the salt level. According to known data [Ref. 9] the water of Mediterranean Sea has a specific resistance of 25Ωcm at 12-15^{o}C. The fact that the specific resistance falls to 15Ωcm at 30^{o}C proves the importance of sea water temperature in the propagation of the corrosion. Higher corrosion is expected in the piping at the outlet of the heat exchanger rather than the inlet. In view of the fact that within sea ports the sea water, apart from salt, contains cyanogens, ammonia, sulfuric and phosphoric salts, use of this sea water in the cooling piping network is not recommended. The local formation of acids that are caused by the presence of the aforesaid salts results in significant acceleration of the corrosion procedure. On the other hand, these salts form chemical compounds with the metallic material of the piping, resulting in local corrosion. The immediate result of using this polluted water, is referred to as “non-duty corrosion” and can begin in the ship building process at the shipyard and emerge later during operations, resulting in the failure of some piping under internal pressure. For vessels travelling in polluted sea areas, occasional washing of the piping with fresh water had satisfactory results. The presence of oxygen also influences the corrosion propagation. The oxidization creates a coating, which in conjunction to the piping material can be porous, and hence does not prevent further corrosion or can create a very dense and continuous form, preventing further corrosion of the metallic coating. The combination of a humid environment, air and a simultaneous formation of porous oxidized coating are usually met at the sea water piping, where the conditions for corrosion are characterized as ideal [Ref. 9]. The presence of air (bubbles) is favored by the turbulent flow, and as a result of this, but also due to additional deterioration created by shocks due to the change of the fluid (water – air- water), avoidance of turbulent flow is highly desirable. Apart from avoidance of abrupt diameter changes and curvatures, the specific literature [Ref. 12 & 16] strongly recommends keeping a maximum speed of steady flow depending on the material of the piping. In the following table (10), various commonly used materials and the maximum relevant recommended flow speed are shown:

MAXIMUM VELOCITY FOR VARIOUS PIPING MATERIALS

Material	Maximum allowable flows speed (m/sec)
Steel (zinc coated)	1.5
CrNi 18 9	2 - 4.3
Cr Ni Mo 18 12	2 - 4.3
Cu Ni 10 Fe	2 - 4.3
Cu NI 30 Fe	2.5 – 3.5
Ni Cu 30 Fe	6
Cu Sn 8	2 - 4.3
Cu Al 5	2 – 2.5
Cu Al 5	1.8 – 2.5

Table 10

The German Ship Registry [Ref. 20] recommends keeping a maximum speed, which for nominal diameters less than 40mm is about 30% less from that figured in table 10, in order to avoid the pollution of sea water micro-organisms, which are greater for the piping of a smaller nominal diameter. In addition, for all piping of the sea water network, keeping a minimum speed of 1m/sec is recommended in order to avoid sea water micro organics precipitation. If this is not possible, use of piping from alloys of copper, cadmium, tin, zinc and lead is recommended. These alloys have inherent natural antipollution properties. Steel piping has an extrusion layer as a result of the way they are manufactured. This layer, if not removed, has catastrophic repercussions, as it blocks the formation of a natural antioxidant protective layer and is peeled out later during the use of the piping, whilst leaving the metal unprotected and simultaneously blocking the small diameter piping and filters. Due to this reason the German Ship registry recommends the use of non zinc plated steel only for nominal diameters over 40mm. Eberius [Ref. 9] claims that zinc plating of steel piping does not have as an immediate result the delay of corrosion of the basic material, as this layer cracks in a relatively short period and does not offer appropriate protection to the metallic coating. The existence of such cracks was ascertained in the inspected piping network of the submarines during the repairs in the Naval Base. Despite that the desired decrease of the corrosion propagation speed is achieved indirectly, since the zinc layer has antipollution properties and requires the perfect cleaning of the metallic coating and therefore the removal of the catastrophic drawing layer as well. However the benefits of the zinc plating are relatively small, and for this reason they must not be overestimated, as referred characteristically in [Ref. 9]. The choice of a better quality piping material is more effective. The data referred by La Que and Tuthill [Ref. 15] which are summarized in table 11, are very useful for the choice of the piping material, having as criterion the maximum allowable flow speed. The behavior of the relevant material at the maximum continuous speed is assessed.

BEHAVIOUR OF VARIOUS PIPING MATERIALS AT THE MAXIMUM VELOCITY

Material	Maximum speed (m/sec)	Comments
Steel	1.5	Minimum resistance
Zinc plated steel	1.5	Minimum resistance
Cast iron	1.5	Minimum resistance
Copper	0.9	Very Sensitive in the formation of turbulent flow
CuZN 28 Sn	1.5	Lower sensitivity in the formation of turbulent flow
CuZN 30 Al	2.4	Good resistance
CuZn 39Sn	3.6	Good resistance
Brass NiZn	1.8	moderate resistance
CuNi 10 Fe	3.6	Satisfactory resistance
CuNi 30 Fe	>4.5	Satisfactory resistance
NiCu 30 Fe	>9	Perfect resistance
X3-Cr Ni 19 10	>9	Perfect resistance
X5- Cr Ni Mo 18 10	>9	Perfect resistance
X Cr Ni Mo 29 20 2	>9	Perfect resistance

Table 11

For the maintenance of the sea water piping, the method of anodes (cathoding protection) is not recommended, since the protective current results in the delay of corrosion at the part of the piping which is opposite from the anode only. For long piping this measure is considered inadequate, but also the installation of zinc rings in the connections is inefficient. A key point to avoid corrosion is the minimization of turbulent flow.

This is explicitly mentioned in all relevant studies and is considered as a unanimous scientific agreement on that.

Furthermore, indicative protective measures to avoid corrosion are:

a. Choice of better material
b. Maintaining the maximum allowable flow speed
c. Avoidance of pollution from micro-organisms by either using zinc plating or using proper materials
d. Frequent washing of the piping with fresh water and/or anticorrosive chemical detergent
e. Installation of filters minimizing pollution

f. Immediate replacement of any parts that have been partially blocked in order to avoid high velocity and local turbulence.
g. Maintaining a minimum required flow speed in order to delay pollution from micro-organisms.
h. Avoidance of abrupt changes in flow direction and piping cross sections.
i. Choice of appropriate cross sections
j. Assurance that the water temperature remains as low as possible. This being particularly important for the output of the heat exchangers.

In [Ref. 9] is noted that use of fresh water for an operational period in a brand new piping or in a piping under cleaning and zinc plating is effective. A measure taken in the last generation of German submarines is the installation of anodes and special anticorrosion devices at the suction piping part, just after the main pump.

5.3 COMMON TYPES OF CORROSION IN THE SEA WATER PIPING

Following a summary of the factors influencing the propagation of the corrosion as well as of the measures that can lead to an effective protection, the different types of corrosion are examined. All the aforementioned are necessary for an accurate reliability prediction of the behavior of the material and consequently of its expected time life.

General corrosion

In such a case almost the entire surface is deteriorated uniformly. The electrochemical process occurs between a large number of anodes and cathodes, such that a uniform deterioration is exhibited. Since no metal is absolutely homogeneous, at an advanced stage of the general corrosion, formation of craters becomes the norm. This type of corrosion is very common in steel piping.

Local corrosion (deposit attack, pitting)

With this type of corrosion, the entire metallic surface can be act as a cathode. The anode, on the contrary, is consisted of small surfaces that deteriorate rapidly, leading to holes being formed on a robust surface. This type of surface, characterized from the pinholes, is exhibited especially in piping from cast iron, steel, stainless steel and aluminum alloys. It is the most dangerous type of corrosion in sea water piping because it is propagated very quickly, whilst cannot be easily detected because the largest part of the corrosion surface seems to be at perfect condition. If extensive surfaces play the role of anodes, then finally the deterioration appears in the form of craters.

Dezincification

A characteristic of this type of corrosion is the dissolution of a chemical element from a chemical compound. This results in a spongy sub layer, which is met mostly at Copper Zinc (CuZn) compound containing more than 15% zinc, where the dissolution of the zinc is possible with even just the presence of sea water. The Copper Zinc (CuZn) compound contains aluminum and nickel, which exhibit dezincification only at higher temperatures, especially in the output or within the heat exchangers. Under such conditions, the dissolution of aluminum and nickel is also possible, cases which are not met in the piping of “Glafkos” submarine.

Impingement Corrosion

In this type of corrosion, the cathodes are surfaces existing in an environment with plenty of air, instead of surfaces existing in areas where ventilation is restricted from the anodes. This type of corrosion is met in all types of metals not protected by a uniform and resistant antioxidant layer. The propagation conditions of this type of corrosion are ideal for piping systems that are inoperational and contain quantities of sea water. The surfaces covered by water are not in direct contact with the air so they act as the anode. On the contrary the surfaces not covered by water form the cathode. An extensive time of piping out of operation will cause damage to the longest parts of the piping. Corrosion of the sea water inlet piping is caused by the same mechanism, where the air bubbles under unfavourable conditions lead to the formation of the aforesaid dipole (anode-cathode), having as a final outcome the quick deterioration of the anode.

Pitting

Apart from the abovementioned corrosion mechanisms, the corrosion of the sea piping through cracks and cavities is well known. Reasons being similar to these of the impingement corrosion: as the air does not reach the bottom of the crack, an anode is formed in this area, while the metal surface plays the role of the cathode. The corrosion frequently initiates from existing small cracks and is extended quickly. Within the formed anode craters in stainless steel and aluminum piping, frequently many iron, aluminum or nickel oxides are formed, from which hydrochloric acid is generated through further hydrolysis. Complete corrosion is very fast under these conditions.

Specific literature also refers to other types of corrosions, which are not frequently exhibited in sea water piping and thus don't consist a further objective of the present study. As the cooling piping of the "Glafkos" type submarine is consisted almost entirely from steel St 35.8 zinc coated, corrosion problems arising from contact of metals with different electrodynamic behavior are not exhibited, therefore the contact corrosion is not included in the study.

5.4 QUANTITATIVE DATA AND PARAMETERS FOR THE CORROSION PROPAGATION SPEED

In order to calculate the reliability and expected time life of the sea water cooling piping, the acquisition of relevant data and use of parameters is necessary. These data and parameters are related to the propagation of a type of corrosion and measurement of the time life of the piping from various materials. The acquired data are summarized in tables 12 and 13. The main source of data are publications of classification societies and of scientific papers including but not restricted to [Ref. 19, 20 &23]

AVERAGE LIFETIME OF PIPING

TYPE OF PIPING USE AND OR MATERIAL	AVERAGE LIFETIME OF THE PIPING (IN YEARS)	NUMBER OF INSPECTED VESSELS
Central cooling piping from zinc plated steel	9.2	54
Piping from Copper	8	5
Pewter plated copper	12.3	92
CuNi 10 Fe and CuNi 30Fe	20	Navy vessels
Fire extinguishing piping from steel	6.9	181
Copper (different use)	17	10
Heating spiral piping from steel	5.1	199
Cooler piping from CuZnAl	16	173
CuNi 30 Fe	18.5	77
CuNi 30 Fe	20	Navy vessels
General use from zinc plated steel	5.7	179
Copper (different use)	5.9	105
CuNi 10 Fe	>20	8
CuNi 30 Fe	>20	50

Table 12

DETERIORATION RATE FOR VARIOUS PIPING MATERIALS

MATERIAL	GENERAL DETERIORATION (MM/YEAR)	LOCAL CORROSION (MM/YEAR)	COMMENTS
Cast iron	0.08 – 0.2	0.3 – 1.5	The general deterioration is proportional to the flow speed
Cast iron containing 20 – 30% Ni	0.05 – 0.08	Minimum corrosion only in non operational condition	
Steel	In clean water 0.06-0.16 In unclean water 0.07 -0.23	0.55 – 0.75	The general deterioration falls from approximately 0.11 mm in 0,05 mm after 5-10 years of operation
Chrome nickel plated steels without lead	minimum	Sensitive (main type: cavitation formation)	Remark: formation of hydrochloric acid via hydrolysis is possible
Chrome nickel plated steels with 2.5-3% lead	minimum	Less sensitive from chrome nickel plated steels without lead	The resistance increases by increasing the percentage of chrome and lead
Copper	In clean water: 0.008-0.06 In unclean water: 0.003	0.1-0.3 High sensitive in the presence of ammonia salts	
Brass (CuZn)	In clean water: 0.06-0.08 In unclean water: 0.1-0.15	0.15-0.3 Main type: dezincification	Unsuitable material due to sponge phenomenon
Brass (CuSn)	In clean water: 0.003-0.035 In unclean water: 0.001	0.13-0.25	The local corrosion is favored from the pollution of the piping

MATERIAL	GENERAL DETERIORATION (MM/YEAR)	LOCAL CORROSION (MM/YEAR)	COMMENTS
Cu-Al compounds	In clean water: 0.003-0.008 In unclean water: 0.003-0.005	0.08-0.25	The local corrosion is favored from the pollution of the piping
Cu-Ni compounds	In clean water: 0.008-0.035 In unclean water: 0.002-0.01	0.03-0.20	The local corrosion is favored from high speed turbulent flow and the pollution of the piping
Nickel (99.2-99.8%)	In clean water: 0.005-0.025 In unclean water: 0.001-0.005	0.05 -0.5	High sensitivity with the formation of sulfuric compounds
Ni-Cu compounds (ie NiCu 30Fe)	In clean water: 0.0025-0.005 In unclean water: 0.02-0.05	0.5-1.2	High sensitivity with the formation of sulfuric compounds
Ni-Cr (i.e NiCr 30 Fe)	0.0005-0.004	0.5 - 1.5 for speeds under 3m/sec	With the mixing of lead the deterioration coefficient for all types of corrosion becomes negligible.
Aluminum (99.5-99.9%)	In clean water: 0.001-0.004 In unclean water: 0.002-0.02	0.05	The pinhole of polluted piping is favored.
Al-Mg compounds (ie. Al Mg Si 0.8)	In clean water: 0.035-0.06 In unclean water: 0.002-0.02	0.13 -1.0	The pinhole of polluted piping is favored.

Table 13

Piping from pure titanium (99.8%) exhibit perfect properties in all cases but they are expensive.

DETERIORATION RATE OF PIPING WITH METALLIC COAT

COAT	GENERAL CORROSION (mm/year)	LOCAL CORROSION (mm/year)
Chrome	Generally tears off in leaves shape	Only in cases of crack formation
Cadmium	0.02-0.03	Minimum, good antipollution properties
Lead	0.015-0.03 In non clean water 0.002-0.007	Minimum, good antipollution properties
zinc	Up to 0.015	Local corrosion of pinhole type

Table 14

Coatings, as mentioned above, have antipollution properties, but do not protect the basic material from corrosion.

