ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

RELIABILITY AVALIABILITY AND MAINTAINABILITY ANALYSIS IN NAVAL SHIPS

M.Sc. THESIS

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Department of Naval Architecture and Ocean Engineering

Marine Engineering Programme

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

SAVAŞ GEMİLERİNDE RAM ANALİZİ

YÜKSEK LİSANS TEZİ

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Oğuz AKKAYA, a M.Sc student of ITU Graduate School Of Scıence Engıneerıng And Technology student ID 508081011, successfully defended the thesis entitled "**RELIABILITY AVALIABILITY AND MAINTAINABILITY ANALYSIS IN NAVAL SHIPS**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my son Tuna and my wife Ayten ,

FOREWORD

Through the thesis, RAM Analysis is conducted for an auxiliary ship class in Turkish Navy. I acknowledge Turkish Navy HQ for the permission to inquire failure data of that ship class and also to publish the results.
I also acknowledge ISOGRAPH who supplied the software RWB 11.0, free of charge, for designing the ship system and calculating the results evaluated with an academic license for a period of six months.

December 2012 Oğuz AKKAYA

TABLE OF CONTENTS

Page

ABBREVIATIONS

CDF	**:** Cumulative Distribution Function
FMEA	**:** Failure Mode and Effectiveness Analysis
FT	**:** Fault Tree
FTA	**:** Fault Tree Analysis
GENSET	**:** Generator Set
MTBF	**:** Mean Time Between Failures
MTTF	**:** Mean Time To Failure
MTTR	**:** Mean Time To Repair
PDF	**:** Probability Distribution Function
RAM	**:** Reliability Availability Maintainability
RBD	**:** Reliability Block Diagram
RWB	**:** Reliability Workbench
SNAMEA	**:** Society of Naval Architects and Marine Engineers
S/G	**:** Steering Gear
TDT	**:** Total Down Time
UKAEA	**:** United Kingdom Atomic Energry Authority

LIST OF TABLES

Page

LIST OF FIGURES

Page

RELIABILITY AVALIABILITY AND MAINTAINABILITY ANALYSIS

IN NAVAL SHIPS

SUMMARY

Reliability Availability and Maintainability (RAM) analysis is performed to predict availability of a system in the future and to make amendments which will increase the performance of an equipment where necessary. Ram analysis has been used for many years by companies to decrease the number of failures of the equipments especially in warranty period.

Naval ships have various missions to accomplish. In order to accomplish the mission, ship availability should be considered with utmost importance. To identify the availability and reliability of a ship, failure rates of ship's components are used. Ram analysis computed by failure rates may be helpful for decision-makers in modernizing the ship equipments. Equipments which have lower reliability and availability, may be exchanged or may be modernized in order to increase the performance of the equipment and availability of the ship.

In order to maintain the availability, i.e., ship may continue to accomplish the missions assigned, Naval Ships should go through reliability, availability and maintainability analysis during both building and life cycle. Through Ram Analysis, components and systems, which reduce the availability of a ship, may be determined.

Reliability and safety methods experienced a rapid development after the Second World War. These methods were mainly concerned with military use for electronics and rocketry studies. The first predictive reliability models appeared in Germany on the V1 missile project where a reliability level was successfully defined from reliability requirements and experimentally verified on components during their development stages. The first formal approach to shipboard reliability was the Buships specification, MIL-R-22732 of July 31, 1960, prepared by the United States of America's Department of Defence and addressed ground and shipboard electronic equipment. After the success gained by RAM Analysis in military area, RAM analysis has been used by commercial purposes. Producers needed to improve the reliability of their items in order to seize the confidence of customers.

In this thesis, some of auxiliary class ships have been examined through the failures occurred between two overhauls. Reliability, availability and maintainability of the systems are calculated on component basis by the help of a commercial software named as Isograph Reliability Workbench. Reliability Block Diagram (RBD) has been prepared and analyzed.

Components affecting the availability of the ship are reported. This information may be used to decide whether these systems or components should be replaced with better systems or components. In this thesis, also a Fault Tree Analysis (FTA) is

carried out manually in order to help ship crew in finding the reasons of common failures which may occur in ships.

Results of RBD and FTA analysis are compared, and it is observed that they agree very well. The results include unavailability of system, failure frequency, unreliability, total down time of system and expected number of failures. While unreliability of system increases with working hours, unavailability of system does not change.

SAVAŞ GEMİLERİNDE RAM ANALİZİ

ÖZET

İngilizcede Reliability, Availability and Maintainability (RAM) analizi olarak kullanılan metod dilimizde Güvenilirlik, Kullanılabilirlik ve Sürdürülebilirlik Analizi olarak yer bulmaktadır.

RAM analizinin yapılış amacı, bir sistemin gelecekte sahip olacağı kullanılabilirliği önceden tahmin ederek, eğer ihtiyaç varsa sistemde yapılmasının faydalı olacağı değerlendirilen değişiklikleri tespit edip, bu değişikliklerin uygulanıp uygulanmaması konusundaki kararlara destek sağlamaktır. RAM analizi uzun yıllardır firmalarca kullanılmaktadır. Firmalar dizayn ve üretim süreçleri içerisinde RAM analizine yer vermektedirler.

RAM analizi ile firmalar ürettikleri ürünlerin tüketicilere sunulduktan sonra, minimum sayıda veya hiç arıza yapmadan kullanım ömürlerini tamamlamalarını hedeflemektedirler. Bu maksatla ürünün çok fazla sayıda arıza yaptığı başlangıç periyodunu tüketiciye sunmadan önce fabrika ortamında tamamlamakta, arıza oranının neredeyse sabit hale geldiği kullanım ömrü periyodunda ürünü tüketiciye sunmaktadırlar. Bu şekilde firmaya ait ürün çok fazla sayıda meydana gelecek arıza nedeniyle piyasada kötü bir üne sahip olmamaktadır. Firma yaptığı RAM analizi sonucunda ürünün kullanım ömrünün başlangıcını tespit ederek tüketiciye sunulacağı zamanı kararlaştırmaktadır. Piyasada ise tüketiciler o firmaya ait ürünlerin az arıza yaptığı imajına sahip olacaklarından, firmaya ait ürünler daha fazla tercih edilir hale gelecektir.

Güvenilirlik ve güvenlik konusundaki çalışmalar özellikle II.Dünya Savaşı'ndan sonra hız kazanmıştır. Bu çalışmalar genellikle elektronik cihazlar ve roket teknolojileri ile ilgili olarak yapılmaktaydı. Bu konuda güvenilirlik seviyesinin tam olarak tespit edildiği ve tespit edilen değerlerin deneylerle sistem bileşenlerinde ispat edildiği ilk çalışma olarak Almnya'da V1 füzelerinin üretiminde uygulamaya konulan RAM analizi sayılabilir. Ram analizi uygulamalarında ilk resmi uygulama ise, 1960 yılında Amerikan Savunma Bakanlığı tarafından elektronik cihazların güvenilirliği konusunda hazırlanan "Buships Spefications, MIL-R- 22732"dir. ABD savunma bakanlığı ve NASA RAM analizi kullanımının yaygınlaşmasında bir tür öncü rolü üstlenmiştir. Füze ve uzay teknolojileri ile üretilen ürünler onarılabilirlik açısından zayıf olduklarından, üretim ve dizayn aşamasında yapılan RAM analizi ile ürün kullanıldıktan sonra ortaya çıkması muhtemel tüm arızaların önlenmesi amaçlanmıştır. Füze ateşlendikten sonra elektronik kartlardan birinde çıkacak bir arızanın onarımı mümkün olmadığından, füze ateşlenmeden önce muhtemel arızaların engellenmesi büyük önem taşımaktadır.

NASA ve Amerikan Savunma Bakanlığı tarafından öncülüğü yapılan RAM analizi uygulamaları daha sonra sivil endüstriler tarafından da benimsenmiştir. Günümüzde beyaz eşya üreticilerine kadar bir çok sektörde dizayn ve üretim aşamalarında yapılan RAM analizi ile ürünler daha az arıza oranları ile tüketicilere sunulmaktadır.

Savaş gemilerine gerçekleştirmek üzere çok çeşitli görevler verilmektedir. Bu görevler verildiği anda geminin bu görevi gerçekleştirmeye hazır bulunması gereklidir. Savaş gemilerinin kullanılabilirliği bu aşamada önemlidir. Kullanılabilirliğin arttırılması için savaş gemilerini oluşturan bileşenlerin RAM analizine tabi tutulmaları gereklidir. RAM analizi yöntem olarak, dizayn ve test aşamalarında gerçekleştirilerek, üretime geçmeden önce ileride sistemlerin kullanılabilirliğini olumsuz etkileyecek parametrelerin tespit edilmesi ve iyileştirmelere gidilmesi şeklinde uygulanabileceği gibi, gemi yaşam periyodunda meydana gelen arızalar istatiksel olarak incelenerek RAM analizi yapılması ve gerekli iyileştirmelerin yapılması da mümkündür. Bu analizler sonrasında karar vericiler güvenilirliği ve kullanılabilirliği olumsuz etkileyen sistemlerin modernizasyonuna veya kullanımdan kaldırılmalarına karar verebilirler.

Bu tezde Türk Deniz Kuvvetlerine ait yardımcı sınıf olarak görev yapan 5 eş gemi çalışma konusu yapılmıştır. Bu gemilerin iki overhol onarımı arasındaki arıza kayıtları incelenerek, gemi tipine ait genel bir güvenilirlik ve kullanılabilirlik değerlendirmesi yapılmıştır.

Öncelikle bir yardımcı sınıf askeri geminin görev ihtiyaçlarını yerine getirebilmesi için gerekli olan minimum sistemler göz önüne alınarak bir gemi sistemi oluşturulmuştur. Bu geminin ana sistemleri olarak ana tahrik sistemi, elektrik üretim sistemi, dümen sistemi ve yara savunma sistemi ele alınmıştır. Bu dört sistemden birinin arızalanması durumunda geminin görev yapamayacağı değerlendirilmiştir. Beş geminin iki overhol arası arızaları incelenmiş, her bir cihazın en fazla sayıda arıza yapanı seçilmek suretiyle beş gemi en çok arıza yapan cihazlardan oluşan sanal bir gemi olarak düşünülmüştür. Bu şekilde elde edilecek sonuçların en kötü senaryoyu ortaya koyacağı değerlendirilmiştir.