All aforementioned deterioration coefficients are average values. The relevant operating factors (flow speed, temperature, turbulence, presence of air bubbles) play an important role in the behavior of the piping systems.

All coefficients are applicable provided the behavior of the maximum flow speeds according, to tables 10 and 11, are not exceeded.

CHAPTER SIX

THEORETICAL BACKGROUND FOR THE QUANTITATIVE ESTIMATION OF RELIABILITY

6.1 DEFINITIONS AND MATHEMATICAL FORMULAE

Calculation of the expected time life is reduced to the calculation of the statistical mean time life using the reliability theory.

For a better insight in the analysis, the following definitions are given [Ref. 21]:

UNRELIABILITY Q(t) of a system, at the time frame [0,t] under given environmental and operational conditions, is the probability of occurrence of a significant failure, hindering the operation of the system within the given time frame.

RELIABILITY R(t) of a system, at the time frame [0,t] under given environmental and operational conditions, is the probability of uninterrupted operation within the given time frame.

Unreliability is expressed mathematically as follows:

$$Q(t) = W(T \leq t) \tag{1}$$

Where T is the time of occurrence of a severe error.

Equation (1) means that the unreliability Q(t) is the probability of occurrence of a severe failure in time T within the time frame [0,t]. The mathematical expression of reliability is therefore:

$$R(t) = W(T > t) \tag{2}$$

From the equations (1) and (2) is concluded:

$$Q(t) + R(t) = 1 \tag{3}$$

This means, that a system will either be operational or it won't (binary condition, Bool's mathematical model).

The unreliability function has the properties:

$Q(0) = 0$ and $Q(\infty) = 1$

And similarly the reliability

$R(0) = 1$ and $R(\infty) = 0$

It is assumed that in time zero, the system under consideration is brand new or at least repaired (as good as new). The random variable in this type of analysis is the time life cycle of the system under consideration. Since, time life cycle is defined as the time until the occurrence of a severe failure occurs, symbolized in the international literature as TTF (time to fail) or TBF (time between repeated failures). If many similar systems are under observation, the determination of equal number of TBF's can take place and consequently the calculation of a MTBF (mean time between failures) is possible. This mean value can be formed as arithmetic mean:

$$M\hat{T}BF = \frac{1}{n}\sum_{i=1}^{n} TBF \tag{4}$$

The unreliability Q(t) then can be determined through the probability density function of the random variable t (time to failure) f(t) as follows:

$$Q(t) = \int_0^t f(r)dr \tag{5}$$

Therefore:

$$f(t) = {dQ(t)}\Big/{dt} \tag{6}$$

The equations for the reliability are similar:

$$R(t) = \int_t^{\infty} f(r)dr = 1 - \int_0^t f(r)dr \qquad (7)$$

And

$$f(t) = -dR(t)/dt \qquad (8)$$

The above derivative of the unrealiability function is defined as the PROBABILITY DENSITY FUNCTION OF THE RANDOM VARIABLE (t).

The Mean value (μ) of a random parameter, such as for example the mean time life of a system which is distributed according to density f(t) is given by the following equation:

$$\mu = E(t) = \int_0^{\infty} r \cdot f(r)dr = \int_0^t R(r)dr \qquad (9)$$

This mean value μ is also called EXPECTED LIFETIME .

The standard deviation is defined as:

$$\sigma^2 = D(t) = \int_0^{\infty} (r - \mu)^2 f(r)dr \qquad (10)$$

Where μ is the expected time life.

We define the DETERIORATION COEFFICIENT (or INTENSITY OF FAILURE) λ(t) which plays a primary role in the description of the reliability behavior of a system.

This coefficient provides the number of failures from a theoretical infinite number of similar systems per unit of time.

The following equation applies:

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{dQ(t)/dt}{R(t)} = -\frac{dR(t)/dt}{R(t)} \qquad (11)$$

Lets assume that the number of inspected systems is n_0 while the number of systems that exhibited a failure after a time period t is n_a and the number of system that were fully operational is n. Then the following equation applies:

$$n_0 = n_a + n \qquad (12)$$

The reliability is the limit of $R(t) = \lim_{n_0 \to \infty} \frac{n}{n_0}$

With the quotient n/n_0 where n_0 is a finite number, an approximate expression of the reliability can be found:

$$\hat{R}(t) = \frac{n}{n_0} \qquad (13)$$

A similar expression can be found for the unreliability:

$$\hat{Q}(t) = \frac{n_a}{n_0} \qquad (14)$$

And the deterioration coefficient:

$$\hat{\lambda}(t) = \frac{1}{n}\frac{\Delta n_a}{\Delta t} \qquad (15)$$

Where Δn_a is the number of systems that exhibited a severe failure within the time frame Δt.

6.2 SELECTION OF THE PROPER DISTRIBUTION FUNCTION FOR THE LIFE CYCLE

After summarizing the aforementioned definitions, which are described more analytically in [Ref. 2, 18, 21 & 22], the selection of the proper functions that express the systems reliability behavior is necessary:

The EXPONENTIAL FUNCTION

$$R(t) = e^{-\lambda t} \text{ and } Q(t)=1-e^{-\lambda t} \qquad (16)$$

is characterized by a constant deterioration coefficient.

Indeed the equation (11) indicates:

$$\lambda(t) = \frac{\lambda e^{-\lambda t}}{e^{-\lambda t}} = \lambda = constant \qquad (17)$$

The solution of the integral (9) gives:

$$\mu = \int_{0}^{\infty} R(r)dr = \frac{1}{\lambda} \qquad (18)$$

and the solution of the integral (10) gives:

$$\sigma^2 = D(t) = \frac{1}{\lambda^2} \qquad (19)$$

According to the equation (8):

$$f(t) = \lambda e^{-\lambda t} \qquad (20)$$

It is noted that the value $\mu = {}^{1}\!/\!_{\lambda}$ given by the equation (18) is, according to the definition, the system’s MTBF which can be approximately calculated with the equation (4). The combination of equations (16) and (18) gives:

$$R(\mu) = R(t = \mu = MTBF = 1/\lambda) = e^{-\frac{1}{\lambda}\lambda} = e^{-1} = 0.37 \qquad (21)$$

This outcome indicates that the mean time lifecycle MTBF of a system is achieved from the 37% of the total number of inspected similar systems, with the only condition that the time lifecycle exhibits an exponential distribution. The exponential function implies a deterioration coefficient λ, which is independent of time. This assumption is allowable, and has physical meaning, only when the deteriorations are RANDOM i.e. uneven and uniformly distributed per unit of time.

6.3 THE NORMAL DISTRIBUTION FUNCTION

For the description of the piping network under consideration, the assumption of a constant deterioration coefficient is not accurate. The corrosion is propagated according to specific mechanisms which are described in chapter 5 of the present study. The expectation for the deterioration coefficient is to be initially zero because the piping is inspected by the manufacturer, rising rapidly during the mean time lifecycle and keeping this raised tendency. The normal distribution function indicates exactly this aforementioned behavior. The normal distribution is defined by the equation:

$$Q(t) = \frac{1}{s\sqrt{2\pi}} \int_0^t e^{-(r-T)^2 / 2s^2} dr \qquad (22)$$

Where T is the value around which the density of the normal function is uniformly distributed.

The density of the normal function has the form:

$$f(t) = \frac{1}{s\sqrt{2\pi}} e^{-(t-T)^2/2S^2} \tag{23}$$

The mean time lifecycle is defined according to equation (9):

$$\mu = E(t) = \int_0^\infty t \frac{1}{s\sqrt{2\pi}} e^{-(t-T)^2 / 2S^2} dt \tag{24}$$

The solution of the integral gives:

$$\mu = E(t) = T \tag{25}$$

For the standard deviation, equation (10) applies:

$$\sigma^2 = D(t) = \int_0^\infty (t-\mu)^2 \frac{1}{s\sqrt{2\pi}} e^{-(t-\mu)^2 / 2S^2} dt \tag{26}$$

The equation (11) gives:

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\frac{1}{\sigma\sqrt{2\pi}} e^{-(t-\mu)^2/2\sigma^2}}{1 - \frac{1}{\sigma\sqrt{2\pi}} \int_0^T e^{-(\tau-\mu)^2 / 2\sigma^2} d\tau} \tag{27}$$

Since the numerator and denominator of the fraction have a zero value for large values of t, the following is applied for the limit according to L’ Hospital [Ref. 3] equation:

$$\lim_{t\to\infty}\lambda(t)=\lim_{t\to\infty}\frac{df(t)/dt}{dR(t)/dt}=\lim_{t\to\infty}\frac{t-\mu}{\sigma^2} \qquad (28)$$

The equation (28) shows that the failure rate λ or deterioration coefficient remains high for large values of time t, which means that the limit of λ(t) is the infinity when t goes to infinity.

The following figures show qualitatively the aforesaid expressions for both the exponential and the normal distribution functions.

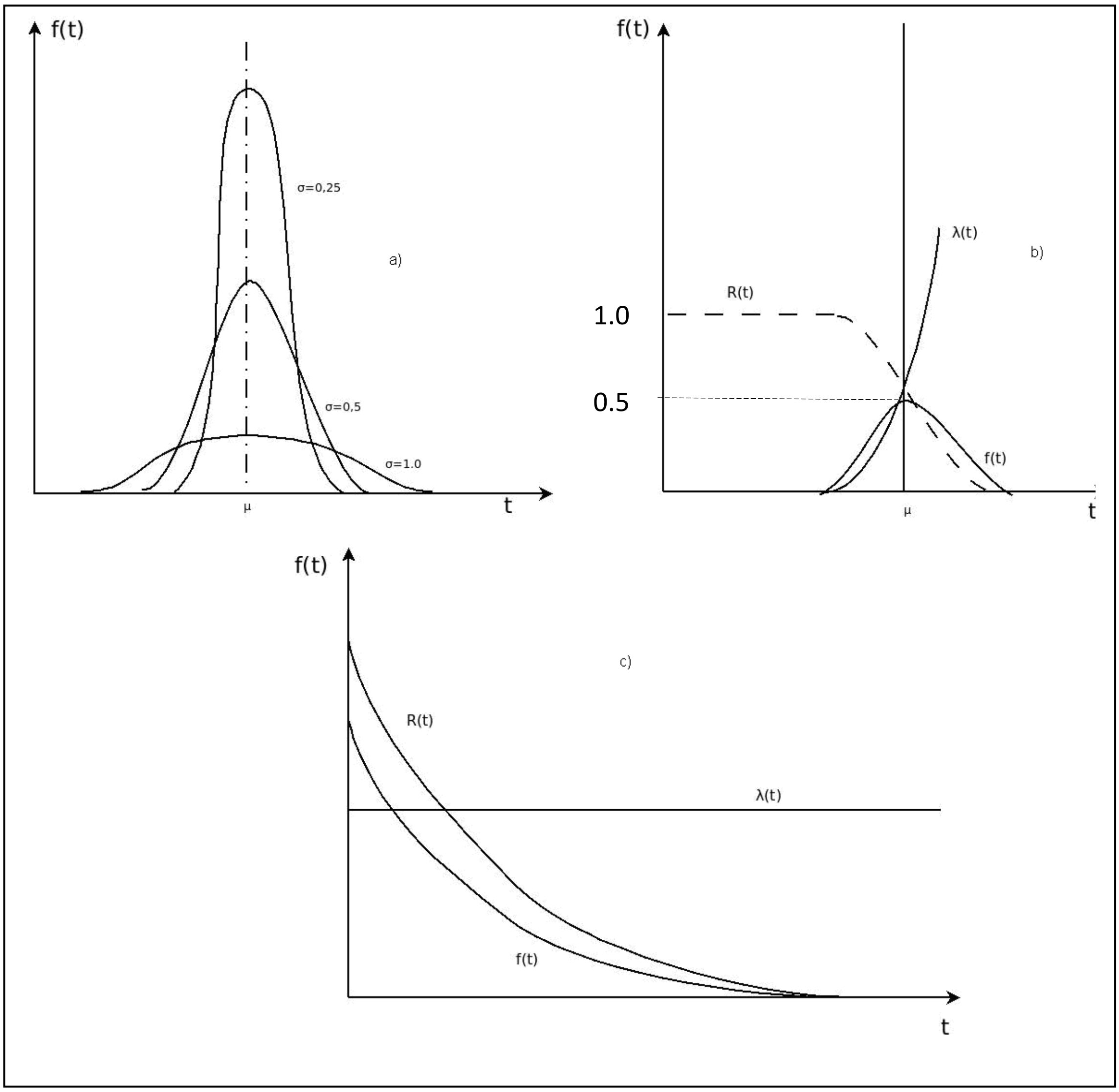


Figure 8

As explained the normal distribution function is deemed as the most suitable function for the description of the piping reliability.

It is worthwhile to mention that other reliability models of two parameters exhibiting the same general behaviour of increasing λ, might show better suitability to the collected data than the normal probability density function used in this study.

Figure (8a) shows the distribution density as a function of time, with the deviation as a parameter for the normal distribution. It is noticed that when deviation is increased, the maximum value of the distribution density is decreased.

Due to the properties of the density distribution, the following equation is valid:

$$\int_{-\infty}^{+\infty} f(r)d\tau = Q(-\infty,+\infty) = 1 \tag{29}$$

This means that the probability for the occurrence of a failure within the time frame $(-\infty,+\infty)$ is 100%. Due to this expression, the areas below the curves of function distributions must be equal to unity for random deviations.

Figure (8b) shows the reliability R(t), the rate of failure or deterioration coefficient λ(t) and the distribution density f(t) as a function of time for a specific deviation and the normal distribution function. The reliability for time equals to zero, has the value 100% according to the definition. It is assumed that the system under inspection for t=0 is as good as new and the probability for the occurrence of a failure is zero. As time of observation increases the reliability function decreases, whilst its form is defined by the deviation. For t=μ the reliability R(t) has the value equal to 0.5. This means that during a reliability experiment an average of 50% of the network piping (systems) under examination will exhibit severe failure within the time frame [0,μ], where μ is the mean life cycle of the said system.

Figure (8c) shows the reliability R(t), the rate of failure or deterioration coefficient λ(t) and the distribution function f(t) for the exponential function. This function is characterized by the constant deterioration coefficient i.e. λ(t)=constant.

As the deviation of the exponential function is depended only on the rate of failure or deterioration coefficient λ which is constant [Ref. 7, 18 & 21], the form of the reliability function is defined according to the choice of only one parameter i.e. the mean lifecycle (1/λ) whilst for the full description of the normal distribution the choice of two parameters is necessary (i.e. of the constant deviation σ and the mean time lifecycle μ).

CHAPTER SEVEN

CALCULATION OF THE PIPING, REQUIRED THICKNESS

The thickness of the piping can be selected according to the following two criteria, namely:

1. The existence of a minimum thickness such as to provide the required strength resistance for the OPERATING pressure. Since the testing of the piping is done on the TESTING pressure which is 50% higher than the operating pressure, the calculation of the required thickness is done for this higher value.
2. Apart from that, the piping must have an additional thickness, permitting safe operation, when after some years of use extensive corrosion has occurred. The minimum required thickness can be calculated according to the theory of the strength of materials. The ADDITIONAL thickness is decreased as time passes due to local or general corrosion. The relation of the ADDITIONAL thickness and the expected mean time life of a type of piping is analyzed in the next chapter 8 of the present study.

In piping under internal pressure, peripheral and radial stresses are formed (σ_t and σ_r). the axial stresses being zero. As shown in the following figure, the higher stresses occurred on the internal surface of the pipe:

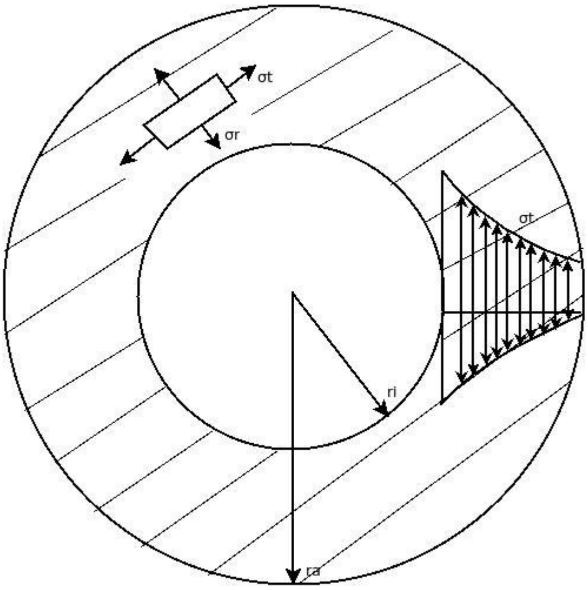


Figure 9

The values of these stresses are given [Ref. 1 & 17] by the following equations:

$$\sigma_t = p_i(n^2+1)/(n^2-1) \tag{30}$$

$$\sigma_r = -p_i \tag{31}$$

Where p_i is the internal pressure and n the ratio of external to internal radii i.e. $n=r_a/r_i$. At standard manufactured piping the external diameter d_a and the thickness s are given. Then the following equation is valid:

$$n = \frac{d_a/2}{\left(d_a/2\right) - s} = \frac{d_a}{d_a - 2s} = \frac{1}{1 - 2\frac{s}{d_a}} \tag{32}$$

The resultant stress σ_{red} is calculated according to Mohr's assumption:

$$\sigma_{red} = \sigma_t - \sigma_r \tag{33}$$

Equation (33) in conjuction with equations (31) and (30) gives:

$$\sigma_{red} = p_i(n^2+1)/(n^2-1) + p_i = p_i\frac{2n^2}{n^2-1} \tag{34}$$

The solution for n gives:

$$n = \sqrt{\frac{\sigma_{red}}{\sigma_{red} - 2p_i}} \text{ with } \sigma_{red} \geq 2p_i \tag{35}$$

If the resultant stress σ_{red} is replaced by the allowable stress σ_{all} for the corresponding materials, then:

$$n = \sqrt{\frac{\sigma_{all}}{\sigma_{all} - 2p_i}} \text{ with } \sigma_{all} \geq 2p_i \tag{36}$$

Due to equations (32) and (36) the following equation is valid:

$$\frac{1}{1-2\frac{f}{da}}=\sqrt{\frac{\sigma_{all}}{\sigma_{all}-2p_i}}\Rightarrow s=\frac{d_a}{2}\left(1-\sqrt{1-2\frac{p_i}{\sigma_{all}}}\right) \qquad (37)$$

In the equation (37) as allowable stress is assumed the value referred in Bach [Ref. 1 & 7].

For the calculation of piping, the following equation is foreseen in the German DIN regulations:

Minimum theoretical thickness $s_0=\frac{d_aP}{200u\,{}^{k}\!/_{f}}$ (38)

Where d_a is the external diameter in mm, s_0 the minimum theoretical thickness of the pipe in mm, P the maximum operating pressure in Kp/cm^2, u is a factor for the welding (in piping without welding this factor equals 1), k is a material constant which corresponds to the accepted yield limit of the material in Kp/mm^2 and *f* is the safety factor which can take the value 1.7 when a material with quality assurance is used, otherwise its value becomes 2.

The required thickness is calculated from the minimum theoretical thickness s_0 according to the following equation.

$$s = s_0 + c_1 + c_2 \tag{39}$$

Where $C_{1,}$ is a safety factor used to compensate for unforeseen reductions in the standardized piping’s thickness. If this unforeseeable reduction is less than eight percent (8%) of the theoretical thickness C_1=0.09 S_o , hence C_2 is a factor used to compensate for the reduction of the thickness due to corrosion in real operational conditions, and is selected arbitrarily based on experience.

CHAPTER EIGHT

CALCULATION OF THE MEAN LIFECYCLE OF THE PIPING OF "GLAFKOS" SUBMARINES

Sea water piping with nominal diameter over 25mm are examined during this study, as during the LTM of the submarines no adequate systematic data was acquired for piping with diameter less than 25mm. During the LTM of the German submarines, it was found that the cooling system of the thrust bearing of the propeller and of the sleeve of the shaft is very sensitive against corrosions, as it is consisted solely of piping with nominal diameter 12 to 25mm. In the past, particular corrosion was observed at the connection piping of the pressure gauges. These data are not considered as adequate for the evaluation of the situation of the piping with nominal diameter less than 25mm. Another reason for not further considering those small diameters is that any damage on them can be isolated without further consequences.

The calculation of the minimum required thickness of the piping can be done either using equation (37) or the German regulation DIN according to equation (38). For the equation (37), [Ref. 1 & 7] of

Bach, gives the following values of allowable stress for the materials used for the piping of “Glafkos” type submarines.

ALLOWABLE STRESSES FOR VARIOUS PIPING MATERIALS

material	Allowable stress according to Bach Reference [1] [kp/mm^2]	yield limit [kp/mm^2]	yield limit 0.2 [kp/mm^2]
St 35	14	24	
St 43	16	26	
Steel 1.4571	18	29	
CuNi10Fe	18		30

TABLE 15

Since the materials of the piping of German submarines are tested and have a quality guarantee, the coefficient *f* of the equation (38) has the value 1.7. The values calculated from the equations (37) and (38) are already on the safe side because the TESTING pressure was considered and not the OPERATING pressure which would be lower. The following table shows the calculated minimum thickness for piping of several nominal diameters.

CALCULATION OF THE REQUIRED POWER THICKNESS

Nominal diameter	External diameter	Testing pressure at	Nominal thickness [mm]	material	Thickness 1 [mm]	Thickness 2 [mm]	Excessive thickness – thickness 2 [mm]
250	267	40	8	St35,8II	3,87	3,78	4,22
200	219,1	40	7,1	‘ ’	3,18	3,10	4,0
	219,1	6	5,9	‘ ’	0,47	0,47	5,43
150	159	6	4,5	‘ ’	0,34	0,34	4,16
125	133	40	4,5	‘ ’	1,93	1,88	2,62
	133	6	4	‘ ’	0,29	0,28	4,72
100	108	40	4	‘ ’	1,57	1,53	2,47
80	88,9	40	3,6	‘ ’	1,29	1,26	2,34
	88,9	6	3,2	‘ ’	0,19	0,19	3,01
	88,9	40	3,2	1.4571	1,00	1,04	2,16
	88,9	6	3,2	1.4571	0,15	0,16	3,04
70	76,1	40	3,2	St35.8II	1,1	1,08	2,12
	76,1	6	2,9	‘ ’	0,16	0,16	2,74
	76,1	40	2,5	St42.2	0,96	0,96	1,50
	76,1	40	2,9	1.4571	0,86	0,86	2,01
	76,1	6	2,9	‘ ’	0,13	0,13	2,77
	76	6	2,5	CuNi10 Fe	0,13	0,13	2,37
50	57	6	2,9	St35.8II	0,12	0,12	2,78
40	44,5	25	2,6	‘ ’	0,12	0,12	2,78
32	38	40	2,6	‘ ’	0,55	0,54	2,06

TABLE 16

Thickness (1) was calculated according to the equation (37) whilst thickness (2) was calculated according to the equation (38). The difference [nominal thickness – thickness (2)] provides the wall thickness that can be deteriorated due to corrosion without any influence on the safe operation of the piping ("excessive" thickness).

The major part of the cooling piping network is consisted of zinc coated steel St35.8II. For zinc plated piping table 14 provides a deterioration coefficient of the coat up to 0,015mm/year in case that local corrosion in the form of "needle" is not observed. After the initial corrosion of the coating, corrosion of the metallic sublayer starts with the deterioration coefficients given in table 13. According to Eberius [Ref. 9] observations, calculation of the mean lifetime for the zinc coating is not always correct. The coating looses very soon its continuity and the corrosion of the metallic sub layer begins, whilst the coating itself has been not yet corroded. The delay of the corrosion due to zinc plating is resulted on the one hand by the antipollution properties of the coating and on the other hand by the good treatment of the basic material necessary for the application of the coating. Due to these reasons, the mean lifetime of the piping is deemed appropriate to be calculated according to the deterioration coefficients of the basic material (table 13), by taking into account the indirect favorable contribution of the zinc coating in the delay of the corrosion speed propagation.

The mean lifetime t_0 (or meantime to failure "μ") of a pipe is given by the equation:

$$t_0(years) = \frac{\delta(mm)}{a(mm/year)} \tag{40}$$

Where δ(mm) is the "excessive" thickness as calculated in table 16 (last column) and the corresponding deterioration coefficient "α" was taken from table 13. From a physical point of view of the parameters, this makes sense. Due to many factors referred in chapter 5 of this study which influence significantly the corrosion speed propagation, a deviation of the actual lifetime from the life time given from equation (9) is expected for each particular pipe.

For the normal function, the mean lifetime was calculated according to the distribution (25). The density of the normal function is given by equation (23). On the contrary, the calculation of reliability and unreliability as given by equation (22) is problematic.

For their calculations, the integration of the density function is required:

According to the definition:

$$\frac{t-t_0}{\sigma}=u \tag{41}$$

And therefore:

$$\frac{du}{dt}=1/\sigma \tag{42}$$

The indefinite integral

$$\mathrm{I}=\frac{1}{\sigma\sqrt{2\pi}}\int e^{-(\tau-t_0)^2/2\sigma^2}d\tau \tag{43}$$

Takes the form:

$$\mathrm{I}=\frac{1}{\sqrt{2\pi}}\int e^{-u^2/2}du \tag{44}$$

This integral does not have an analytical solution. For this reason the function $e^{-u^2/2}$ is replaced by the relevant exponential series:

$$e^x=1+\frac{x}{1!}+\frac{x^2}{2!}+\dots+\frac{x^k}{K!}+\dots$$

And therefore

$$e^{-u^2/2}=1-\frac{u^2}{2}+\frac{u^4}{2^2 2!}-\frac{u^6}{2^3 3!}+\dots$$

The integration gives:

$$\int e^{-u^2/2}du = u-\frac{u^3}{2\cdot 3}+\frac{u^6}{2^2\cdot 5\cdot 2!}-\frac{u^7}{2^3\cdot 7\cdot 3!}+\ldots \qquad (45)$$

Replacing the upper limit of the integration for t=t_0+nσ and the lower for t_0-nσ where t_0 the mean life time, n a random number, σ the deviation finally we get:

$$Q(t)=\frac{1}{\sqrt{2\pi}}\left\{\frac{t-t_0}{\sigma}-\frac{{(t-t_0)/\sigma}^{3}}{2\cdot 3}+\frac{{(t-t_0)/\sigma}^{5}}{2^2\cdot 5\cdot 2!}-\frac{{(t-t_0)/\sigma}^{7}}{2^3\cdot 7\cdot 3!}+\ldots.\right\}_{t_0-n\sigma}^{t_0+n\sigma} \qquad (46)$$

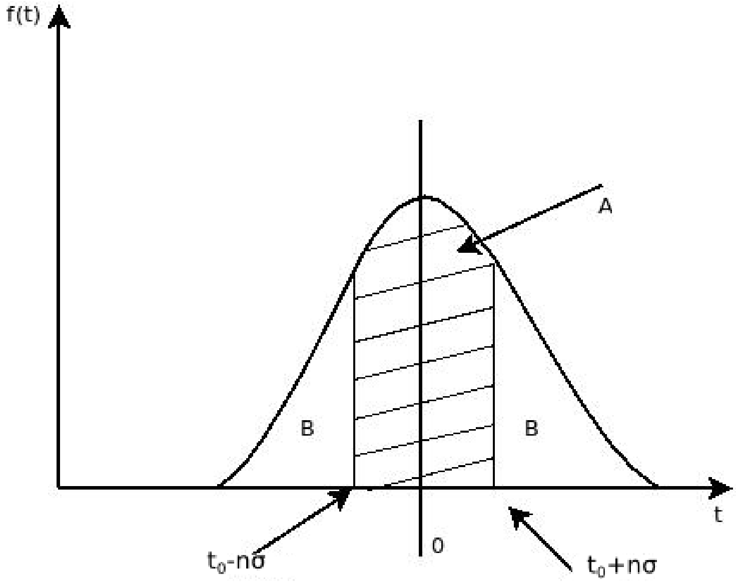
which gives:

$$Q=\frac{2}{\sqrt{2\pi}}\left\{n-\frac{n^3}{3\cdot 2}+\frac{n^5}{5\cdot 2^2\cdot 2!}-\frac{n^7}{7\cdot 2^3\cdot 3!}+\ldots+(-1)^{k+1}\frac{n^{(2k-1)}}{(2k-1)(k-1)!2^{(k-1)}}+\ldots.\right\} \qquad (47)$$

The calculation of the equation (47) is possible when n and k are given, where k are the members of the exponential series, to be taken into consideration. Its solution is facilitated by the remark that its terms can be reductively determined as follows:

$$\begin{gathered}\frac{(-1)^{k+1}n^{(2k-1)}}{(2k-1)(k-1)!2^{k-1}}\underrightarrow{x\left[-\frac{(2k-1)n^2}{}\right]}\frac{n(2k+1)}{(2k+1)k!2^k} \\ \mathit{termk}\xrightarrow{\qquad\qquad\qquad\qquad\qquad}\mathit{term}(k+1)\end{gathered} \qquad (48)$$

For reasons of better understanding, the meaning of the calculated integral is shown in the following figure (area A).



f(t): Probability density function of the variable t (time to failure)

Where: 2B+A=1 and thus B= (1-A)/2

Figure 10

For different values of n, the following values of the integral were calculated:

VALUES OF THE PROBABILITY INTEGRAL

n	I
1	0,6827
2	0,9545
3	0,9973
4	0,9999

Table 17

The series of the equation (47) is convergent. The convergence speed is dependent on the value of n. For this particular problem of piping reliability, up to 20 terms of the exponential series were used to achieve the best possible accuracy. It was shown that normally the calculation of 10 terms is adequate for the determination of the area A. The following case study is referred as example:

Let's assume a mean life time t_0=20 years and a deviation σ=5. The probability for the damage of the piping within the time frame [20-1x5, 20+1x5]=[15-25] is 68,27% and within the time frame [20-2x5,20+2x5]=[10,30] is 95,45%.