Analizin yapılmasında Isograph firması tarafından verilen akademik lisans kullanılarak, Reliability Workbench 11.0 ticari programı kullanılmıştır. Programda öncelikle RBD modülünde gemi sistemi oluşturulmuştur. Daha sonra sistemin alt sistemleri ve alt sistemlerin kullanılabilirliğini etkileyen olaylar RBD modülüne eklenmiştir. Kullanılabilirliği etkileyen her bir olayın arıza modelleri, geçmişte meydana gelen arızalardan hesaplanan MTTF ve MTBF değerleri girilerek oluşturulmuştur. Isograph RWB tarafından, oluşturulan sistem ve arıza modelleri doğrultusunda analiz yapılarak, gerek alt sistemlerin, gerekse ana sistemlerin güvenilirlik, kullanılabilirlik değerleri hesaplanmış ve raporlanmıştır. Geminin görev yapmasını etkileyecek arızaların işlendiği bir hata ağacı FT modülünde hazırlanarak bu modülle de hesaplama yaptırılmış ve sonuçlar karşılaştırılmıştır.

Elde edilen sonuçlar gemi tipinin kullanılabilirlik açısından tatmin edici seviyede olduğunu göstermiştir. Güvenilirlik analizinde güvenilirliğin zamanla azaldığı tespit edilmiştir. Bu sorunun iki overhol arası süreyi azaltarak giderilebileceği vurgulanmakla birlikte, gemilerin kullanılabilirlik oranlarının yüksekliği nedeniyle sadece önemli cihazlarda yapılacak koruyucu ve ara bakımlarla yetinilebileceği değerlendirilmiştir.

1. INTRODUCTION

Reliability, Availability and Maintainability (RAM) analysis is performed to predict availability of a system in the future and to make amendments which will increase the performance of the system. RAM analysis has been used for many years by companies to decrease the number of failures of the equipments especially in warranty period.

Naval ships have various missions to accomplish. In order to accomplish the mission, ship availability should be considered with utmost importance. To determine availability and reliability of the ship, failure rates of ship's components are used. Ram analysis computed by failure rates may be helpful for decision-makers in modernizing the ship equipments. Equipments which have lower reliability and availability, may be replaced or modernized in order to increase the performance of the equipment and availability of the ship.

1.1 Purpose of Thesis

In order to maintain the availability, i.e., ship may continue to accomplish the missions assigned, Naval Ships should go through reliability, availability and maintainability analysis during both building and life cycle. Through Ram Analysis, components and systems, which reduce the availability of ship, can be determined. In this thesis, some of auxiliary class ships have been examined through the failures occurred between two overhaul. Reliability, availability and maintainability of the systems are calculated on component basis by the help of a commercial software. Components affecting the availability of the ship are reported. This information may be used to decide whether these systems or components should be replaced with better systems or components.

In this thesis a Fault Tree Analysis (FTA) is carried out to help ship crew in finding the reasons of common failures which may occur in ships.

1.2 7 Literature Review

Reliability and safety methods experienced a rapid development after the Second World War. These methods were mainly concerned with military use for electronics and rocketry studies. The first predictive reliability models appeared in Germany on the V1 missile project where a reliability level was successfully defined from reliability requirements and experimentally verified on components during their development stages (Bazovsky, 1961).

The first formal approach to shipboard reliability was the “Buships Specification, MIL-R-22732” of July 31, 1960, prepared by the United States of America’s Department of Defence and addressed ground and shipboard electronic equipment. Subsequently in 1961 the Bureau of Weapons issued the MIL standards concerning reliability models for avionics equipment and procedures for the prediction and reporting of the reliability of weapon systems. This was due to the fact that the growing complexities of electronic systems were responsible for the failure rates leading to a significantly reduced availability on demand of the equipment (MIL 1960).

In February 1963 the first symposium on advanced marine engineering concepts for increased reliability was held at the office of Naval Research at the University of Michigan. In December 1963 a paper entitled “Reliability Engineering Applied to the Marine Industry” was presented at the Society of Naval Architects and Marine Engineers (SNAME) and the following year in June another paper, entitled “Reliability in Shipbuilding”, was presented. Following the presentation of these two papers, SNAME in 1965 established Panel M-22 to investigate the new discipline as applied to marine machinery and make it of use to the commercial marine industry.

In the last three decades, stimulated by public reaction and health and safety legislation, the use of risk and reliability assessment methods has spread from the higher risk industries to an even wider range of applications. The Reactor Safety Study undertaken by the U.S.A. (U.S Nuclear Regulatory Commission (1975)) and the Canvey studies performed by the UK Health & Safety Executive resulted from a desire to demonstrate safety to a doubtful public. Both these studies made considerable use of quantitative methods, for assessing the likelihood of failures and for determining consequence models.

There is a long history in the United Kingdom (UK) on research, development and successful practical application of safety and reliability technology. There is a continuing programme of fundamental research in areas such as software reliability and human error in addition to further development of the general methodology. Much of the development work was carried out by the nuclear industry. Based on the considerable expertise gained in the assessment of nuclear plants, a National Centre for System Reliability (NCSR) was established by the UK Atomic Energy Authority (UKAEA) to promote the use of reliability technology. This organization plays a leading role in research, training, consultancy and data collection. The NCSR is part of the safety and reliability directorate of the UKAEA, which has played a major role in formulating legislation on major hazards, and has carried out major safety studies on industrial plants. It is noted that some of the major hazard studies commissioned at the national level in the UK have included the evaluation of the risks involved as a result of marine transportation of hazardous materials such as liquefied gases and radioactive substances. It is expected that the recent legislation in relation to the control of major hazards will result in a wider use of quantitative safety assessment methods and this will inevitably involve the marine industry.

Most chemical and petrochemical companies in the UK have made use of safety and reliability assessment techniques for plant evaluation and planning. Similar methods are regularly employed in relation to offshore production and exploration installations.

The Royal Navy has introduced reliability and maintainability engineering concepts in order to ensure that modern warships are capable of a high combat availability at optimum cost. The application of these methods has been progressively extended from consideration of the operational phase and maintenance planning to the design phase. To date, comparatively little use of safety and reliability assessment methods has been made in connection with merchant shipping. Lloyd's Register of Shipping has for a long period, collected information relating to failures and has carried out development work to investigate the application of such methods to the classification of ships. Apart from this, some consultancy work has also been carried out on behalf of ship owners. One example is the P&O Grand Princess , for which a comprehensive safety and availability assurance study was carried out at the concept design stage of this cruise ship (Best and Davies, 1999). Established risk assessment techniques were used including Failure Mode and Effects Analysis (FMEA), flooding risk analysis and fire risk analysis. The resultant ship was believed to be better and safer than it would have been otherwise. P&O has now developed an in-house safety management system which is designed to capture any operational feedback, so as to improve the safety and efficiency of its cruise fleet operation and to use it for better design in the future. The merchant ship-building yards in the UK, having seen the success of the warship yards in applying Availability, Reliability and Maintainability (ARM) studies at the design stage, are actively seeking benefits from adopting a similar approach. Some joint industry-university research projects are being undertaken to explore this area (Molland, 2008).

1.3 Applications of RAM Analysis

Reliability Availability and Maintainability (RAM) analysis is established at first by NASA and US Air Force, and later improved especially by household appliance producers in order to decrease the costs paid by themselves during the warranty period of the product.

NASA has established this approach to reduce the chance of failure which may occur during the space program, since failures could not be repaired after launch of the space crafts. That’s why, to achieve minimum number of faults during space craft production has been very important for NASA. US Air Force followed NASA in RAM analysis applications.

Especially in flight operations, some failures cause fatal consequences which makes the reliability highly important. As in space programs of NASA, US Air Force started to apply reliability programs particularly for electronic equipments. The aim was to decrease the failure rate of electronic devices. Reliability programs held by US air Force motivated US Department of Defence (DoD) to indicate some standards for reliability programs. MIL-STD-721C Definition of Terms for Reliability and Maintainability is one of the sources stating the definitions about RAM Analysis. Another source printed by DoD about RAM Analysis is MIL-STD-756B Reliability Modelling and Prediction including the information on modelling and predicting the reliability of a system. DoD has established lots of standards on reliability by publishing handbooks and directives.

After the success gained by RAM Analysis in military area, RAM analysis was used by commercial purposes. Producers needed to improve the reliability of their items in order to seize the confidence of customers. Extended warranty periods are preferred by end user when two items to be bought were compared. Since extending the warranty period would increase the after-sales services costs, producers thought that it would be more economical to produce reliable items, instead of losing more money in repairs. Producers aimed to serve their products in their useful life in which less number of failures occur. Figure 1.1 shows bathtube curve including three phase of product life. First phase is initial period through which fabric tests are applied to products. In the initial period number of failures is high. Producers aim to deliver the products to costumers after this period. Second phase is useful life of the product in which number of failures is less than initial period and wear-out period. During this period failure rate (λ) is constant.

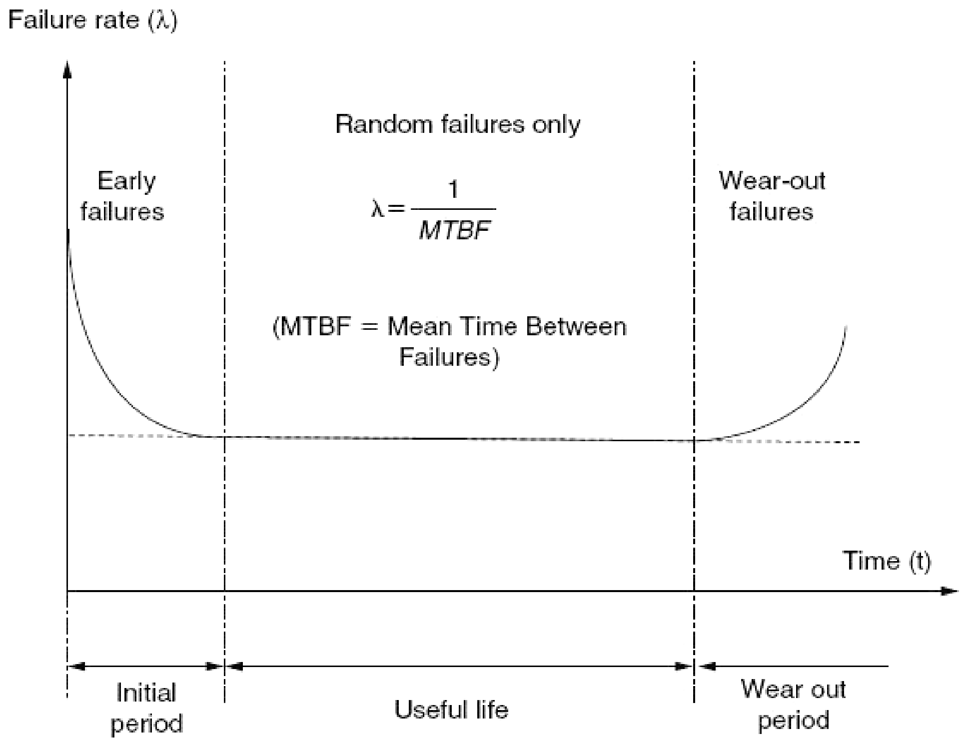

Figure 1.1 : Bathtube curve.