From a physical point of view, the value of the deviation (σ) will depend on the homogeneity of the manufacturing material of the piping and on the propagation speed of the corrosion for this particular case. The manufacturing material is tested by the relevant department of the German Ship's Register and can be assumed as homogeneous. This is certified by various certificates submitted by the shipyard to Hellenic Navy. On the contrary the propagation velocity of the corrosion may exhibit large deviations from the mean value for the reasons referred in chapter 5.

For the evaluation of piping reliability of “Glafkos” type submarine, the following procedure is followed:

1) The mean time life is calculated according to the equation (40) for a corrosion velocity corresponding to “needle” or crates formation (case B) and to general corrosion (case A). The influence of the zinc coating on the corrosion velocity is taken into account in the calculation.

2) A mean constant deviation is considered for both cases which is expressed as a percentage of the mean value $\sigma=\gamma t_0$ where γ=empirical value having a range $0.2 < \gamma < 0.3$ and chosen $\gamma=0.25$. *

* The choice of value of γ from empirical and accurate data prevailed to the alternative option namely to select the values of μ (meantime to failure) and “σ” (standard deviation) as they could fit to a model from observed data.

3) The probability of the random time life of a piping to be less than an allowable time frame is calculated. For the inspected piping, this allowable time frame was set at 6 years, while for the non inspected ones the limit was 12 years. The choice was basically arbitrary, but for the inspected piping the time passed from the year of manufacture until the first LTM of the submarine was taken into account and for the non inspected piping the estimated time that will pass until the second LTM of the submarine from the year of manufacturing.

Let assume that t_1 is the minimum time life limit, setting:

$$t_1 = t_0 - n\sigma \tag{49}$$

Where

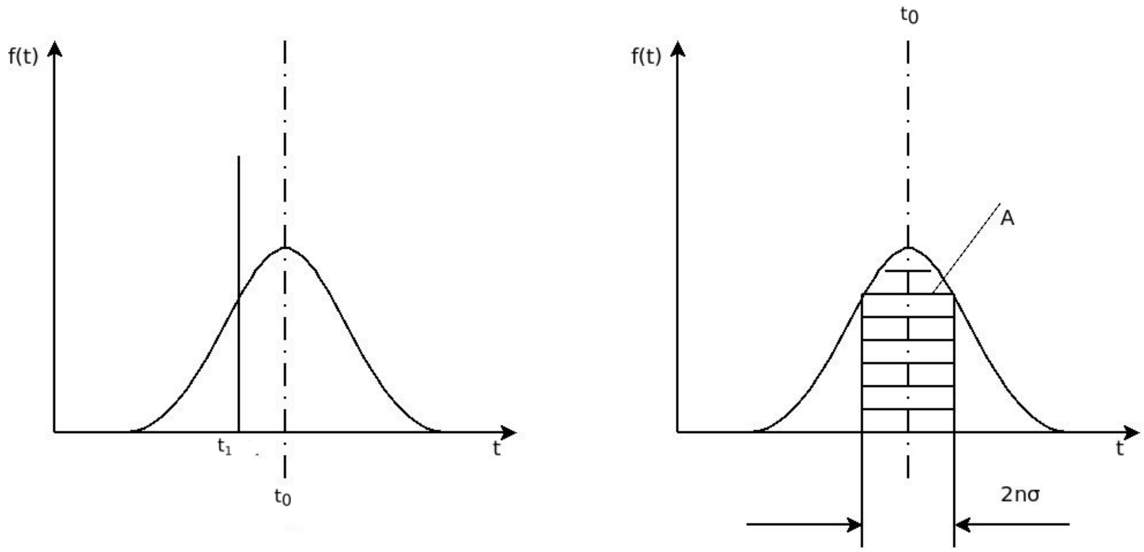
$$\sigma = \gamma t_0 \tag{50}$$

Then we have:

$$n = \frac{t_0 - t_1}{t_0}\frac{1}{\gamma} \tag{51}$$

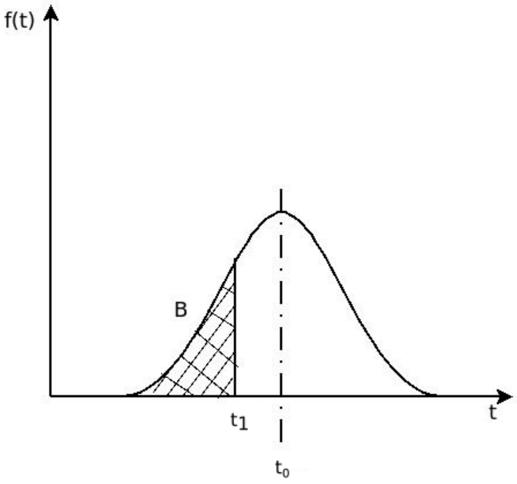
Where γ is the percentage which relates the deviation σ with the mean life time t_0.

This procedure is shown schematically in the following figures:



determination of the minimum time life

determination of n and corresponding area A



determination of area B

Figure 11

The area B is the PROBABILITY that this specific time life of the piping, to be less than the defined minimum life time t_1.

The obvious relation 2B+A=1 is used for the calculation of the area B.

The calculations were done through a computer program that has the following diagrammatical form:

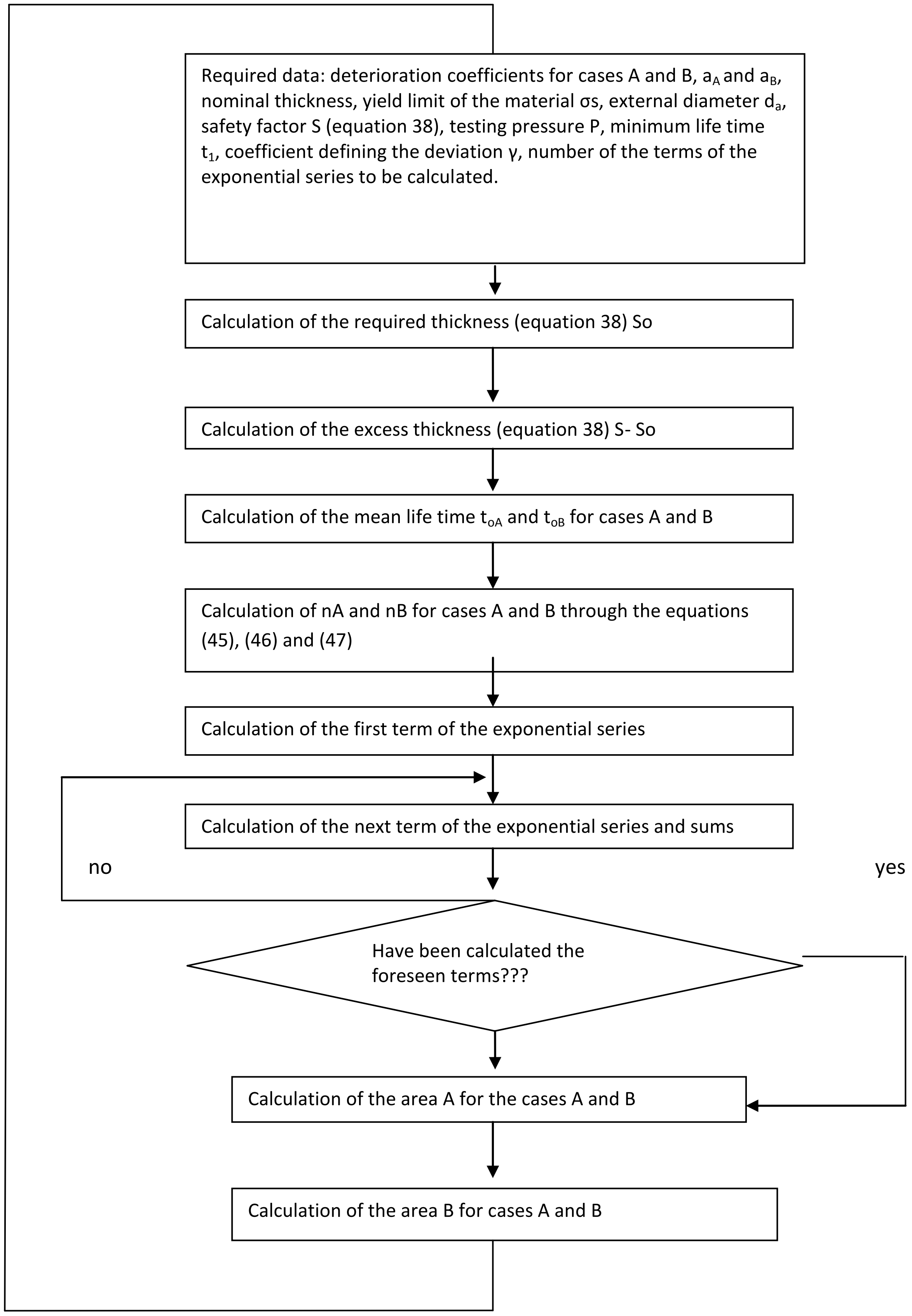

Required data: deterioration coefficients for cases A and B, a_A and a_B, nominal thickness, yield limit of the material σs, external diameter d_a, safety factor S (equation 38), testing pressure P, minimum life time t_1, coefficient defining the deviation γ, number of the terms of the exponential series to be calculated.
Calculation of the required thickness (equation 38) So
Calculation of the excess thickness (equation 38) S- So
Calculation of the mean life time t_{oA} and t_{oB} for cases A and B
Calculation of nA and nB for cases A and B through the equations (45), (46) and (47)
Calculation of the first term of the exponential series
Calculation of the next term of the exponential series and sums
no
yes
Have been calculated the foreseen terms???
Calculation of the area A for the cases A and B
Calculation of the area B for cases A and B

Figure 12

Note 1:

It is clarified that cases A and B correspond to general and local corrosion respectively. The results are shown in the following table 18.

CALCULATION OF PIPING DAMAGE ROBABILITY AFTER SIX AND TWELVE YEARS OF USE

Nominal diameter [mm]	External diameter [mm]	Nominal thickness [mm]	Excess thickness [mm]	Testing pressure [atm]	material	Yield limit [kp/mm^2]	Mean lifetime in years to$_A$ Case A (General Corrosion)	Mean lifetime in years to$_B$ Case B (Local Corrosion)	Damage probability after 6 years Case A (%)	Damage probability after 6 years Case B (%)	Damage probability after 12 years Case A (%)	Damage probability after 12 years Case B (%)
250	267	8	4,22	40	St 35.8II gul	24	42	21	0,2	0,9	0,9	7,5
200	219,1	7,1	4,0	40	‘’	24	40	20	0,2	1	1	9,2
		5,9	5,43	6	‘’	24	54	27	0,2	0,5	0,5	3,1
150	159	4,5	4,16	6	‘’	24	42	21	0,2	6,9	0,9	7,9
125	133	4,5	2,62	40	‘’	24	26	13	0,5	3,6	3,6	39,2
		4	3,72	6	‘’	24	37	19	0,3	1,2	1,2	11,9
100	108	4	2,47	40	‘’	24	25	12	0,6	4,3	4,3	46,2
80	88,9	3,6	2,34	40	‘’	24	23	12	0,7	5,2	5,2	53,4
		3,2	3,01	6	‘’	24	30	15	0,7	2,2	2,2	24,9
		3,2	2,16	40	1.4571	29	108	22	0,1	0,8	0,2	6,9
		3,2	3,04	6	1.4571	29	152	30	0,1	0,4	0,1	2,2
70		3,2	2,12	40	St 35.8II gul	24	21	11	0,9	7,4	7,4	68
		2,9	2,74	6	‘’	24	27	14	0,5	3,1	3,1	34
		2,5	1,5	40	St42,2 gul	26	19	10	1,2	9	11,4	77,8
		2,9	2,01	40	1.4571	29	100	20	0	1	0,2	9
		2,9	2,77	6	1.4571	29	138	28	0	0,5	0,1	3
	76,1	2,5	2,37	6	CuNi10Fe	30	158	24	0	0,6	0,1	5
50	57	2,9	2,78	6	St35.8II gul	24	28	14	0,7	2,9	2,9	32,5
10	11,5	2,6	2,21	25	‘’	24	22	11	0,8	6,4	6,4	61,9
32	38	2,6	2,06	40	‘’	25	21	10	0,9	8,2	8,2	72,8

TABLE 18

Cases A and B are referred to GENERAL and LOCAL corrosion respectively.

A concluding final remark and explanation. In the present study a reliability model with non constant failure rate has been used i.e. one where the time to failure is distributed according to a normal probability density function. The exponential function which has a time independent failure rate i.e. constant, was considered as non appropriate as it does not represent a model close to reality. When we say failure rate or time to failure we mean the time required for a specified part of the thickness of the pipe to be destroyed by corrosion.

The selected distribution function is a two parameters one which in our case are the meantime to failure “μ” and the standard deviation of the distribution “σ”.

The meantime to failure “μ” or “t_0” (in years) is defined equal to the ratio of the excessive thickness “δ” (in mm) divided by a corresponding deterioration coefficient “α” (mm/year) and obviously has the physical meaning of how many years are needed in order the excess thickness to be “destroyed” by corrosion [see equation (40)].

The standard deviation of the distribution “σ” is defined as the product of the meantime to failure (“μ” or “t_0”) times an arbitrarily chosen parameter “γ”, which in our case has the value $\gamma=0.25$. For a mean life time $t_0=20$ years the deviation $\sigma=5$.