Currently most of the companies prepare reliability programmes to perform RAM Analysis in design phase. According to the results obtained from RAM Analysis, producers make necessary changes on project or product to increase the reliability. Making alterations in design phase decreases the expenditures of the company for the faults of the product which will be experienced after-sale phase. Repairs or corrections after the product sold also cause bad reputation for the product and company.

Because of the reasons explained above, RAM Analysis has gained well-deserved importance in almost every engineering area. Reliability prediction has been made for repairable and non-repairable items currently. For non-repairable and repairable items, reliability analysis has been made respectively on the basis of Mean Time To Failure (MTTF) and Mean Time Between Failures (MTBF). For both types the aim targeted is to decrease the number of failures and increase MTTF or MTBF especially in warranty period of the product. Increasing the reliability of the products by programs hold has given producers an opportunity to extend the warranty periods. Thanks to the extended warranty periods, producer have got advantage in competition against the rivals. Products with extended warranty periods have been chosen by the customers, since these products made people think that they were more reliable than before. Producers also have got cuts in expenditures in warranty period which is determined according to the first phase of bath-tube curve for failures. RAM Analysis has shortened the first part of the curve through which more failures occurred compared with the latest life cycle of the product. Hence, producer still believe the benefits of RAM Analysis and commonly use reliability programmes in design periods.

Since increasing concern and need for RAM Analysis in industrial area, reliability has found a place in engineering education as lectures on different engineering programmes. Some international meetings, conferences and trainings have been held about reliability and still continue. Some software have been prepared and provided commercially in order to make reliability calculation of the complex systems.

A marine application of RAM Analysis is "*Study of Reliability, Maintainability and Availability: A Case Study of a Shuttle Tanker ropulsion System*" by Balingwi.(1999). In this research, ship propulsion system is modelled in order topredict and optimize the effectiveness of the ship propulsion system. The objectives of this research were to review the process of evaluatinga shuttle tanker propulsion system's reliability, maintainability and availability, and to investigate the computurised simulation statistical approach to help manage the information which is required in making intelligent maintenance and repair decisions.

2. DEFINITIONS

2.1 Reliability

Reliability may be expressed as: “The probability that an item will perform required function without failure under a stated condition for a stated period of time” (O’Connor, 1981). A customer, purchasing the product, accepts that it may fail at some future time. Coupling this acceptation with a warranty period relieves the customer about the failures of the item in future. But this relief does not last after warranty period. During the warranty period problems are solved by producer without any charge. It seems that failures occurred during warranty period are not problem for both side, customer and producer. In fact it is not so. Increase in number of failures causes warranty costs for the producer increase, as it is inconvenient for the customer also. Outside the warranty period, only customer suffers about the failures. In both cases, producer will probably incur a loss of reputation which may affect future business relations.

Reliability may also be expressed in other ways. One of the definition states that “reliability for non-redundant items is the duration or probability of failure-free performance under stated conditions. For redundant items it may be expressed as the probability that an item can perform its intended function for a specified interval under stated conditions” (MIL-STD 721C).

2.2 Maintainability

Maintainability is an expression about repairable items. Non-repairable items are the ones used just for once and disposed i.e. fuel filters. Systems are repaired when they fail, and some labour force is spent for the system to work properly. These all efforts are fulfilled to maintain the system. How easy the system can be carried out by repair and other maintenance work shows the maintainability of the system.

Maintainability can be quantified as the mean time to repair (MTTR). The time needed for repair including several activities may be divided into three groups as below (O'Connor, 1981);

1. Preparation time which consist of finding person for the job, travel,obtaining tools and test equipment,
2. Active maintenance time at which job is actually done,
3. Delay time caused by waiting for the spare parts etc after the job has already been started.

Maintainability is expressed as "the measure of the ability of an item to be retained in or restored to specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair" (MIL-STD 721C).

Maintained systems may be subject to corrective and preventive maintenance. Corrective maintenance includes all actions to return a system from a failed to an operating or available state. The amount of corrective maintenance is therefore determined by reliability. Corrective maintenance action cannot be planned. It may be needed even when it is not expected. The aim of preventive maintenance is to retain the system in an operational or available state. This aim may be achieved by preventing the failures before they happen. In a mechanical system it may be possible by the ways of lubrication, cleaning, inspection and calibration which are made in schedule. Preventive maintenance affects reliability of a system directly.

2.3 Availability

According to military standards of US Department of Defence, availability is described as; "a measure of the degree to which an item is an operable comitable state at the start of a mission when the mission is called at unknown (random) time (MIL-STD 721C). It is needed to explain the difference between availability and dependability. Availability concerns the time before the mission starts. If system is ready to perform the mission when it is ordered, then availability of the system is mentioned. But, if we talk about the system's ability to continue its performance during the mission, then we emphasize dependability of the system.

The time taken to repair the failures and to carry out the preventive maintenance removes the system from the available state. There is thus a close relationship between reliability and maintainability , one affecting the other and both affecting availability and costs. Assuming that maintenance actions occur at a constant rate, in a steady state after a transient behavior has settled down availability may be formulated as below (O'Connor, 1981);

$$Availability = \frac{MTBF}{MTBF + MTTR + Mean\,Preventive\,Maintenance\,Time}$$

2.4 Redundancy

The existence of more than one means to accomplishing a given mission is called as redundancy. In naval ships redundancy has high importance to increase the availability of a system without any interruption.

2.5 Mean Time Between Failures (MTBF)

MTBF is described as the mean number of life units during which all parts of item perform in their specified limits, during a particular time interval under stated conditions. MTBF is a basic measure of reliability for repairable items.

2.6 Mean Time To Failure (MTTF)

MTTF is the mean number of life units of an item divided by the total number of failures within that population during a particular measurement interval in stated conditions. MTTF is a basic measure of reliability for non-repairable items.

2.7 Mean Time To Repair (MTTR)

The sum of corrective maintenance times at any maintenance level of repair divided by the total number of failures within an item repaired at that level during a particular interval in stated conditions. MTTR is a basic measure of maintainability.

3. **RELIABILITY**

In the broadest sense, reliability is associated with dependability, with successful operation, and with the absence of breakdowns or failures. It is necessary for engineering analysis, however, it is about defining reliability quantitatively as a probability. Thus reliability is defined as the probability that a system will perform its intended function for a specified period of time under a given set of conditions.

A product or system is said to fail when it ceases to perform its intended mission. This cessation may occur as entirely breakdown or as lower performance for the mission intended. A generator may not produce electricity because of the absence of exciting current. This type of failure may be referred as complete breakdown of the generator. But if it produces energy lower than it is intended, it has lower performance. This may be caused by a failure on fuel supply system of the engine. In both case generator does not perform well. It is necessary to define failure quantitatively in order to take into account the more subtle forms of failure. Having knowledge of why the failure occurred in detail would help to calculate the reliability of the system more accurately.

The expression of time in the definition of reliability may vary in some cases. When we consider a intermittently working device can we talk about calender time? If the operation is cyclic, such a on-off of a switch, time is likely to be cast in terms of number of the operations. If we consider a pump working intermittently, we should cast the time in terms of hours of operation. If we use calender time in calculations, then we must consider the frequency of starts and stops and the ratio of operating to total time. Instead of calender time, it seems better to use operating hours for the best practice.

3.1 Reliability Mathematics

Reliability concerns the probability of a device to have failure in a specific time period. Reliability can be specified as the mean number of failures in a given time which can be also described as failure rate or can be expressed as the mean time between failures MTBF for repairable items, or as the mean time to failure MTTF for non-repairable items. Repairable items are repaired and returned to use again after repair. For repairable items, it is usually assumed that failures occur at constant rate, and it is expressed as (O'Connor, 1981);

$$\lambda = \frac{1}{MTBF} \quad \textbf{(3.1)}$$

3.2 Redundancy

Redundancy has great importance in naval ships. All naval ship are designed in capability to serve continuously even when some devices have faults which prevent the device performing the mission properly. In order to provide uninterrupted mission accomplishment, main devices have standby systems which will work in case of failure of actual one. Thus, system performance is kept in any case of system failure.

3.3 System Structures

It is generally excepted that there are four generic types of relationships between a device and its components. These relationships may be expressed as series, parallel, k out of n and others. These relationships directly affect the redundancy of the system.

3.3.1 Series systems

The simplest and most commonly encountered configuration of components is the series system. "A series system is one in which all components must function properly in order for the system to function properly" (Nachlas, 2005). According to the definition, if one of the components fails, then system cannot perform the properly. Reliability block diagram for a series system may be shown as in Figure 3.1.

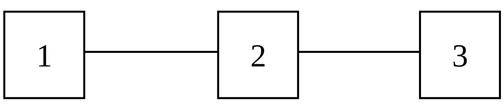

Figure 3.1 : Series system.

The function of system may be expressed as;

$$\Phi(x) = \prod_{i=1}^{n} x_i \tag{3.2}$$

Only the functioning of all components yields system function.

3.3.2 Parallel system

The second type of components' structure is the parallel structure. "A parallel system is one in which the proper function of any component implies system function" (Nachlas, 2005). One example of a parallel system is the set of two engines on a two engine electric supply system of a ship. As long as at least one of the engine function properly, supplement of electricity through the ship may be accomplished. The function for parallel system is;

$$\Phi(x) = \coprod_{i=1}^{n} x_i = 1 - \prod_{i=1}^{n}(1 - x_i) \tag{3.3}$$

The structure function for a parallel system may be expressed as Figure 3.2;

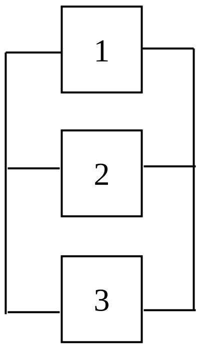

Figure 3.2 : Parallel system.

Conceptually a parallel system is failed when all system components are failed. Parallel arrangement of components is often referred to as redundancy. This is because the proper function of any of the parallel components implies proper function of the structure. Thus, the additional components are redundant until an actually performing component fails. Frequently, parallel structures are included in product designs specifically because of resulting redundancy. Often but not always, the parallel components are identical. At the same time, there are actually several ways in which the redundancy may be implemented. A distinction is made between redundancy obtained using a parallel structure in which all components function simultaneously and that obtained using parallel components of which one functions and the others wait as standby units until the failure of functioning unit.

3.3.3 K-out-of-n systems

"A k-out-of-n system is one in which the proper function of any k of the n components that comprise the system implies proper system function" (Nachlas, 2005). In this type of structures, the number of components needed to imply the function properly is indicated by letter k, while system has more number of similar components which is indicated by letter n.

Electric supply system of a large ship may be described by this type of structure. In large naval ships for example in frigates, there several number of generators to for electric supply. These generators placed in different parts of the ship may be designed to supply different networks or all may supply all the networks. In naval ships generators are designed to a power more than the ship needs. Even in a small naval boat such as coast guard boats, there are at least two generators for electric supply, even though one is enough. In large ships having 5 generators, 3 of them are on and it is enough to function the electric system. It has no importance which of the 5 generators are on.

The function for a k-out-of-n system;

$$\Phi(x) = \begin{cases} 1 \;\; if \; \sum_{i=1}^{n} x_i \geq k \\ 0 \end{cases} \quad \textbf{(3.4)}$$

3.4 Failure rate

The failure rate which is donated by λ, is expressed in terms of failures per unit time, such as failures per hour or failures per 100 hours or failures per 1000 hours. It is computed as a simple ratio of the number of failures, *f*, during a specified test interval *T*;

$$\boldsymbol{\lambda} = \frac{\boldsymbol{f}}{\boldsymbol{T}} \quad \textbf{(3.5)}$$

3.5 Mean time between failures (MTBF)

During the operating period, when failure rate is fairly constant, MTBF is reciprocal of the constant failure rate to the number of failures (Govil, 1983)

$$\text{MTBF} = \boldsymbol{\frac{1}{\lambda}} = \boldsymbol{\frac{T}{f}} \qquad \textbf{(3.6)}$$

3.6 Mean time to failure (MTTF)

For an information on *n* items with failures $t_{1,}t_{2,}.....t_n$, MTTF is defined as;

$$\text{MTTF} = \boldsymbol{\frac{1}{n}\sum_{i=1}^{n} t_i} \qquad \textbf{(3.7)}$$

3.7 Mean time to repair (MTTR)

For an information on *n* items with repair times $t_{1,}t_{2,}.....t_n$, MTTR is defined as;

$$\text{MTTR} = \boldsymbol{\frac{1}{n}\sum_{i=1}^{n} t_i} \qquad \textbf{(3.8)}$$

3.8 Reliability

The constant failure rate model for continously operating systems leads to an exponential distribution (Lewis, 1996). Probability density function for a constant failure rate (PDF);

$$f(t) = \lambda e^{-\lambda t} \qquad \textbf{(3.9)}$$

Similarly, cumulative distribution function (CDF) becomes

$$F(t) = 1 - e^{-\lambda t} \qquad \textbf{(3.10)}$$

And reliability may be written as

$$\mathrm{R(t) = e^{-\lambda t}} \qquad \textbf{(3.11)}$$

4. FAULT TREE ANALYSIS (FTA)

Fault Tree Analysis (FTA) is a formal deductive procedure for determining combinations of component failures and human errors that could result in the occurrence of specified undesired events at the system level (Ang and Tang ,1984).

It is a diagrammatic method used to evaluate the probability of an accident resulting from sequences and combinations of faults and failure events. This method can be used to analyse the vast majority of industrial system reliability problems. FTA is based on the idea that:

1. A failure in a system can trigger other consequent failures.
2. A problem might be traced backwards to its root causes.
3. The identified failures can be arranged in a tree structure in such a way that their relationships can be characterised and evaluated (Andrews and Moss, 2002).

4.1 Benefits To Be Gained From FTA

There are several benefi ts of employing FTA for use as a safety assessment tool. These include:

1. The Fault Tree (FT) construction focuses the attention of the analyst on one particular undesired system failure mode, which is usually identified as the most critical with respect to the desired function.
2. The FT diagram can be used to help communicate the results of the analysis to peers, supervisors and subordinates. It is particularly useful in multi-disciplinary teams with the numerical performance measures.
3. Qualitative analysis often reveals the most important system features.
4. Using component failure data, the FT can be quantified.

5. The qualitative and quantitative results together provide the decision-maker with an objective means of measuring the adequacy of the system design.

An FT describes an accident model, which interprets the relation between malfunction of components and observed symptoms. Thus the FT is useful for understanding logically the mode of occurrence of an accident. Furthermore, given the failure probabilities of the corresponding components, the probability of a top event occurring can be calculated. A typical FTA consists of the following steps:

1. System description.
2. Fault tree construction.
3. Qualitative analysis.
4. Quantitative analysis.

These steps are illustrated in Figure 4.1 .

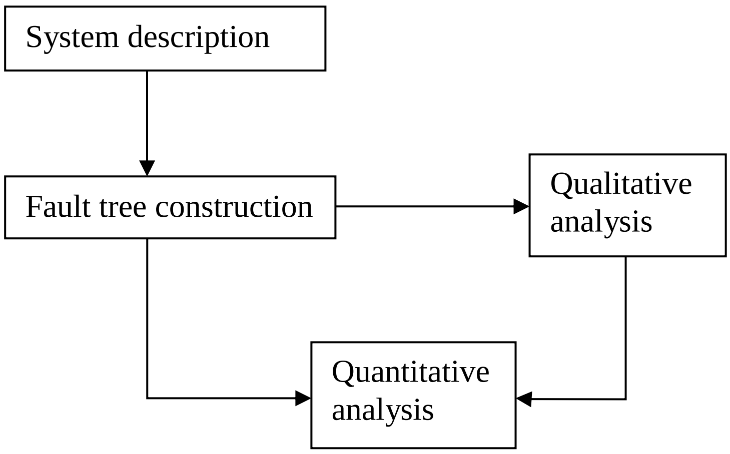

Figure 4.1 : FTA Construction Steps.

4.2 System Definition

FTA begins with the statement of an undesired event, that is, failed state of a system. To perform a meaningful analysis, the following three basic types of system information are usually needed:

1. Component operating characteristics and failure modes: A description of how the output states of each component are infl uenced by the input states and internal operational modes of the component.

2. System chart: A description of how the components are interconnected. A functional layout diagram of the system must show all functional interconnections of the components.
3. System boundary conditions: These define the situation for which the fault tree is to be drawn.

4.3 Fault Tree Construction

FT construction, which is the first step for a failure analysis of a technical system, is generally a complicated and time-consuming task. An FT is a logical diagram constructed by deductively developing a specific system failure, through branching intermediate fault events until a primary event is reached. Two categories of graphic symbols are used in an FT construction, logic symbols and event symbols.

The logic symbols or logic gates are necessary to interconnect the events. The most frequently used logic gates in the fault tree are AND and OR gates. The AND gate produces an output if all input events occur simultaneously. The OR gate yields output events if one or more of the input events are present. The event symbols are rectangle, circle, diamond and triangle. The rectangle represents a fault output event,

which results from combination of basic faults, and/or intermediate events acting through the logic gates.

The circle is used to designate a primary or basic fault event. The diamond describes fault inputs that are not a basic event but considered as a basic fault input since the cause of the fault has not been further developed due to lack of information. The triangle is not strictly an event symbol but traditionally classified as such to indicate a transfer from one part of an FT to another. Figure 4.2 gives an example of a fault tree.

To complete the construction of a fault tree for a complicated system, it is necessary first to understand how the system works. This can be achieved by studying the blue prints of the system (which will reflect the interconnections of components within the system). In practice, all basic events are taken to be statistically independent unless they are common cause failures. Construction of an FT is very susceptible to the subjectivity of the analyst. Some analysts may perceive the logical relationships between the top event and the basic events of a system differently. Therefore, once the construction of the tree has been completed, it should be reviewed for accuracy, completeness and checked for omission and oversight. This validation process is essential to produce a more useful FT by which system weakness and strength can be identified.

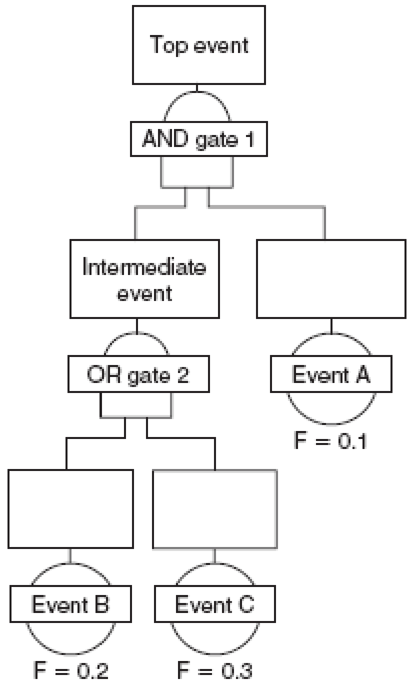

Figure 4.2 : FTA Example.

4.4 Qualitative Fault Tree Evaluation

Qualitative FTA consists of determining the minimal cut sets and common cause failures. The qualitative analysis reduces the FT to a logically equivalent form, by using the Boolean algebra, in terms of the specific combination of basic events sufficient for the desired top event to occur. In this case, each combination would be a critical set for the undesired event. The relevance of these sets must be carefully weighted and major emphasis placed on those of greatest significance.

4.5 Quantitative Fault Tree Evaluation

In an FT containing independent basic events, which appear only once in the tree structure, then the top event probability can be obtained by working the basic event probabilities up through the tree.

In doing so, the intermediate gate event probabilities are calculated starting at the base of the tree and working upwards until the top event probability is obtained.

When trees with repeated events are to be analysed, this method is not appropriate since intermediate gate events will no longer occur independently. If this method is used, it is entirely dependent upon the tree structure whether an overestimate or an underestimate of the top event probability is obtained. Hence, it is better to use the minimal cut-set method.

The occurrence probability of a top event can then be obtained from the associated minimum cut sets. The following two mini-trees are used to demonstrate how the occurrence probability of a top event can be obtained:

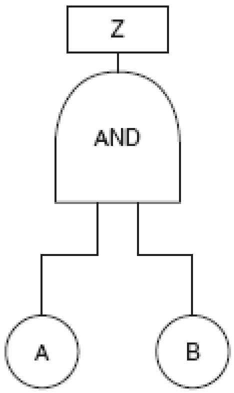

Figure 4.3 : Minimum Cut Set 1.

Obviously the minimum cut set for the mini-tree below is $A \cdot B$.

If one event is independent from the other, the occurrence probability of top event *Z*:

$$P(Z) = P(A.B) = P(A)xP(B) \quad \textbf{(4.1)}$$

where P(A) and P(B) are the occurrence probabilities of events A and B.

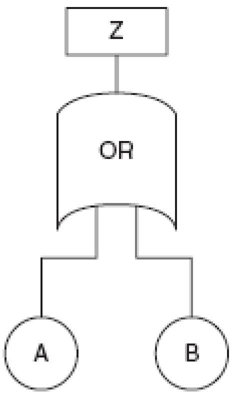

Figure 4.4 : Minimum Cut Set 2

Obviously the minimum cut set for the mini-tree above is *A* + *B*.