The choice of $\gamma=0.25$ corresponds to the median value of the range $0.2<\gamma<0.3$ as it comes from empirical but well tested over the years data of Germanischer Lloyd. This choice in conjunction to the mean life time of $t_0=20$ years indicates a standard deviation $\sigma=5$. From a physical point of view this value also makes sense because the deviation in our case depends on two parameters namely the homogeneity of material production (piping) and on the propagation speed of the corrosion. In our case, (material for demanding customer, corrosion rate within limits) we can hardly find this product i.e. the standard deviation to exceed a value of 5.

Generally speaking in systems reliability the fundamental approach is to choose a model that exhibits the desired properties explaining the stochastic behaviour of the systems under consideration, use data from the operation of the system and “fit” the parameters to the collected data. In our case we worked differently i.e. we “assign” values to the parameters from the existing reliable literature and we checked the conformity of the outcome with the collected data. There are two reasons for that:

One is that when we started availability of relevant data was very restricted.

The second and equally important is that we preferred to use empirical, accurate and well tested over the years data instead of trying to fit our data in order to quantify the corresponding parameters of the model.

When we first faced the issue i.e. to predict the condition of the non inspectable parts of piping based on the restricted measurements taken, we did not know that circumstances in the future would made abundance of relevant and useful data. In this aspect the special way of capturing input data played crucial role in deciding our approach. Much more important is the fact that the more data we collected the better the conformity to our used model.

Of course, other reliability models of two parameters exhibiting the same general behaviour of increase λ, might show even better suitability to the collected data from the normal probability density function used in this study. This could be the subject of another future work. In chapter 2.3 are mentioned cases related to reliability and maintenance in which models of different parameters are used.

CHAPTER NINE

DATA ACQUIRED DURING THE LTM OF “TRITON” SUBMARINE

During the LTM of “Triton” submarine, extensive parts of the sea cooling piping networks were dismantled and inspected. In order to assess the satisfactory or not condition of the piping, the following criterion was set:

Parts of the piping that exhibited (showed) deterioration more than 15% of the wall thickness after the sandblasting, were deemed as rejectable and were replaced. The other parts of the piping that exhibited deterioration less than 15% of the wall thickness were cleaned with sandblasting and were reinstalled after their zinc coating was applied.

In sight of the condition of the replaced piping parts showed that the mean deterioration level was approximately 40% of the initial thickness of the wall. The deterioration percentage of the parts that were deemed as non-rejectable was 10% on average. Table 19 summarizes the results of the inspection of the piping of the “Triton” submarine.

OVERVIEW OF INSPECTION RESULTS OF THE PIPING OF TRITON SUBMARINE

NOMINAL DIAMETER [MM]	EXTERNAL DIAMETER [MM]	NOMINAL THICKNESS [MM]	TOTAL LENGTH OF INSPECTED PIPING [M]	KEPT PIPING LENGTH [M]	REPLACED PIPING LENGTH [M]	PERCENTAGE OF REPLACED PIPING (%)
250	267	8	1.75	1.75	0	0
200	219.1	7.1	3.25	3.25	0	0
150	159	4.5	4.81	2.81	2	41.6
125	133	4.5	55.38	15.63	39.75	71.8
100	108	4	28.63	24.19	4.44	14.6
80	88.9	3.2	19.75	6.0	13.75	69.6
70	76.1	3.2	30.75	17.75	13.00	42.3
50	57	2.9	500	2.25	2.75	55.0
40	44.5	2.6	10.25	7.5	2.75	16.8
32	38	2.6	7.63	5.38	2.25	29.5
		Total	167.20	86.51	80.69	48.26

TABLE 19

The total length of the piping was estimated at about 200m, of which 167m were inspected, as shown in table 19. The following table 20 shows the piping which during the LTM of submarines, were found to be sensitive to corrosions.

OVERVIEW OF PIPING HIGHLY SENSITIVE TO CORROSION OF GLAFKOS SUBMARINE

PIPING NUMBER (IDENTITY)		PARTICULAR COOLING PIPING NETWORK	NOMINAL DIAMETER [MM]	DESCRIPTION OF PIPING
020650	020660	Cooling piping network of engines exhaust	80	Cooling piping of internal valves of exhaust
020670	020680			
020500	020490	Cooling piping network of air compressors and generators	50	Cooling piping of main generator 1
020360	020370	‘’	‘’	Cooling piping of main generator 2
020530	020540	‘’	‘’	Cooling piping of main generator 3
020520	020510	‘’	‘’	Cooling piping of main generator 4
020340	021130	Main piping network	80	Inlet at Bb electrical motor cooler
021140	020170	‘’	80	Inlet at stb electrical motor cooler
020250	021120	‘’	80	Outlet from stb electrical motor cooler
021110	020180	‘’	80	Outlet from stb electrical motor cooler
020470	020480	Cooling piping network of diesel engines	70	Water from engine 1 to stb piping - Water from engine 2 to Bb piping
020030		Main piping network	125	Suction of main cooling pump
020240		‘’	125	Discharge of main cooling pump
020410		Cooling piping network of diesel engines	125	Outlet of cooling water at piping 020420
020260	020270	Cooling piping network of air compressors and generators	70	Cooling piping of generator 4 Cooling piping of generator 3
020300	020310	Cooling piping network of thrust bearing and propeller shaft tunnel	12	The entire cooling piping network of thrust bearing and propeller shaft tunnel
021000	020320		20	
020700	020810		25	
021010				

TABLE 20

CHAPTER TEN

ANALYSIS OF OUTCOMES AND POTENTIAL SUGGESTIONS

10.1 COMPARISON BETWEEN CALCULATED, ACTUAL MEASUREMENTS AND LITERATURE’S DATA

Measurements acquired during the LTM of the “Triton” submarine and values calculated using the reliability theory, are summarized in tables 19 and 18 respectively. These figures are not directly comparable as different criteria were used in order to decide if the piping in each case has to be replaced or not. During the LTM of the submarine decrease of the nominal thickness by at least 15% was set as a replacement criterion. On the contrary in the calculations, the mean life time was defined in relation to the “excess” thickness, that is the piping thickness which in brand new condition is in excess of the required thickness which ensures the safe operation of the pipe under the testing pressure*. To facilitate the data comparison, the behavior of each piping from brand new condition till the decreasing of the nominal thickness up to 15% is calculated hereafter. This calculation was based on the mathematical/computer model showed in Figure 13.

Note 2:

As excess thickness is defined the difference between the nominal thickness (actual thickness of the standard pipe in brand new condition) and the necessary thickness to resist on the testing pressure.

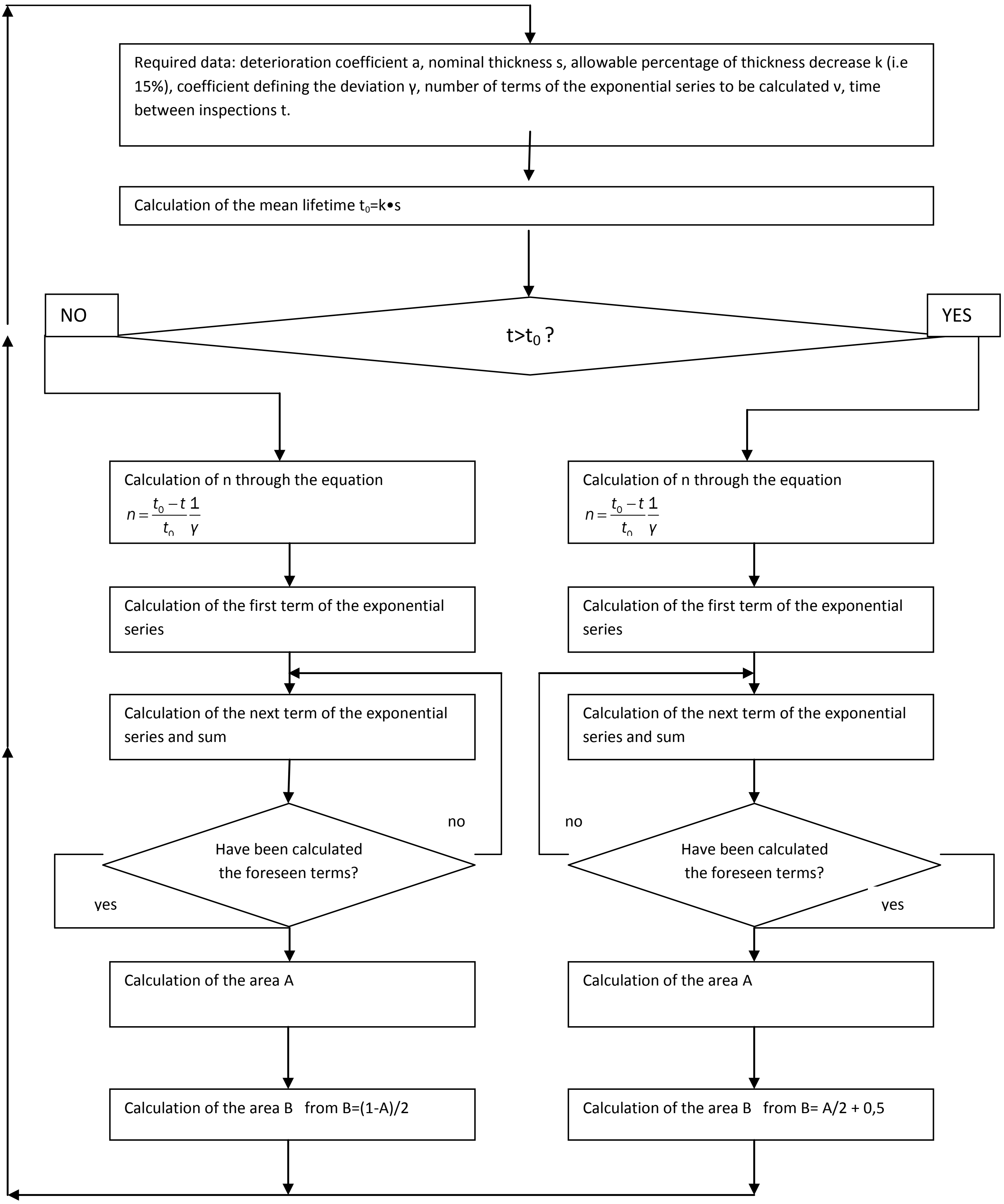

Required data: deterioration coefficient a, nominal thickness s, allowable percentage of thickness decrease k (i.e 15%), coefficient defining the deviation γ, number of terms of the exponential series to be calculated ν, time between inspections t.
Calculation of the mean lifetime t_0=k•s
NO
$t>t_0$?
YES
Calculation of n through the equation $n=\frac{t_0-t}{t_0}\frac{1}{\gamma}$
Calculation of n through the equation $n=\frac{t_0-t}{t_0}\frac{1}{\gamma}$
Calculation of the first term of the exponential series
Calculation of the first term of the exponential series
Calculation of the next term of the exponential series and sum
Calculation of the next term of the exponential series and sum
no
no
Have been calculated the foreseen terms?
Have been calculated the foreseen terms?
yes
yes
Calculation of the area A
Calculation of the area A
Calculation of the area B from B=(1-A)/2
Calculation of the area B from B= A/2 + 0,5

Figure 13

The two different calculations are shown in the following two cases respectively

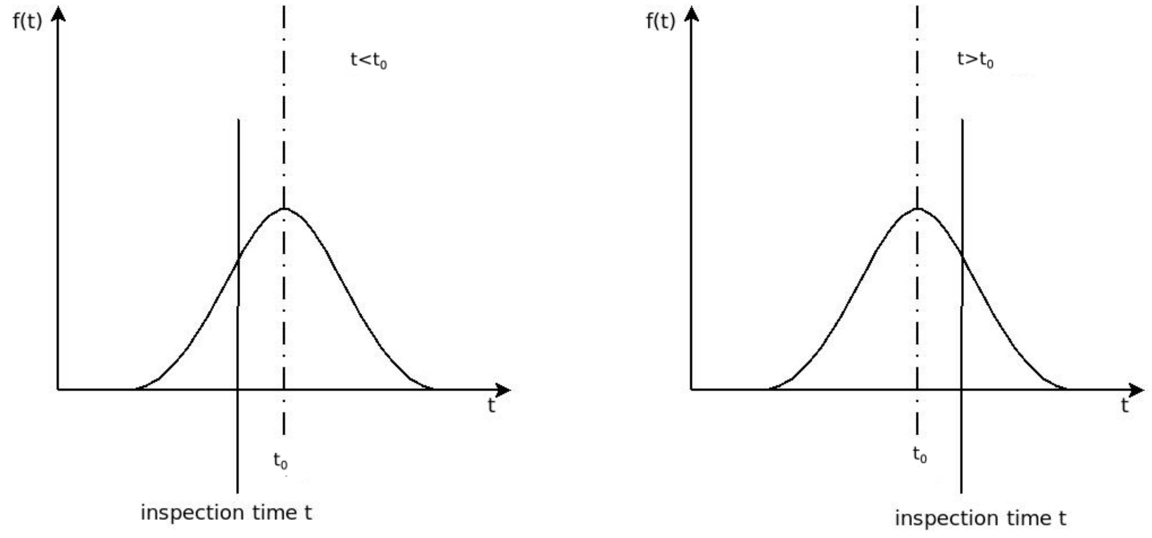


Figure 14

It is clarified that the distinguishing cases $t>t_0$ and $t<=t_0$ was not necessary for the calculation of table 18 because case $t>t_0$ (inspection time greater than the mean lifetime) is not applicable for any piping. The situation is different when as allowable deterioration we consider the decrease of the nominal thickness per 15%. The described computer/mathematical model gives the following results for the various piping as shown in table 21.