If one event is independent from the other, the occurrence probability of top event *Z* is

$$P(Z) = P(A + B) = P(A) + P(B) - P(A)xP(B) \quad \textbf{(4.2)}$$

where P(A) and P(B) are the occurrence probabilities of events A and B.

FTA may be carried out in the hazard identification and risk estimation phases of the safety assessment of ships to identify the causes associated with serious system failure events and to assess the occurrence likelihood of them. It is worth noting that in situations where there is a lack of the data available, the conventional FTA method may not be well suited for such an application.

5. SCOPE OF THE THESIS

Through this thesis, reliabilities of the main systems, which are crucial for the mission of the ship, have been analyzed. Firstly, the main systems required to accomplish the mission of the ship are determined. Systems are chosen so that even if one of the systems is failed, ship cannot perform the mission. Failure data are needed to compute reliability of the ship. They have been collected from 5 sister ships of Turkish Navy (TN). These ships are at service as auxiliary ships.

Data have been collected from 5 ships for the period between two overhaul periods of the ships. Data from all ships are analyzed and the one which has highest number of failures is chosen for the project. Events are chosen from different ships and a virtual ship is determined with the events which are the highest among others. In this way the results compiled by the project will be the worst case for the ship class.

The systems chosen for an auxiliary ship are propulsion system, steering gear system, damage control system and electric supply system, shown in Figure 5.1. These systems have been branched to subsystems and components. Each component's number of failures' data has been used to compute failure rate of the components. Failure rates, MTTF, MTTR and MTBF have been computed on a MS Excel sheet. It is assumed that components have constant failure rates and reliability values are computed according to exponential distribution as shown Equation 3.11.

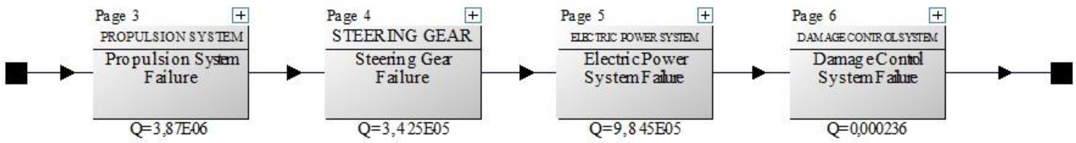

Figure 5.1 : Ship SystemRBD.

Failure rate and MTBF data have been imported to Isograph Reliability Workbench 11.0. By using the software RBDs for each system including all components, have been prepared. MTTF and MTTR values of the components have been imported to the software and unavailability and unreliability values of the system have been computed.

After preparing RBDs for the ship's systems, fault tree (FT) construction has been produced by the software. Since FT produced by software is complicated and hard to follow, simplified FT of the systems are prepared manually.

5.1 Assumptions

Through the thesis, five of an auxiliary class of Turkish Navy Ships have been examined. Failure reports of five ships have been collected. The mostly experienced failures in all ships have been examined and the one which has highest failure rate among identical components has been chosen for analysis. For all the systems working hour has been identified as the time between two overhaul period, which is being executed as 6 years for the class of ships in Turkish Navy.

For the systems and components serving as auxiliary apparatus e.g. fuel transfer pump, fire-figthing pump, hatches, portholes etc., six years of maintenance period, which is equal to 52560 hours has been identified as working hours.

For propulsion units, number of failures have been collected in all ships and it assumed that five ships' propulsion systems are identical. The number of working hours of chosen component has been taken into account. The working hour is recalculated directly proportional to ship's overhaul period 6 years, 52560 hours in order to use the same project time for all the ship systems.

For electric production generators No:1 and No:2 of all ships have been examined and in order to represent the worst case, highest number of failures of the componenets have been chosen as in propulsion system.

For Steering Gear System working hours of the components have been taken according to the number of working hours of the propulsion components, since Steering Gear would have the same working hours with propulsion system.

5.2 Utilization of Isograph Reliability Workbench 11.0.

Isograph Reliability Workbench is a windows based commercial software capable of reliability production. First step in software is preparing reliability block diagram. Blocks for each component must be prepared and linked according to the system construction. For this thesis, values which should be filled in are MTTF and MTTR for each event. After linking the components and filling the MTTF and MTTR values, software computes the unavailability of the components and systems to compute total unavailability of the project (Isograph, 2011).

The Reliability Block Diagram (RBD) module allows the user to build an RBD to represent the system to be modelled. The blocks in the diagram represent sub systems, components and events that can occur in the system. The logic of the system is dictated by the way in which the blocks are connected together.

Once the RBD is constructed, the diagram may be populated with failure and repair information. Analysis of the system returns estimates of system parameters, minimal cut set data and importance information for highlighting critical areas of the system.

Before building an RBD it is first necessary to create a System. A System represents the highest level of the system to be modelled. Once created, the new System will appear in the Tree Control under the RBD Pages node. The user may then select the System in the Tree Control and add RBD structure in the diagram area.

In the RBD, blocks represent sub systems, components and events. Each block can have failure and repair data associated with it. The arrangements in which the blocks are connected determine the logic of the system and thus affect the minimal cut sets and system parameters. An example of RBD shown in Figure 5.2.

Nodes may be used to commence and terminate parallel RBD arrangements, and to manipulate the behaviour of those arrangements. For example, in a voted arrangement the vote number is applied at the output node. Nodes may also be used to alter the shape of connections on screen.

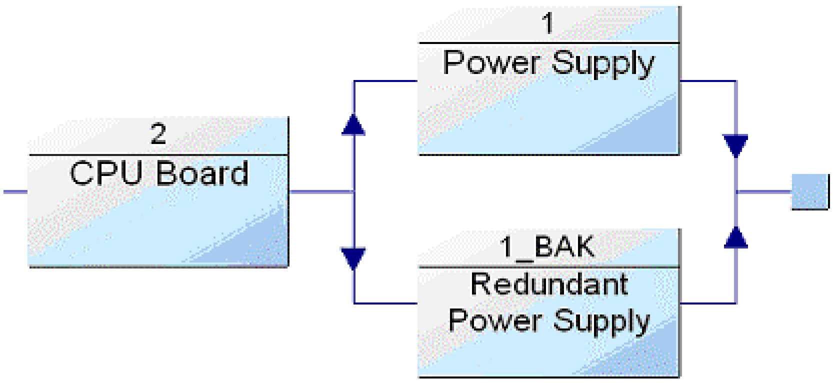

Figure 5.2 : RBD construction example.

A large RBD can become difficult to view and to navigate. Hence, as an RBD gets larger it may become necessary to break it down into more manageable pieces. Furthermore, the user may wish to view results for different sub systems, as well as for the system as a whole. Both of these goals can be achieved using the sub system facility of the RBD module.

In order to determine system parameters such as unavailability and failure frequency the user must allocate failure and repair data to the component blocks in the RBD. This is done via the Generic Failure Models. A Generic Failure Model may be created containing failure and repair information. Screenshot of Generic Failure Model input box is shown in Figure 5.3. It may then be allocated to one or more blocks in the RBD. Blocks which use the same Generic Model will share the same failure data but will remain independent of one another. List of the generic failure models generated for this project is illustrated in Appendix A.

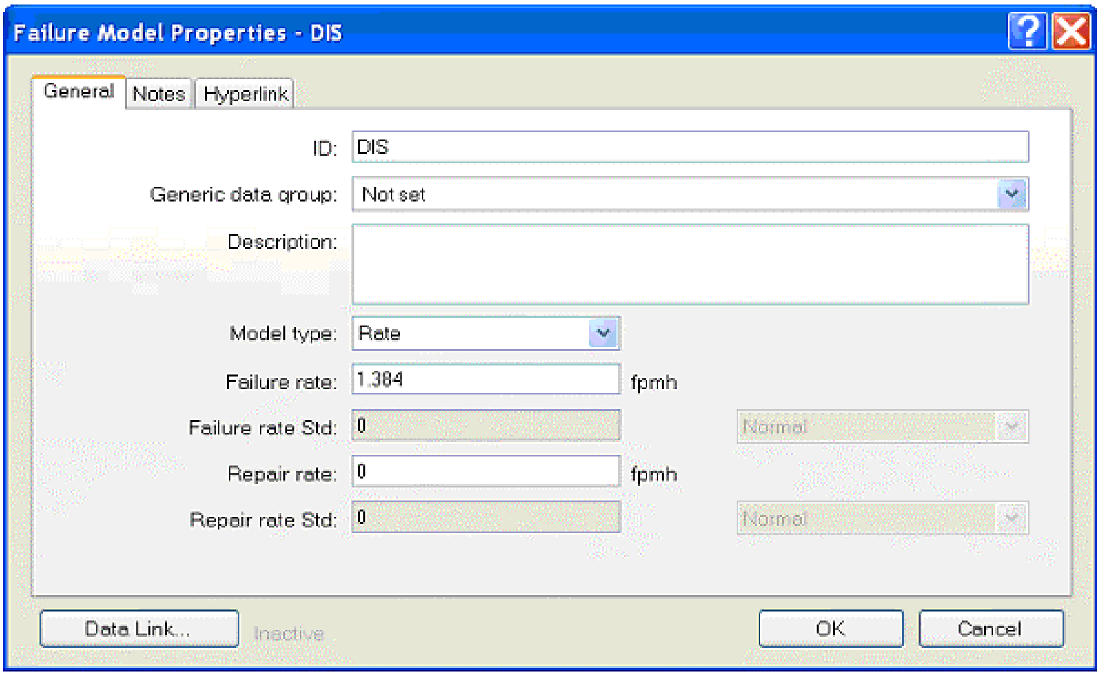

Figure 5.3 : Failure model window.

Before analyzing the project, the user must first make sure that the system lifetime is set correctly. For this thesis, life-time is assigned as 6 years meaning 52560 hours and actual working hours of main engines 2500/2550 hours and of generators 3260/3270 hours are projected to 6 years life-time.

The Fault Tree module allows the user to build a fault tree to represent the system to be modelled. An example of FT is shown in Figure 5.4. A fault tree consists of logic gates representing systems and sub systems, and basic events at the roots of the tree representing component failures and events. The type of logic gates selected dictate the way in which the failures interact.

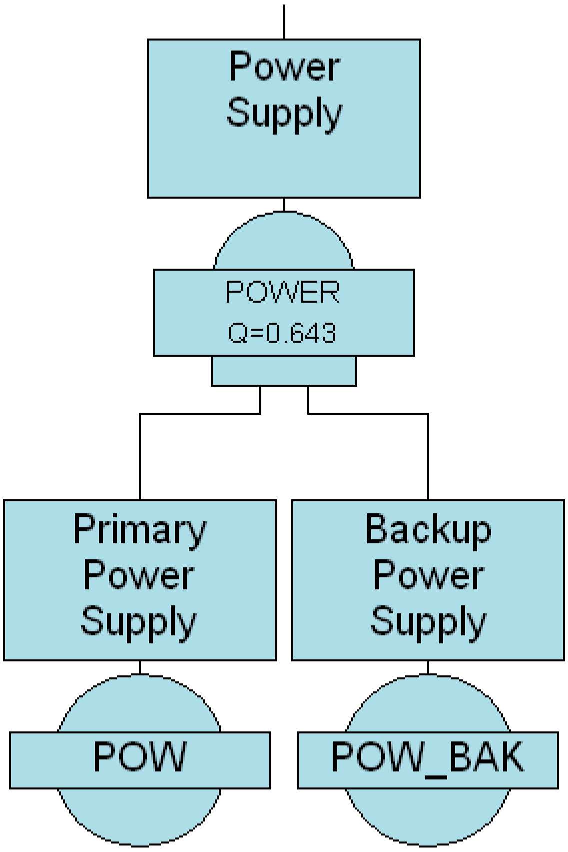

Figure 5.4 : Faul tree example.

Failure mode, unavaliability values may be shown under blocks after completing the analysis. Results may be exported by various reports. Some reports generated by Isograph Reliability Workbench 11.0.are shown in Appendices A-I.

5.3 Isograph Reliability Workbench 11.0. Calculations

5.3.1 Unavailability of a component (Q) and component failure frequency (ω)

To calculate the unavailability of a component, software needs inputs of failure rate (λ), MTTF and MTTR values, which are both calculated on a MS Excel sheet. Failure rate (λ) is defined as;

$$\lambda = \frac{1}{\text{MTTF}} \qquad \textbf{(5.1)}$$

The unavailability of a component (Q) is calculated by the software as;

$$Q(t) = \frac{\lambda.MTTR}{1+\lambda.MTTR} \quad \textbf{(5.2)}$$

Failure frequency of the component is;

$$\omega(t) = \lambda(1 - Q(t)) \quad \textbf{(5.3)}$$

5.3.2 Unavailability of a sub-system and system (Q_{sys})

The structure of a reliability block diagram (RBD) defines the logical interaction of failures within a system. Individual blocks may represent single component failures, sub-system failures and other events that may contribute towards system failures. The reliability behavior of an individual sub-system block may be represented by a RBD at a lower hierarchical level.

For the system to be successful in its operation, at least one path must be maintained between the system input and output nodes. A simple series arrangement of 3 blocks A, B and C would only require one of the blocks to fail to eliminate the single success path from input to output node. Simple series arrangement of a system is shown on Figure 5.5.

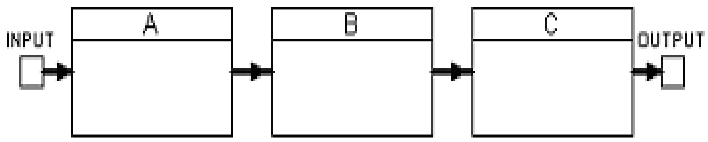

Figure 5.5 : Simple series arrangement.

System unavailability of a serially connected components is calculated as,

$$Q_{sys} = \sum_{i=1}^{n} Q_i \quad \textbf{(5.4)}$$

For the example series arrangement above, System unavailability is,

$$Q_{sys} = Q_A + Q_B + Q_C \quad \textbf{(5.5)}$$

A simple parallel arrangement of 3 blocks A, B and C would require all 3 blocks to fail to eliminate the 3 success paths from input to output node.

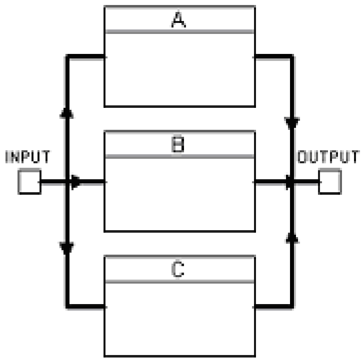

Figure 5.6 : Simple parallel arrangement.

Figure 5.6 shows a simple parallel arrangement of components. System unavailability of a parallel connected components is calculated by;

$$Q_{sys} = \prod_{i=1}^{n} Q_i \qquad \textbf{(5.6)}$$

For the sysytem shown on Figure 5.5, system unavailability;

$$Q_{sys} = Q_A . Q_B . Q_C \qquad \textbf{(5.7)}$$

Since only one path is enough for the success of the system, if one of the componenets' unavailability equals to zero, then system unavailability becomes zero. Total ship unavailabilty is calculated by Equations (5.5) and (5.7) according to the systems' types of arrangement.

5.3.3 Cut sets occurance probability (Q_{cut})

The RBD Module uses efficient minimal cut sets generation algorithms to analyze large and complex RBDs. Cut sets represent a minimal combination of failures which will cause the system to fail. Table of the cut sets generated by software, which are affecting system unavailability, is illustrated on Appendix B.

Cut set occurance probability may be expressed as,

$$Q_{cut} = \prod_{i=1}^{n} Q_i \qquad \textbf{(5.8)}$$

where Q_i is the unavailability of the ith event in the cut set.

Failure frequency of the cut set may be expressed as,

$$\omega_{cut} = \sum_{j=1}^{n} \omega_j \prod_{\substack{i=1 \\ i \neq j}}^{n} Q_i \qquad \textbf{(5.9)}$$

6. **TOTAL SHIP RELIABILITY ANALYSIS**

RWB software analyzes the system and, unavailability and unreliability results of the components and systems are computed by RWB. A block in RBD represents an event of a component or a system which has more than one component's events. Serial or parallel arrangement of components determines how the calculations are carried out. Sub-system results are computed through components contributing system unavailability. At the end, for this project, a total ship unavailability result is calculated by the software. The list of the events contributing to ship unavailability and prepared as blocks in RBD are listed with generic failure types in Appendix C. Those blocks which have no generic failure data represent a sub-system or system in RBD and they do not need generic failure data input, since components' generic failure data are used in calculation.

6.1 MTTF-MTTR Calculations

According to the model type chosen for the project, RWB needs some inputs for the calculation. For this project, MTTF model type has been chosen and necessary inputs are MTTF and MTTR values. The MTTF and MTTR values have been calculated on MS Excel Worksheet and shown in Appendix D. These values have been imported to RWB via Generic Failure Models.

Data used to calculate MTTF and MTTR are listed on event basis in Appendix E and Appendix F respectively.

In order to calculate MTTF and MTTR values, data from ships' log books have been used. MTTF and MTTR have been calculated by the Equations (3.7) and (3.8) respectively on a MS Excel worksheet.

6.2 Unavailability Calculations

RWB makes unavailability calculations for the system, sub-systems and components acccording to the values inserted into events' generic failure models. Before starting the analysis, RBD should be prepared.

RBD has been constructed according to the effects of the events about the accomplishment of the ship's mission. After constructing the RBD, generic failure models were prepared and attached to the relevant events. Software analayzed the system and unavailabilities have been computed. RBDs with unavailability results for the system, sub-systems and events are shown in Appendix G.

RWB has calculated unavailabilities of the events according to the Eqs. (5.1) and (5.2). Unavailabilities of the sub-systems and system have been calculated by RWB according to the Eqs**.** (5.4) and (5.6).

In order to find unavailability of a serially arranged system or sub-system, unavailabilities of the events or sub-systems composing the relevant sub-system or system are summed. To find unavailability of a sub-system or system constructed in parallel, unavailabilities of the events or sub-systems are multiplied. Hence, in a parallel arrangement, if one of the events has unavailability value as zero, then mission can be accomplished and unavailability of the sub-system or system equals to zero.

6.3 Results and Discussion

RWB calculates system unavailability and this result may show how reliable the system is. RWB reports unavailability, failure frequency and unreliability of each RBD blocks. This report is shown in Appendix H.

Unavailability of the sub-system is a function of MTBF, MTTR and preventive maintenance. In this project, preventive maintenance time is neglected. Unavailability and failure frequency of a sub-system are constant. Since reliability of the system is the function of failure rate (λ) and time as indicated at Equation (3.11), RWB calculates system and sub-systems' unreliabilities in 20 working hour steps. As shown in Appendix H, unreliability value of the sub-systems are increasing proportionally with working hours. Unreliability of the system (F_{sys}) is calculated by the software as;

$$F_{sys} = 1 - e^{-\int_0^T \lambda_{sys}(t).dt} \quad \textbf{(6.1)}$$

Where λ_{sys} is system failure rate and calculated as;

$$\lambda_{sys} = \frac{\omega_{sys}}{1-Q_{sys}} \quad \textbf{(6.2)}$$

Where ω_{sys} is system failure frequency and calculated as;

$$\omega_{sys} = \sum_i^n \omega_{cuti} \qquad \textbf{(6.3)}$$

Reliability values may be calculated by Eq. (6.4);

$$R_{sys} = 1 - F_{sys} \qquad \textbf{(6.4)}$$

RWB also calculates total down time (TDT_{sys}) and number of expected failures (Wsys) by the Eqs. (6.5) and (6.6) respectively.

$$TDT_{sys} = \int_0^T Q_{sys}(t).dt \qquad \textbf{(6.5)}$$

$$W_{sys} = \int_0^T \omega_{sys}(t).dt \qquad \textbf{(6.6)}$$

6.3.1 Unavailability of main sub-systems

Four main sub-system have been constructed for the ship type examined. These sub-systems are serially arranged and directly affect the availability of the ship. Unavailability diagram of main sub-systems is shown in Figure 6.1.

Figure 6.1 : Unavailability of main sub-systems.

Since unavailability is a function of failure rate (λ) and MTTR, it does not change with working hour. System unavailability is computed through the unavailabilities of the cut sets by cross-product method in RWB as;

$$Q_{sys}(t) = \sum_i^n Q_{cuti}(t) - \sum_i^{n-1}\sum_{j=i-1}^{n} Q_{ij}(t) + \sum_i^{n-2}\sum_{j=i+1}^{n-1}\sum_{k=j+1}^{n} Q_{ijk}(t) \ldots \textbf{(6.5)}$$

Ship total unavailability may be calculated also by summation of main sub-systems' unavailabilities. Sub-system Damage Control contribution is higher than other systems, since the unavailability of portholes increases the unavailability of water-tight compartments. Total ship system's unavailability was calculated by RWB as Q=0,0003726. The availability of the system and sub-systems may be calculated by;

$$Availability = 1 - Q \qquad \textbf{(6.6)}$$

The availability of total ship system then becomes 0,996274. This availability value is very high and shows that, during the project time, the ship is highly capable of accomplishing the mission.

6.3.2 Number of expected failures of main sub-systems

Number of expected failures of the sub-systems are calculated by RWB and shown in Figure 6.2. Damage Control system has highest number of expected number of failures.