CALCULATION OF DETERIORATION PROBABILITY GREATER THAN 15% IN SIX AND TWELVE YEARS

NOMINAL DIAMETER [MM]	TESTING PRESSURE AT	MATERIAL	MEAN TIME TO DECREASE THE INITIAL THICKNESS PER 15% [YEARS]	DECREASE PROBABILITY PER 15% AFTER 6 YEARS (%)	DECREASE PROBABILITY PER 15% AFTER 12 YEARS (%)	PERCENTAGE OF REPLACED PIPING AFTER 6 YEARS
290	40	St35.8II gul	12	4.8	30	0
	40	‘ ’	10.65	7.5	66.4	0
	6	‘ ’	8.85	14.2	88.2	
150	6	‘ ’	6.75	35.6	99.3	41.6
125	40	‘ ’	6.75	35.6	99.3	71.8
	6	‘ ’	6.00	50.0	100	
100	40	‘ ’	6.00	50.0	100	14.6
80	40	‘ ’	5.4	64.4	100	69.6
	6	‘ ’	4.8	79.8	100	
	40	1.4571	24	0.713	4.8	
	6	1.4571	24	0.713	4.8	
70	40	St35.8IIgul	4.8	79.8	100	42.3
	6	‘ ’	4.35	89.7	100	
	40	St42.2gul	4.69	82.5	100	
	40	1.4571	21.75	0.834	6.8	
	6	1.4571	21.75	0.834	6.8	
	6	CuNi10Fe	25.00	0.69	4.15	
50	6	St35.8IIgul	4.35	89.7	100	55.0
40	25	‘ ’	3.9	96.4	100	26.8
32	40	‘ ’	3.9	96.4	100	29.5

Table 21

The probability of decreased thickness of a piping by a given percentage is not a function of the testing pressure, but it is related only to the rate of failure or deterioration coefficient and to the nominal thickness. This results in the calculation to become simpler. However this criterion is not as accurate as the proposed one. Calculation of the excess thickness and selection of a replacement criterion when the reduction of this excess thickness is higher than a given percentage (not of the nominal thickness) is a more accurate approach. Given that, table 18 contains more accurate results than table 21. Table 21 allows us to compare the calculated figures and acquired data of the inspection. Notwithstanding data acquired during the inspection are referred only to nominal diameters and not to materials, we realize that with testing pressure and the use of the specific piping , there is much coincidence with the calculated results. Considering on one hand that the choice of the deterioration coefficient is arbitrary within given limits, on the other hand that during the inspection the criterion “deterioration of at least 15% of the nominal thickness” cannot be measured exactly especially in cases of local corrosions, the coincidence of the actual and calculated values is deemed as satisfactory. Moreover the coincidence of the calculated mean lifetime and measured lifetime as indicated in table 12 is again satisfactory enough.

10.2 CONCLUSIONS ON THE PREVIOUS COMPARISON

a. The deterioration found in the piping networks of "GLAFKOS" submarine is justified as an expected outcome of the quality and properties of the materials used and of the operating conditions.

b. The first objective was to compare the actual measurements of the accessible parts of the piping and the outcome of the developed mathematical model for the very same piping. If the comparison is satisfactory, extrapolate the assessment using the same mathematical model to:

   (1) The non accessible parts of the same piping (Present situation)

   (2) The piping after certain years of operation under similar conditions.

   This "assessment of condition" means to calculate the probability the piping to fulfill or not certain predetermined criteria and consequently to provide a "sense of confidence" for the reliability of the piping or on the contrary "dictate" the necessity for replacement of the piping immediately or after a certain period of time.

c. Based on all a.m. the general conclusions are as follows:

    (1) The estimated condition of non inspected inaccessible parts of the piping networks during the LTM is not worrying. As shown in table 18, the probability of local damage of the piping after six years does not exceed a single digit of percentage while the mean lifetime is always greater than ten years. There are cases when the probability for local damages is less than one (1%) percent, and the mean lifetime goes up to thirty (30) years.

    (2) On the contrary to the aforesaid, the probability for a local damage after twelve years is increased in some cases up to 70% while the mean lifetime in some cases is less than twelve years. It is clarified that the above are valid for the TESTING pressure which is 60% higher than the maximum pressure of operation. In addition the probability for the failure of piping with diameter greater than 150mm is less than 10%

    (3) The behavior of piping with diameters between 40 and 100mm can be considered more critical while the main piping with diameters up to 250mm show greater

reliability. In particular for piping diameters between 40 and 100 mm and for local damages the probability of failure after twelve (12) years of operation goes up to 77.8% and the mean lifetime varies between 10 and 30 years.

(4) The use of better materials for the piping (i.e CuNi10Fe as used in the next generation of submarines or CuNi30Fe) is the more effective way to delay the corrosion propagation.

d. It is noted emphatically that all conclusions and proposals are on the conservative side and therefore the behavior of the piping is anticipated to be better than foreseen in the present study.

10.3 THE FULL PROOF VERIFICATIONS OF THE MODEL

a. As already said the model has proven its applicability and validity in an initially rather restricted way. In order to be more specific on the term “restricted” the validity of the model was checked:

    (1) In every case that a part of the piping was accessible and consequently inspectable. The accessible parts constitute only a small percentage of the whole piping.
    (2) By the fact that the non accessible parts of the piping have not shown meanwhile a non predicted damage.
    (3) Quantitevely, all measurements taken were very much in conformity with the calculations presented in Tables 16 and 18.

b. The initially so to say restricted validity and applicability of the model is due to the following two reasons:
    (1) On one hand to the size of the sample of the piping per se (type, number etc.)
    (2) On the other hand the time frame of observance which covered an initial period from five to eight years of operation of the piping.

c. Five years later from the a.m. model’s inauguration, the Navy decided to inspect fully all sea water network pipings of the submarines during the second Long Term Maintenance (LTM) of them. Hereafter, we cannot state “restricted validity of the model”. In order to achieve the task of full inspection of all pipings the maintenance period was extended to nine months for the first submarine down escalated to seven months for the fourth and last, taking learning effect into consideration.

d. Every piping and each part of it was:
   (1) Dismantled, removed and taken out of the submarine
   (2) “Cleaned” by chemical procedures and / or light sand blasting in a bare metal condition.

   From the first indication and measurements taken was realized that the condition of the piping was very much in conformity with the prediction of the model as presented in Table 21.

e. Given that the probability for a piping to operate with reduced excess thickness after twelve years of operation is high and taking into consideration the fact that all submarines had then completed a life from fifteen up to twenty years, was prudently decided to REPLACE ALL PIPINGS WITH NEW ONES FROM THE SAME MATERIAL. This was an administrative decision based on the technical outcomes of the present study.

f. This decision obviously has had many side effects amongst which was the opportunity to take all necessary measurement in the pipings by cutting them along side into two semi – cylindrical pieces. Even more, and after taking all necessary measurements, parts of the piping were used in a systematic way in destructive and non destructive tests. These tests allowed us to concentrate more on the parameters influencing the deterioration of pipings like welding, smoothness of the surface, velocity and temperature of the fluid, curvatures and abrupt changes of flow and so on.

g. As far as the model of this study the actually verified conclusion is that:

   “The more measurements are taken, the more characteristic is the sample used, the better is the conformity with the prediction of the model”

   As we had the opportunity to use a real scale model of four submarines not operating always in similar conditions, with total length of piping exceeding four kms and covering a substantial period of operation of more than fifteen years on the average per submarine, we have had the “satisfaction” to verify that the model used had a very good conformity with the measurements taken so far.

h. Taking into account all lessons learned and experience gained two major new decisions were taken;

   (1) Neither to inspect nor to replace any sea water piping before eight years of operation unless they are strong indications dictating the opposite. By strong indications we mean that although the model does NOT anticipate corrosion defects before eight years, there might be cases, due mainly to local conditions and circumstances, where corrosion creates troubles in a shorter period.

   (2) From eight to twelve years of operation to follow the condition of the piping more closely, when such an opportunity is given and replace all piping AFTER the twelve years period but NOT LATER than sixteen years. If everything goes well the period from eight to twelve years is an interim “period of observance” in which unpleasant surprises are not foreseen. The period from twelve to sixteen years is a “replacement period” during which in every given opportunity replacement of the pipings by new one should take place. If relevant

opportunities are not given, a programmed replacement period after twelve but not later than the end of the 16th year should take place.

The distinctive periods of 8, 12, 16 years are correlated to the basic conclusions coming out mainly from the Tables 18 & 21 with a necessary explanation that the outcome of the Tables is inherently very conservative for several reasons already explained as e.g. calculations are done for the TESTING and the OPERATING pressure, excessive thickness is by far more than 15% etc.

Those a. m. new administrative decisions, having as technical background the outcomes of the present study, had as a direct and immediate result to shorten substantially the maintenance period of the submarines and consequently to increase their operational availability.

Furthermore, their maintenance cost was reduced, all major maintenance periods could be easily programmed and synchronized with other relevant simultaneous requirements.

Much more important is considered the fact of providing the sense of confidence and assurance to all parties involved that the condition of the piping is not anticipated to “surprise” them unpleasantly.

The value of creating, establishing and maintain such a sentiment cannot be measured but, in my view, it is worth much more than all other consequences together.

i. After more than twelve years later the newly decided change of piping took place. The outcome of inspection of the piping was again a satisfactory verification of the reliability of the present model used. In that case no measurements in a systematic way were taken. It was a rather qualitative assessment of the condition of the piping.

10.4 PROPOSALS AND OVERVIEW OF PIPING’ RELIABILITY

1. Based on the outcomes of the study the following proposals to the relevant Authorities were made as practical measures to be taken under the circumstances (financial and operational availability, safety of personnel etc) on a consecutive way. The proposals are a combination of good engineering practice and as said, outcomes of the study:

a. <u>Measures related to prevention and maintenance:</u>

(1) Frequent wash of the network piping with fresh water

(2) Frequent chemical cleaning f the network piping

(3) Avoidance of increased flow speeds due to partial blocking of the piping

(4) Proper operation of heat exchangers (coolers)

b. <u>Measures to be implemented by the Naval base.</u>

(1) Partial inspection of the network piping as extensively as the time allows in literally every given availability of the submarine. In such a case we don’t expect to “visit” the non inspectable parts of the piping.

(2) Full inspection of the network piping during the next LTM of the submarine and replacement of the parts of piping as deemed necessary. This of course implies removal of almost every machinery and equipment hindering the full inspection.

2. In the previous chapters, we set the purpose and the particular targets of this study and described the procedure, to be followed.

   The main concept is the description of the deterioration (and therefore the condition of the piping network) as a function of time through the normal distribution function. Since the description of the condition of the piping networks as a function was made possible, acceptance criteria were defined which enable a directly comparable check for the satisfaction or not of the criteria in the existing condition of the piping and most important in foreseen condition at whatever future time.

   As anticipated, in all studies of this type the closer the mathematical model represents the actual situation the better the outcome of the results.

   It can be said that the mathematical models of the present study simulate very well the actual situation and therefore in most of the cases the actually measured results and the calculated ones coincide well (see table 18,21, chapter eight, etc).

3. Furthermore, if we juxtapose the main research, questions or objectives of the study, as are explicitly mentioned in the relevant chapter 2.4, we can claim without any reluctance that the outcomes of the study fully covered our endeavors and in most of the cases have exceeded them.
    a. As already explained, in the preliminary stages of this study, we tried to examine how other Navies of the world cope with the same problem i.e. to assess the reliability of non accessible piping onboard their ships and their submarines in particular. Much to our surprise very few generic information were available of almost no practical usefulness at all. Even some efforts to "gather" information through the official channels of the Alliance were in vain. The explanation, the more plausible one, is that national secrecy policies in conjunction with the variety of "material" used have not allowed or facilitated common ways to tackle the issue.
    b. This lack of external "help" obliged us to develop our own means namely the scope and outcome of this study. For more than thirty (30) years, a certain

number of submarines followed a schedule of full maintenance (preventive and corrective) of their pipings’ networks aligned with the conclusions and in strict compliance with the proposals of this present study as they were developed during the years.

c. Taking into consideration:

(1) The number of submarines involved (eight on the average)

(2) The extensive time frame (thirty years) examined

(3) That for the <u>same</u> scope of work every activity of repair/ maintenance was less costly and shorter in time than the previous one (Learning curve positive)

(4) That the operational availability of the submarines was constantly improving over the years

and last nut not least

DURING THIS EXTENSIVE PERIOD NEITHER SIGNIFICANT DEVIATION FROM THE PREDICTIONS OF THE MODEL USED WAS OBSERVED, NOR ANY REAL DAMAGE OF THE PIPINGS PERSE HAS TAKEN PLACE IN OPERATIONAL CONDITION OF THE SUBMARINES, is an index of merit of the whole project and work done, its results, its direct implementation, its innovative methodology and its heavy impact on the reliability, cost of maintenance, operational availability and safety of both personnel and material in the sensitive branch of submarines.

d. In a few words, over the years has been proven in the most undoubtfull way that the effort spent was not in vain. This is something that every person working in projects of similar nature and ambiguity wishes to meet at the end of his “adventure”. Does not happen to all of them. Good luck is always needed.

10.5 <u>RELIABILITY OF OTHER ENGINEERING SYSTEMS OF MAJOR IMPORTANCE, STATE OF THE ART</u>

a. As an outcome of the review of literature on Reliability, Safety, Cost Optimization of Maintenance, Corrosion Mechanism, etc. (see chapter 2.3) we can say that in all sectors of human activities minimization of cost maintenance in conjunction with increase of systems reliability, availability and operability have a paramount importance and consequently every element of knowledge which can contribute to the achievement of the aforementioned objectives is highly utilized.

b. If we restrict to the most relevant sectors of engineering applicability then oil industry, energy production, offshore platforms and nuclear installation are more close as far as reliability' s importance is concerned. A close examination of the different domains reveals that:

    (1) The objectives are the same namely "pay less and secure more"
    (2) The ways these objectives are achieved present a big variety, diversification in the modelling used, scientific parameters and background examined, methodology applied, etc.
    (3) Despite the differences in the ways all (or the vast majority) have in common to be a derivative of an already proven successful approach.

c. A few typical study cases have been examined and their relevant "factors" are as follows:

(1) OIL AND GAS INDUSTRY

Maintenance optimization is of great interest to this industry as it is faced with high maintenance costs absolutely necessary to ensure reliable, safe and uninterrupted operation of offshore installations. Maintenance operation models so far are mostly used for risk-based inspection for selected equipment and not for the whole maintenance. Reliability Centered Maintenance (RCM) concept and Risk Based Inspection (RBI) concept are gaining further application nowadays. In the models used mostly exponential lifetime distribution is used in Monte Carlo simulations. To apply these models detailed lifetime models need to be developed and their parameters determined because without enough relevant data the models break down.

(2) NUCLEAR POWER PLANTS. A MODEL TO ASSESS THE MAINTENANCE STRATEGY

The model is a RCM (Reliability Centered Maintenance) one, which very commonly is used to work out preventive maintenance programmes. However, the probabilistic nature of failures renders difficult to compare different options on quantified bases and in particular to assess the impact of a preventive maintenance program in terms of availability and costs, the impact of operating conditions on equipment reliability, availability, maintenance cost or to perform a maintenance task ranking to comply with budgetary and/or time constraints. The model is better applicable to rather “simple” systems in which the so called “opportunistic” maintenance approach can be used in order to decrease the maintenance cost.