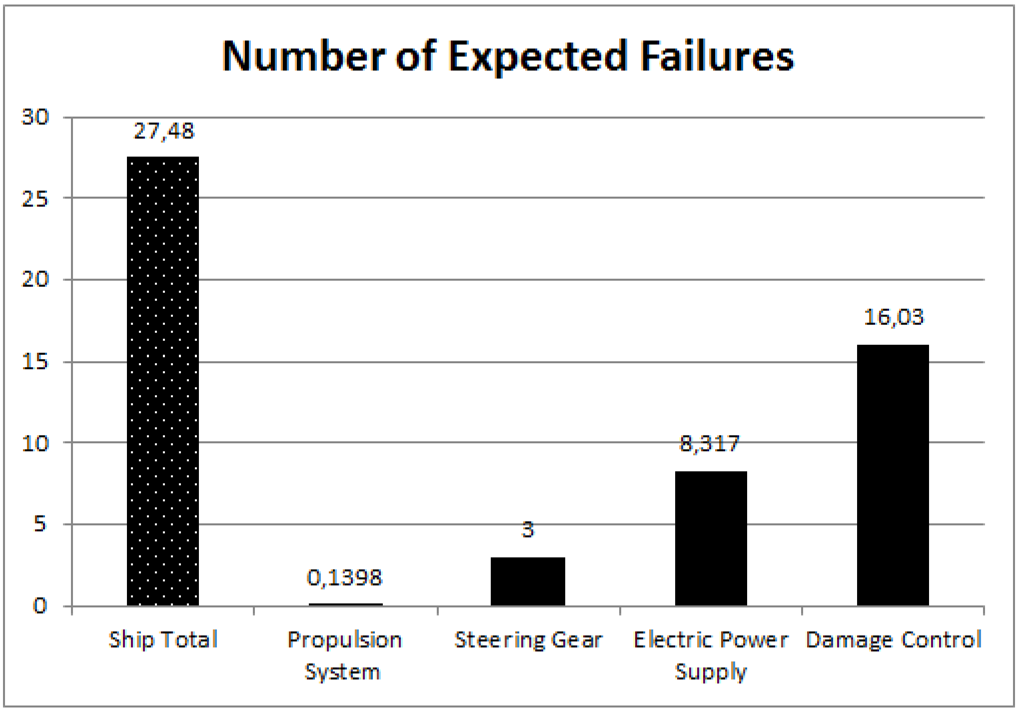

Figure 6.2 : Number of expected failures of main sub-systems.

6.3.3 Unreliability of main sub-systems

Unreliabilities of system and sub-systems are calculated and plots are prepared by RWB, as shown in Figure 6.3 and Figure 6.4 respectively. It is observed from these figures that, unreliabilities of the system and sub-systems are increasing with working hour, since reliability is an exponential function of failure rate (λ) and time.

Since failure rate (λ) is constant for the project time, 52560 hours, working hour of the system increases the unreliability of the system. Reliability of a component can be calculated by Eq. (3.11) and by the unreliability results of RWB.

It is usual that reliability of the system decreases towards the end of the project time. When Figure 6.4 examined, it is obvious that, Damage Control main sub-system has the most contribution to low reliability value of the system. Contributions of the main sub-systems via their sub-systems are examined below in detail.

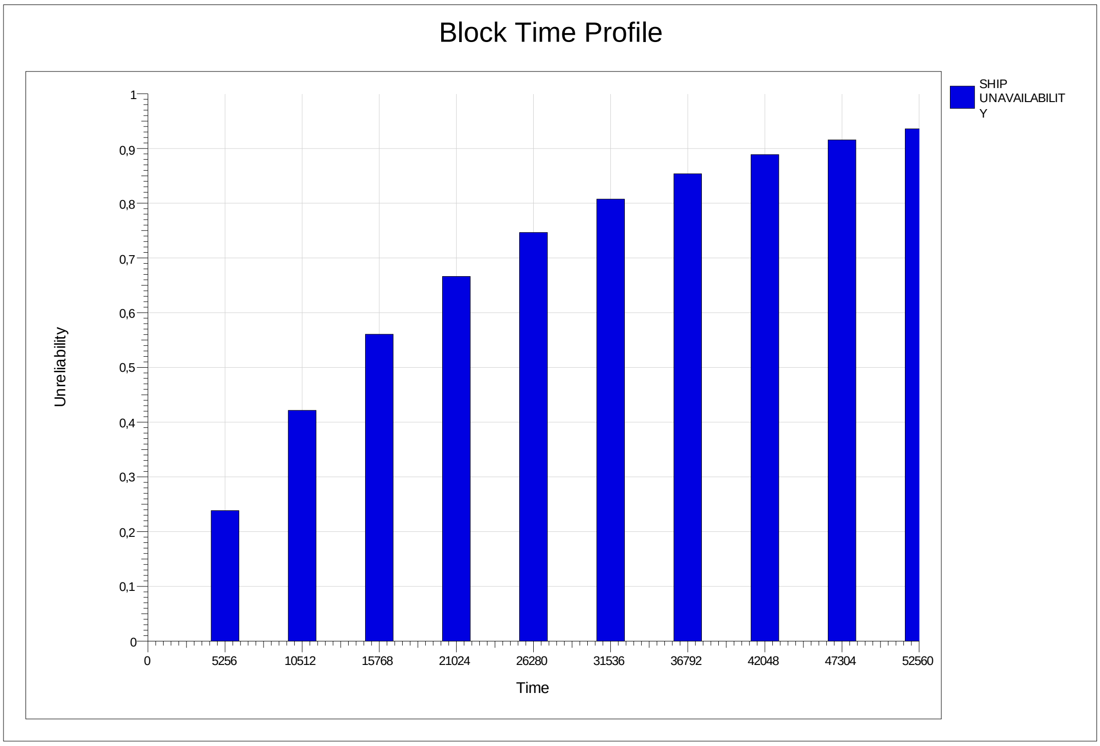

Figure 6.3 : Unreliability of system.

6.3.3.1 Contribution of propulsion sub-system

Propulsion system is composed of two main diesel engines including events and sub-systems. RWB result summary of propulsion system is shown on Table 6.1. As shown on Table 6.1, Total Down Time (TDT) of propulsion system, which is consisted of Main Engine No:1 and Main Engine No:2, is 0,202 hours through project time 52560 hours. This low value is due to the parallel arrangement of main engines in propulsion system RBD. Only one of the engines is accepted as sufficient in order to accomplish the mission of the ship.

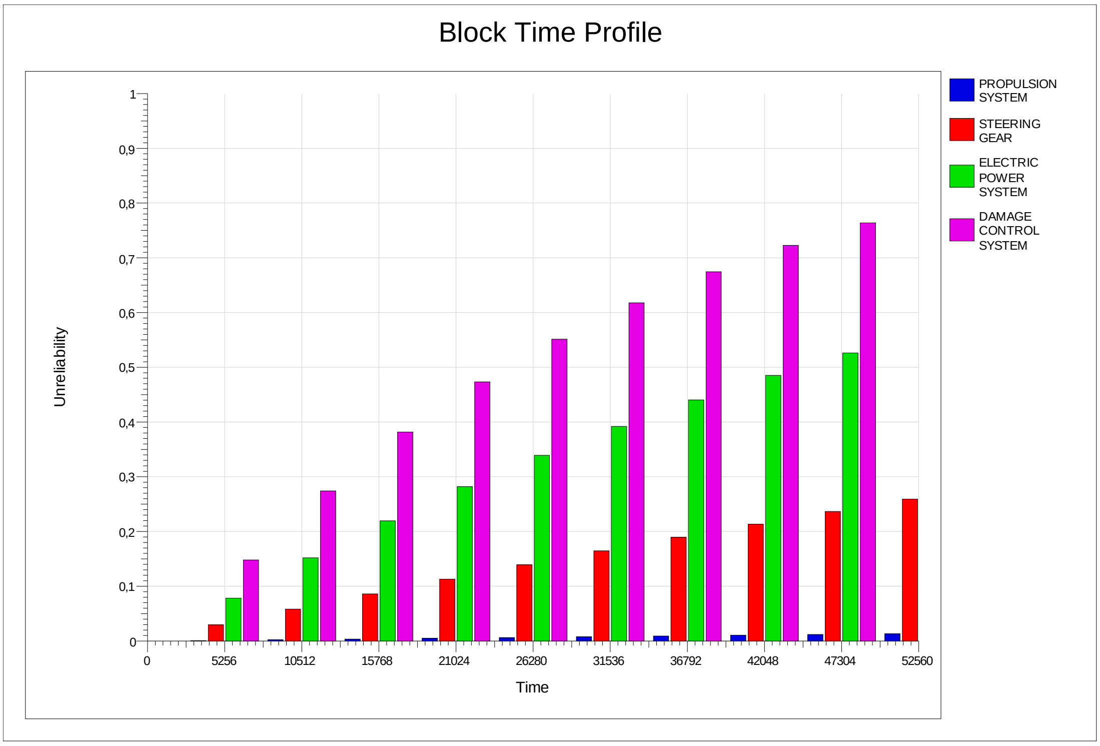

Figure 6.4 : Unreliabilities of main sub-systems.

When Table 6.1 is examined, it is seen that, unreliabilities of each engine are calculated as 1. But RWB calculated propulsion system's unreliability as 0,1305, since RWB uses cut sets' unreliabilities and unavailabilities to calculate system's unreliability and unavailability. Cut sets used in calculation are illustrated in Appendix B. These cut sets are generated by software according to their effects on sub-system's success.

Table 6.1 : Propulsion system result summary.