(3) RCM METHODOLOGY AND ITS ESTABLISHED CONSEQUENCES RCM (RELIABILITY CENTERED MAINTENANCE)

When and where used, have consequences which can be analysed using different criteria or multicriteria. By definition RCM is a systematic methodology seeming to plan effective predictive and preventive maintenance thus helping to prevent the most common causes of failure of critical equipment and ensure that adequate levels of components are available at the lowest possible cost. In order to analyze consequences decision theory is used i.e. statistics and probabilistic approach dealing with uncertainties.

(4) RELIABILITY MODELS ADJUSTMENT AND SYSTEMS OPTIMIZATION. THEORETICAL APPROACH

Different theoretical models are used to assess the system reliability taking into account the maintenance, the specific conditions of use and the environment. Tools can be made available to adjust these models from feedback operational data but they may give wrong results, especially when the parameters in the model are greater than two (2). The reason is simply that these tools implement local optimization methods (pseudo gradient, non linear simplex, etc.) to make adjustments by the maximum likelihood method while the model functions have multiple optima. Using a Global Optimizer can overcome these difficulties because it is based on a hybrid technique combining generic algorithms and non linear simplex which makes correct adjustments in the past. Beyond that shows the coupling possibilities of such optimization tool with assessment system model to optimize different parameters such as period of preventive actions, depreciation duration, etc. The model used combines an exponential and a Weibull for the overall second and third parts of the bathtub curves (occasional failures and wear). The model consists of two blocks in series, one corresponding to an exponential law and the second to a Weibull law. It seems that the method could be applied to the problem of submarines piping at hand.

(5) MAINTENANCE FOR TIME DEPENDENT DETERIORATING SYSTEMS

The study of the existence of possible change of deterioration rate of a deteriorating system in industrial problems is of great importance. It seems sensible to consider the maintenance problem in this framework. When the system undergoes a change of rate of deterioration, it seems reasonable to incorporate the on line information available about the system in the maintenance schedule. The deterioration level (the system state) at time t can be summarized by a scalar random ageing variable X_t. When no repair or replacement action has taken place, (X_t) $t \geq 0$ is an increasing stochastic process with initial state $X_o = 0$. The behaviour of the deterioration process after a time t depends only on the amount of deterioration at this time. If the state of the process reaches a predetermined threshold L the system is said to be failed. The threshold L is chosen in respect of the properties of the considered system and can be seen as a safety level which should not be exceeded. To a certain extent this is the approach used in this study.

(6) THE PHENOMENON OF CORROSION

A multistate markov model is presented for modelling the physical phenomenon of loss of containment in ammonia storage tanks owing to corrosion. It takes into consideration inspection maintenance and repair of the tank with mean time to failure forty (40) years. Failure mechanism is modelled as a multistate model each representing a fix length for the critical crack growth. Test and repair is simulated through the possibility of detecting the crack and its length and taking the necessary remedy measures. Quality of repair is simulated through different degrees of efficiency both in the duration of repair and state at which the vessel is found after completion of repair. Variation of the failure probability over the lifetime of the vessel and the corresponding downtime owing to test and repair is calculated as a function of the period of testing. Optimum test period can be determined for a given value trade-off between these two measures.

Corrosion per se is a complicated phenomenon but it exhibits a general characteristic as far as its dependence on time is concerned. The failure mechanism consists in the formation of a crack that grows until a critical value is reached followed by the structural failure of the containment. The growth of the crack as a function of time is a stochastic phenomenon and hence the time to failure exhibits a corresponding stochastic variability. Furthermore, the probability that a failure will occur during the early phase of the crack growth should be small and increases rapidly around a certain point in time.

(7) PIPELINES’ INTERNAL CORROSION RELATED TO ROUTING, DESIGN AND MAINTENANCE OPTIMIZATION

This study cases presents a close similarity to our study although instead of corrosion due to sea water deals with corrosion in the a crude oil piping system and particularly electrochemichal corrosion in carbon steel pipelines carrying mixtures of oil with water and carbon dioxide (CO_2). Another major difference is that examined results vary from pipeline leakage to full bore rapture. In our study even beginning of leakage was not allowed. As accurate corrosion prediction and management are key factors in meeting the design life requirements of an oil or gas pipeline numerous mathematical models have been proposed for modelling the corrosion inside pipelines. These models are divided into three main categories namely mechanistic (with strong theoretical background), semi-empirical and empirical models. The use of a very well known empirical model called Norson model allows the optimized design of the piping as far as total cost and energy consumed are concerned. Corrosion has a major impact on the total pipeline cost and consequently may yield to different choices for the pipeline routing.

CHAPTER ELEVEN

REFLECTIVE AND REFLEXIVE LEARNING FROM THE PROJECT

11.1 REFLECTIVE AND REFLEXIVE

The purposes of this last chapter are in brief:

a. To reflect the outcomes of the study
b. To assess the significance of the project
c. To "introduce" the applicability of the principles of the model to other relevant engineering domains
d. To provide explanations for my own role in the project
e. To value the projects for its stakeholders

From all a.m. the outcomes of the project are such that:

a. Can convince everyone concerned that are absolutely correct. This was repeatedly proven in every opportunity during the years as explicitly mentioned in the text in relevant places.
b. Can withstand every adverse criticism done both with good and bad faith. This is a result of their validity.

c. Their applicability can cover every case of criteria (or combination of criteria) for replacement and/or reliability assessment.
d. Can provide “proofs” of their adequacy both theoretical and practical.

As described already the main objective of the project was to find a “rational way” to verify and assess the reliability of the inaccessible piping of a submarine or if we elaborate further “to assure all persons and authorities involved, that piping which due to inaccessibility and space obstacles cannot be inspected, either they retain adequate strength to comply with the forces imposed and can be left as they are or they have been “weakened” and they should be replaced and/or repaired”. In such a way we can make certain that all parts retain the necessary reliability that allows the submarine to be further safely used.

The significance of the project is self explanatory by simply considering the possible alternatives of the aforementioned objective, i.e. not being in a position to “assure” that the piping retain or not the necessary reliability allowing the submarine to be safely used.

Alternative one

Not being in a position to provide the required assurance for the reliability. In such a case the direct and only outcome would be to reduce drastically the operational use of the submarine and consequently minimize her “war merit” something absolutely undesirable if not even unacceptable for any Navy with self respect and tradition.

One sub-alternative of alternative one is to reduce the operational capabilities to a smaller extent than required by the actual condition of the piping. Under these conditions we could put into jeopardy the safety of the submarine which can result in a nightmare calamity.

Alternative two

This consists of making “inspectable” all piping, of the submarine disregarding the consequences on the financial cost and on the prolongation of the general overhaul. This very conservative approach, definitely provided all needed assurance for the reliability of submarine’s systems and parts, but has severe and undesirable repercussions. If on the contrary we could achieve our said objectives the direct and side benefits are numerous and valuable including amongst them:

a. The implementation of the general overhaul within specified and reasonable budget and time frame constraints.
b. By using the “rational approach” the reliability of submarine’s systems can be objectively and accurately assessed.
c. The very same “rational approach” could be used for the assessment of any inaccessible piping system and its principles suitably modified can be extended not only to piping but to other inaccessible systems as well.

To be more specific for point (a) above, the general overhaul of a submarine without the difficulties of the inaccessible piping is designed for a workload of 200.000 man-hours and an initial duration of six calendar months. Has been calculated that by following the conservative alternative approach namely to make every piping inspectable the totally required man-hours can reach the figure of 800.000 and the time frame reaches three calendar years. For a total of eight submarines that eventually have to be overhauled we have an increase in man-hours of 4.8 million and much more important the duration of one overhaul becomes six times longer.

For point (b) above, if we manage to assess the reliability of submarine’s piping in every moment, not only we will be in a position to know when each of them has to be replaced and/or repaired, but we can program its necessary replacement (or at least the most important ones) to coincide with the scheduled general overhaul therefore saving effort, time and money.

For point (c) above, we presumed that the mathematical model to be used must be such that can be applied to every piping (inaccessible) system either it belongs to a “crowdy” nuclear reactor environment or to the network of a public water authority of a city. The differences in geometry, working conditions and materials in every case used are “represented” by the different standard coefficients used in the terms of the mathematical model. But even if, for the time being, we restrict the anticipated benefits from the project to the Navy, the main target audiences for the outcome will be on one hand the submariners’ community that would feel “at ease” being given a submarine without any restriction in operation and accurately assessed reliability, on the other hand the engineering community of the Navy being in a position to implement a general overhaul in a specified time frame and within budget.

Obviously by extrapolating, those two audiences are extended to the highest echelon of the Navy and the Ministry of Defence as well.

11.2 MY OWN ROLE AS WORKER / RESEARCHER

The real issue of assessing the reliability of non accessible structural parts of a submarine was “presented” in the preparation stage of the general overhaul of the submarines in Salamis Naval Dockyard. The Technical Directorate, which carries the main load for the implementation of the general overhaul, is supported by the Planning and Design office (PDO) which was and still is the engineering and scientific “arm” of every relevant activity in the Naval Base. With a complement of about fifty persons, two thirds of them highly educated engineers and scientists, a well organized and updated library, drawings and technical data of all systems of every unit of the fleet, is in a position to provide tangible and workable solutions to almost every technical, engineering or scientific problem the technical Directorate was faced with. In parallel, the Planning and Design Office was in continuous cooperation with the builders of the ships, the makers of their systems with other affiliated entities in Greece and abroad.

Therefore, to start with, we had in place a very suitable “vehicle” to be used.

On that time, I had the privileged responsibility to be in charge of the (PDO) which implied on one hand that the task to find the approach for assessing the reliability of the structural parts was totally on me, but on the other hand that I had the freedom to proceed as I thought and all necessary available resources were in my disposal. Furthermore, my academic studies in conjunction with my hands on experience and my expertise as a naval engineer, formulated a strong “tool” in the endeavours to tackle the issue. Having worked in the repairs of submarines, having dived with them extensively in the past, provided me with a deep knowledge of the operational requirements of a submarine and much more important an insight in the mentality of the submariners community. All these at the end meant an “acceptance” and “approval” by them.

It is obvious that my personal role as a worker was predominant, and the fact that I “extended” this role to the one of worker researcher was rather unavoidable.

11.3 VALUE OF THE PROJECT

As far as the value of the project this is summarized as follows:

To the Navy:

a. Ability to predict the condition of non inspectable pipings of a submarine.
b. Better planning and control of the general overhaul of ships.
c. Increased confidence on assessment of reliability and availability of submarines.
d. Increased self confidence of the operating crews.
e. Save money and effort.

To the Industry and Maritime Community

a. Applicability of the same principles in modelling non inspectable pipings.
b. Consequence of the above is that all aforementioned values for the Navy are equally applied for them as well.

To the University

a. A new study case for sharing of learning.
b. Added resource information in a subject of highly engineering merit with tangible and applicable outcome ready for immediate practical use.

To myself

a. Proved my capability to meet the requirements of the University on a doctorate level.
b. Received once more the so called job satisfaction from doing things of added value.
c. Had the benefit from the new requirements of learning.
d. Fulfilled a long pending ambition.

Number of Words: 22467

LIST OF REFERENCES

(1) Bach, J.D. (1974). Theory of Elastic Deformation. (Last Edition). New York: John Wiley & Sons

(2) Barlow, R. (1980). Mathematical Theory of Reliability. New York – London – Sydney: John Wiley & Sons, Inc.

(3) Brostein & Semendjojew. (1976). Taschenbuch der Mathematik. Zürich & Frankfurt: Verlag Harri Deutsch

(4) Cassee, H. (1992). 'Piping Systems'. R. Harington. Marine Engineering. New York: Society of Naval Architects and Marine Engineers. pp 782-826. The chapter on piping systems covers the Design Development, Design Details, Ship Service Systems etc. providing insight to all relevant topics.

(5) Defects and Failures in Pressure Vessels and Piping. (1980). New York: H. Thielsch – Reinholb Publishing Corporation. The title is self explanatory for the content of the book. A very practically oriented and useful book for the development of our project. Chapter seventeen of the book titled Service Failures – Corrosion is a historical document.

(6) Description and Operating Instructions of Sea Cooling Water Systems for Class 1222 Submarines. (1972). Kiel: Howalds Werke Deutsche Werft. Describes in every necessary detail the “as built” piping systems of submarines. It is an absolutely essential document for our project containing valuable information for the pressure, the geometry, the material etc. of every single meter of the piping systems. Furthermore, it provides a “first glance” routing of the piping, enabling us to assess about the accessibility and the inspectability of each piping.

(7) Dübel, H. (1980). Taschenbuch für den Maschinenbau. Berlin, Heidelberg & New York: Springer Verlag

(8) Dym Clive L. (1980). Theory of Shells. London: Pergamon Press. The book covers the basic theories of design pipings considering them as an expanded shell in their first fundamental force of surfaces.

(9) Eberius, E. (1970). Korrosion und Korrosionsschutz am und im Schiff. Handbuch der Werften. (XIV). Berlin: Springer Verlag

(10) Ewerth, H. & Neumann, P. (1995). The Silent Fleet. Kiel: HDW. The book refers mainly to the development of submarines with special emphasis on their future.

(11) Frederick, S. & Capper H. (1980). Materials for Marine Machinery. New York: John Wiley. The book deals with materials for Marine Machinery in general, but two chapters of it, the first titled “Salt water systems” and the second “Fatigue Failures in Service” are very much related to our subject.

(12) Hassan, H. & Robinson W. (1980). ‘Maintenance and Care of Condensers Ch. Tube Failures’. Cornell Maritime Press. Modern Marine Engineers Manual (Volume I). New York: SNAME. pp 620-670

(13) Hodge, P. (1959). Plastic Analysis of Structures. New York: McGraw Hill. The book is based on the analysis of structures not in the usual elasticity theory but in the plastic analysis which is taking into consideration the ability of many materials to carry stresses above the yield strain. This corresponds extensively to the modelling of piping systems onboard submarine and presents a lot of additional advantages for design pipings as well.

(14) Kraus, H. (1976). Thin elastic shells. New York: John Wiley & Sons

(15) La Que, F.L & Tuithill, A.H. (1962). Werkstoffauswahl für Schiffsrohrleitungen end Kondensatoren. Hamburg: HANSA 99

(16) La Que, F.L. (1975). Marine Corrosion. New York: J. Wiley & Sons

(17) Masubuchi, K. (1975). Analysis of Welded Structures. London: Pergamon Press. The book is a major treatment of residual stresses, distortion and their influences on the service behaviour of welded structures, including specific applications of piping systems.

(18) Messerschmitt, Bolkow & Blohm. (1980). Technische Zuverlässigkeit. Berlin, Heidelberg & New York: Springer Verlag

(19) Möhler, J.B. (1975). Electroplating for the Metallurgist Engineer & Chemist. New York: Chemical Publishing Co, Inc.

(20) Richtlinien für den Korrosionsschutz in Wasserführenden Systemen. (1970). Hamburg: Germanischer Lloyd

(21) Ryabinin, I. (1976). Reliability of Engineering Systems. Moscow: MIR Publishers

(22) Störmer, H. (1970). Mathematische Theorie der Zuverlässigkeit. München: R. Oldenburg Verlag

(23) Thielsch, H. (1979). Defects and failures in pressure vessels and piping. New York: Reinhold Publishing Corporation

(24) Timoshenko, S. & Woinowsky-Krieger, S. (1970). Theory of Plates and Shells. New York: McGraw Hill Book Company

(25) Uhlig, H. (1948). Corrosion Handbook. N. York: Mc Graw Hill. It is a classical handbook covering the whole spectrum of corrosion both theoretically and in practical applications. Corrosion due to sea water is the main issue as well as topics of our special interest like the effect of mechanical factors in corrosion fatigue, cavitation fatigue, cavitation erosion etc.

(26) Woodward, J.B. (1975). Head and flow calculations for piping designs. Ann Arbor USA: University of Michigan. The book introduces the concepts and techniques of pressure drop calculations in piping with emphasis on principles and marine hydraulic systems as the ones extensively used onboard submarines. Very useful book for practical data, containing many relevant references.

APPENDIX ONE

LIST OF FIGURES

APPENDIX TWO

LIST OF TABLES

APPENDIX THREE

LIST OF ABBREVIATIONS

1 LTM : Long Term Maintenance

2 MAK : Long Term Maintenance

3 SND : Salamis Naval Dockyard

4 PEAK : Mid term Maintenance

5 MTM : Mid term Maintenance

6 Numbers in piping : Denote the "official" identity of the piping

7 (material) gal : means galvanized

8 Bb : left side of the submarine

9 Stb : right side of the submarine

10 St 35.8.II : steel of type st 35.8.II

11 1. 4571 : steel of type st 1.4571

12 TTF : Time to Fail

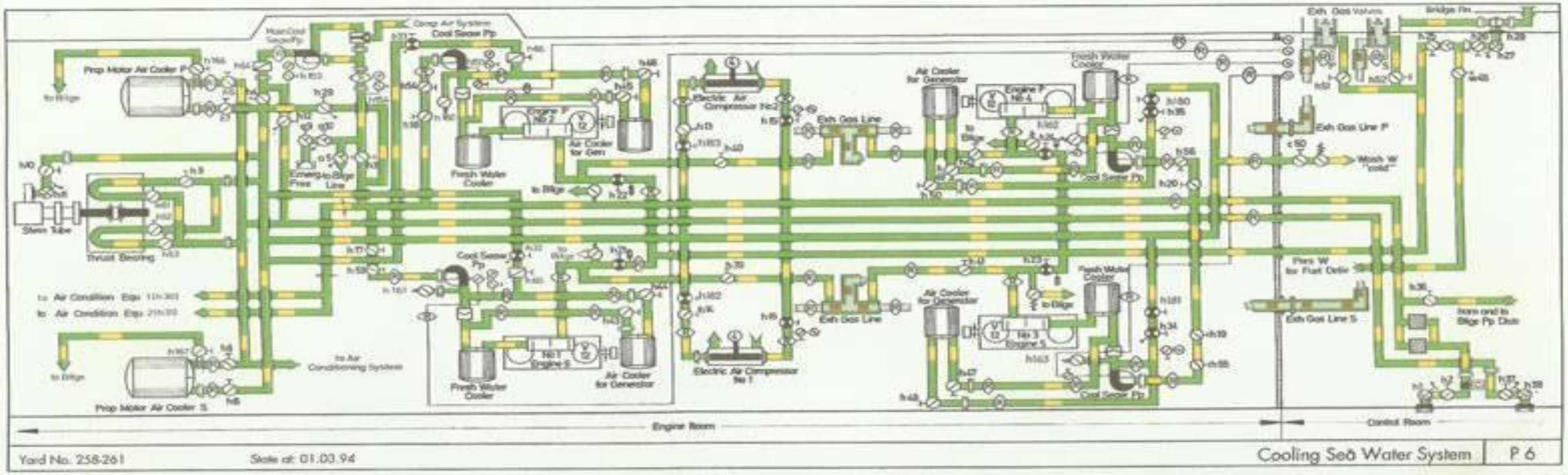
13 MTBF : Mean Time between Failure

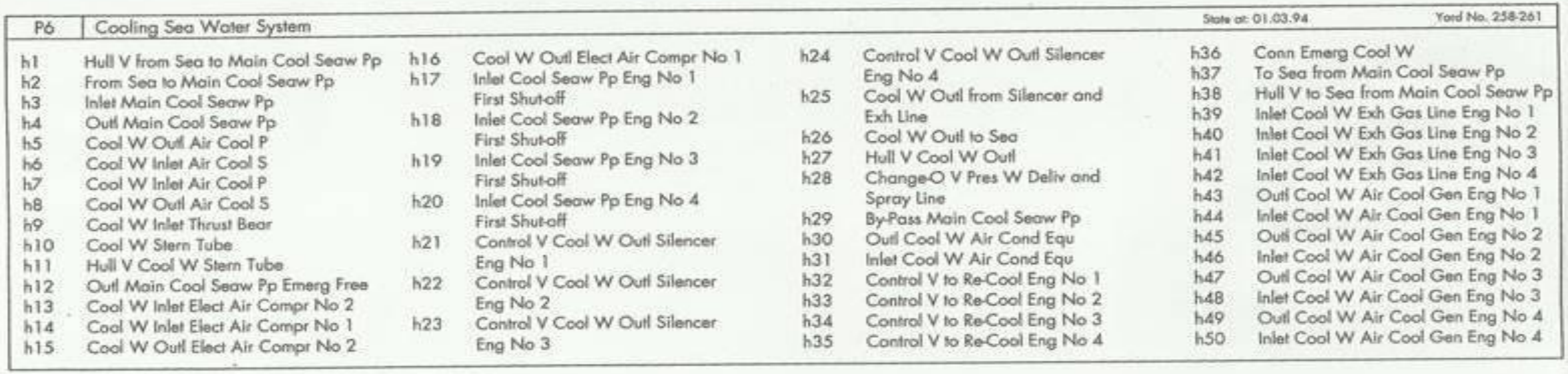
14 MTTR : Mean time to Repair

15 PDO : Planning and Design Office

APPENDIX FOUR

GENERAL DRAWING OF THE COOLING PIPING SYSTEM





P6 Cooling Sea Water System

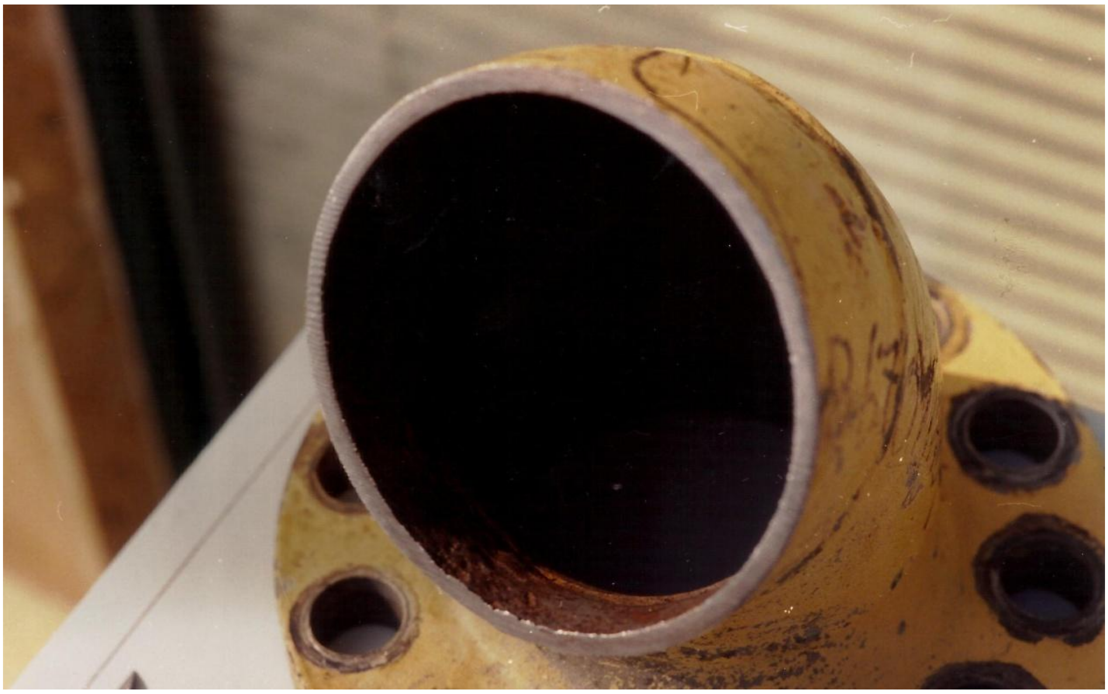
State at: 01.03.94 Yard No. 258-261

h1	Hull V from Sea to Main Cool Seaw Pp
h2	From Sea to Main Cool Seaw Pp
h3	Inlet Main Cool Seaw Pp
h4	Outl Main Cool Seaw Pp
h5	Cool W Outl Air Cool P
h6	Cool W Inlet Air Cool S
h7	Cool W Inlet Air Cool P
h8	Cool W Outl Air Cool S
h9	Cool W Inlet Thrust Bear
h10	Cool W Stern Tube
h11	Hull V Cool W Stern Tube
h12	Outl Main Cool Seaw Pp Emerg Free
h13	Cool W Inlet Elect Air Compr No 2
h14	Cool W Inlet Elect Air Compr No 1
h15	Cool W Outl Elect Air Compr No 2
h16	Cool W Outl Elect Air Compr No 1
h17	Inlet Cool Seaw Pp Eng No 1 First Shut-off
h18	Inlet Cool Seaw Pp Eng No 2 First Shut-off
h19	Inlet Cool Seaw Pp Eng No 3 First Shut-off
h20	Inlet Cool Seaw Pp Eng No 4 First Shut-off
h21	Control V Cool W Outl Silencer Eng No 1
h22	Control V Cool W Outl Silencer Eng No 2
h23	Control V Cool W Outl Silencer Eng No 3
h24	Control V Cool W Outl Silencer Eng No 4
h25	Cool W Outl from Silencer and Exh Line
h26	Cool W Outl to Sea
h27	Hull V Cool W Outl
h28	Change-O V Pres W Deliv and Spray Line
h29	By-Pass Main Cool Seaw Pp
h30	Outl Cool W Air Cond Equ
h31	Inlet Cool W Air Cond Equ
h32	Control V to Re-Cool Eng No 1
h33	Control V to Re-Cool Eng No 2
h34	Control V to Re-Cool Eng No 3
h35	Control V to Re-Cool Eng No 4
h36	Conn Emerg Cool W
h37	To Sea from Main Cool Seaw Pp
h38	Hull V to Sea from Main Cool Seaw Pp
h39	Inlet Cool W Exh Gas Line Eng No 1
h40	Inlet Cool W Exh Gas Line Eng No 2
h41	Inlet Cool W Exh Gas Line Eng No 3
h42	Inlet Cool W Exh Gas Line Eng No 4
h43	Outl Cool W Air Cool Gen Eng No 1
h44	Inlet Cool W Air Cool Gen Eng No 1
h45	Outl Cool W Air Cool Gen Eng No 2
h46	Inlet Cool W Air Cool Gen Eng No 2
h47	Outl Cool W Air Cool Gen Eng No 3
h48	Inlet Cool W Air Cool Gen Eng No 3
h49	Outl Cool W Air Cool Gen Eng No 4
h50	Inlet Cool W Air Cool Gen Eng No 4

APPENDIX FIVE

CHARACTERISTIC SAMPLES OF CORRODED PIPING

Picture 1



Picture 2

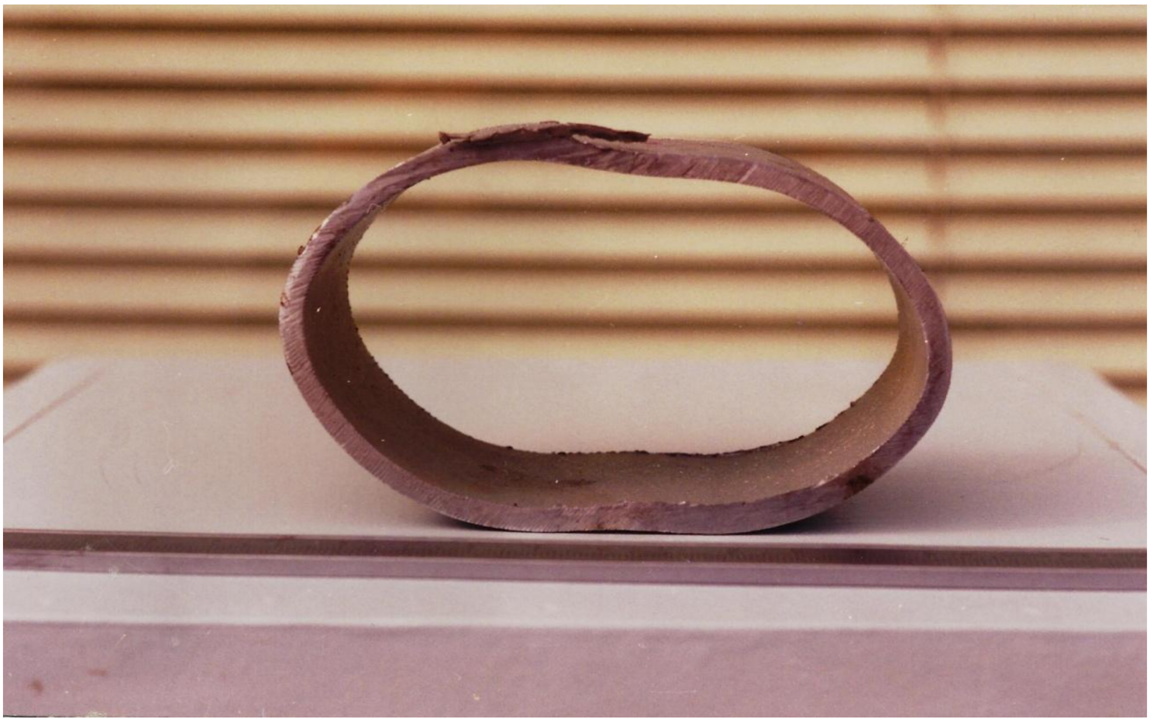
Picture 3

Picture 4

Picture 5

Picture 6

Picture 7



Picture 8