	Unavailability	Unreliability	No.of Expected Failures	TDT	MTTF	MTTR
Propulsion System	3,87E-06	0,1305	0,1398	0,202	3,74E+05	1,448
Main Eng. No:1	0,002248	1	31.93	117,6	1641	3,701
Main Eng. No:2	0,00172	1	37,93	89,94	1383	2,383

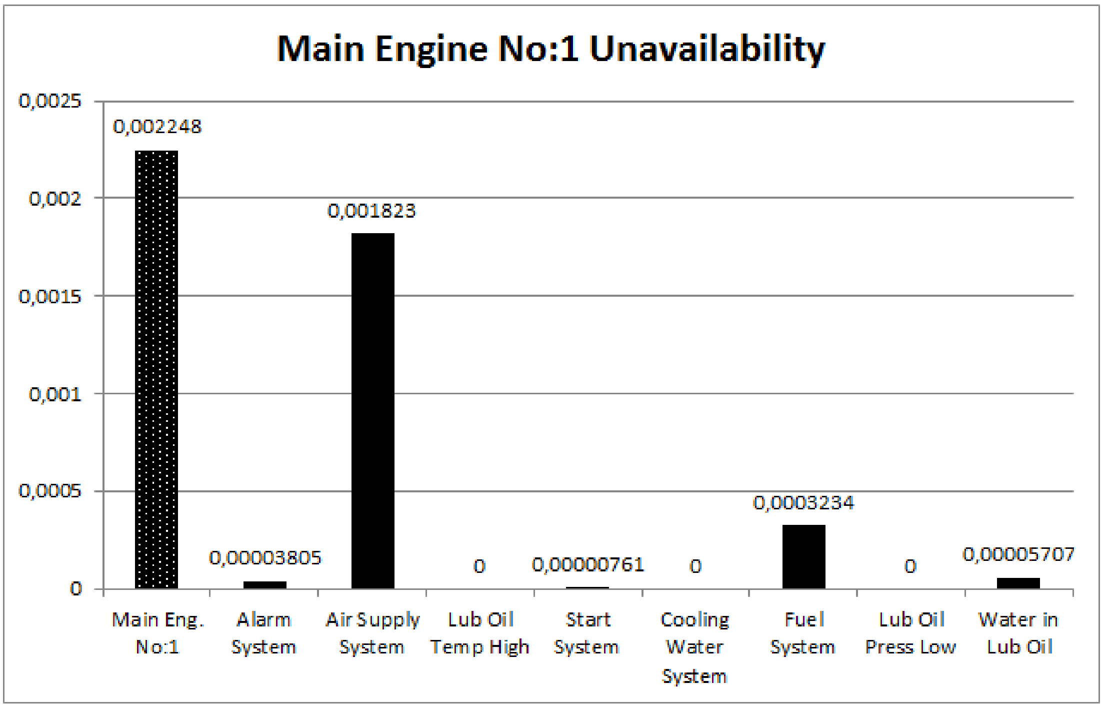

Figure 6.5 : Main Engine No:1 unavailability diagram.

Contributions of sub-systems to Main Engines' unavailabilities are shown in Figures 6.5 and 6.6 Unavailabilities of the sub-systems are constant since failure rate does not change with time.

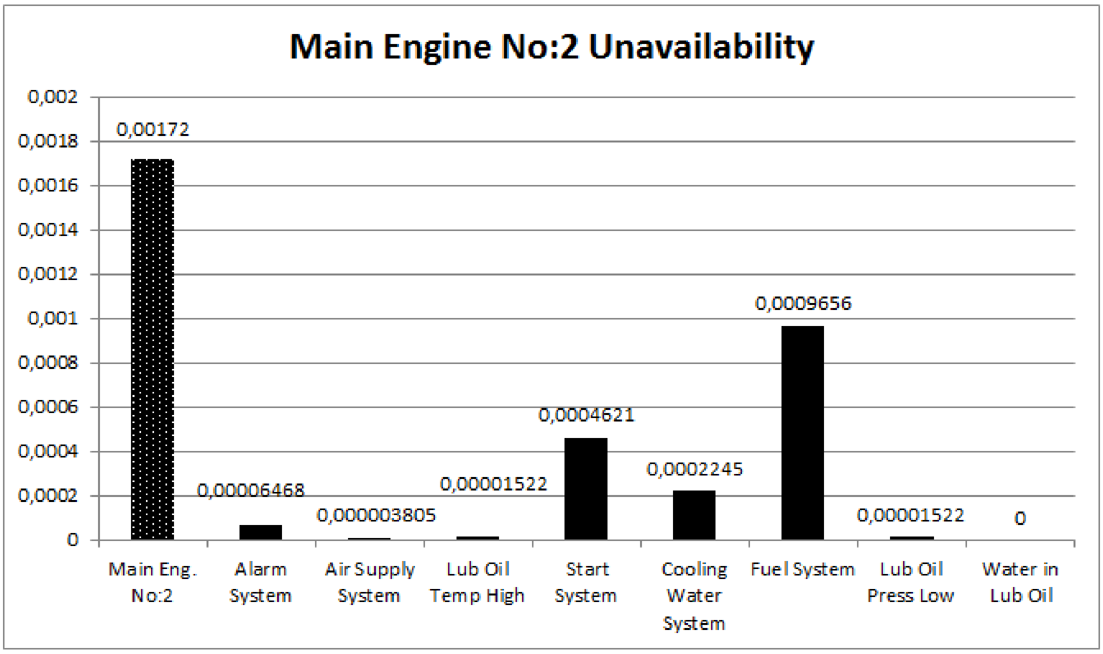

Figure 6.6 : Main Engine No:2 unavailability diagram.

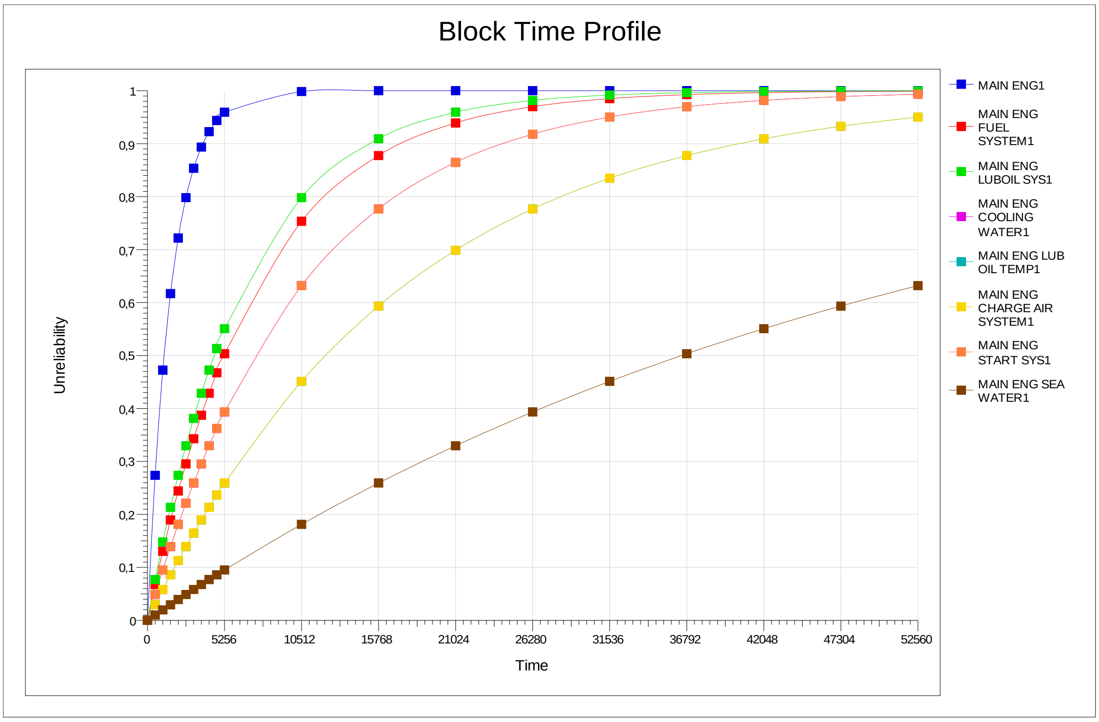

Figure 6.7 : Main Engine No:1 unreliability-time diagram.

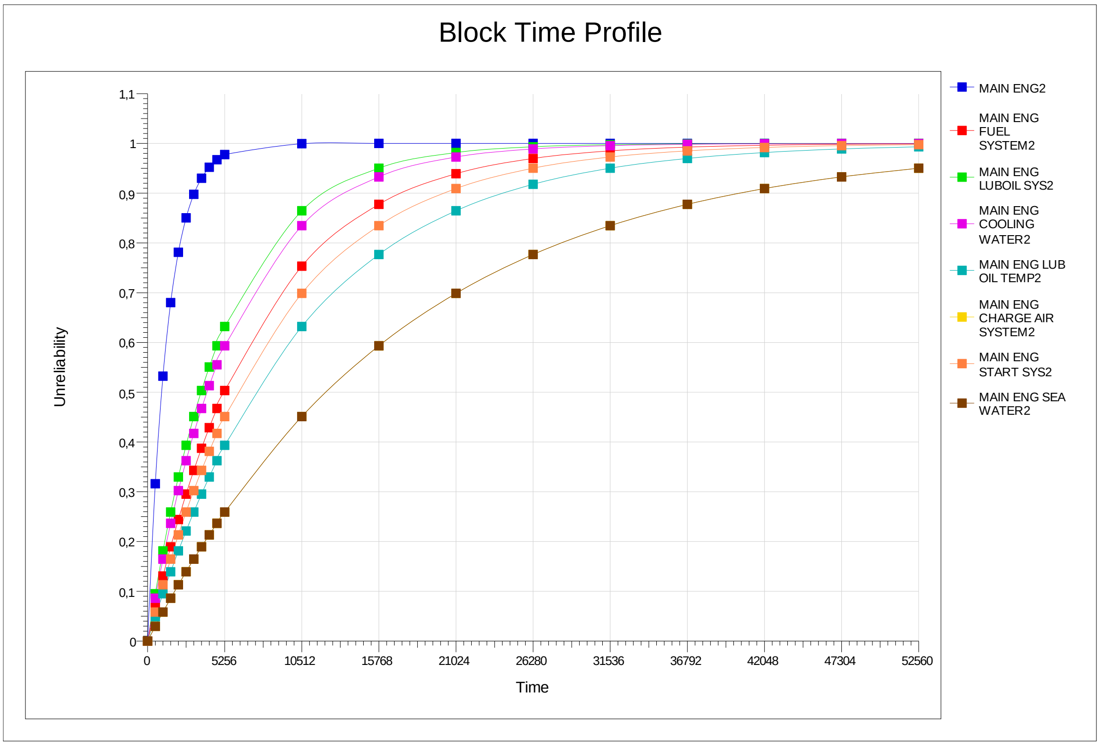

Figure 6.8 : Main Engine No:2 unreliability-time diagram.

Sub-systems' contribution to unreliabilities of Main Engines are shown on Figures 6.7 and 6.8 As shown on diagram, unreliabilities of the sub-systems increase with working hours.

6.3.3.2 Contribution of steering gear sub-system

Result summary of steering gear sub-system is shown on Table 6.2. As seen on Table 6.2, almost all sub-systems of steering gear have unavailability values of zero. System unavailability and unreliability are affected by failures of S/G electric supply section board.

Table 6.2 : Steering Gear System Result Summary

	Unavailability	**Unreliability**	**No.of Expected Failures**	**TDT**	**MTTF**	**MTTR**
Steering Gear System	3,425E-05	0,9502	3	1,791	1,751E+04	0,6
S/G Pumps	0	0,003622	0,003628	0	1,441E+07	-
S/G Hyd.Sys	0	0,000454	0,0004541	0	1,151E+08	-
S/G Room Components	0	0,0001325	0,0001325	0	3,945E+08	-

The availability value for steering gear sub-system is calculated as 0,99966. Unreliability of steering gear sub-system versus working hour is shown on Figure 6.9. As expected, because of constant failure rate, reliability of the system decreases with time.

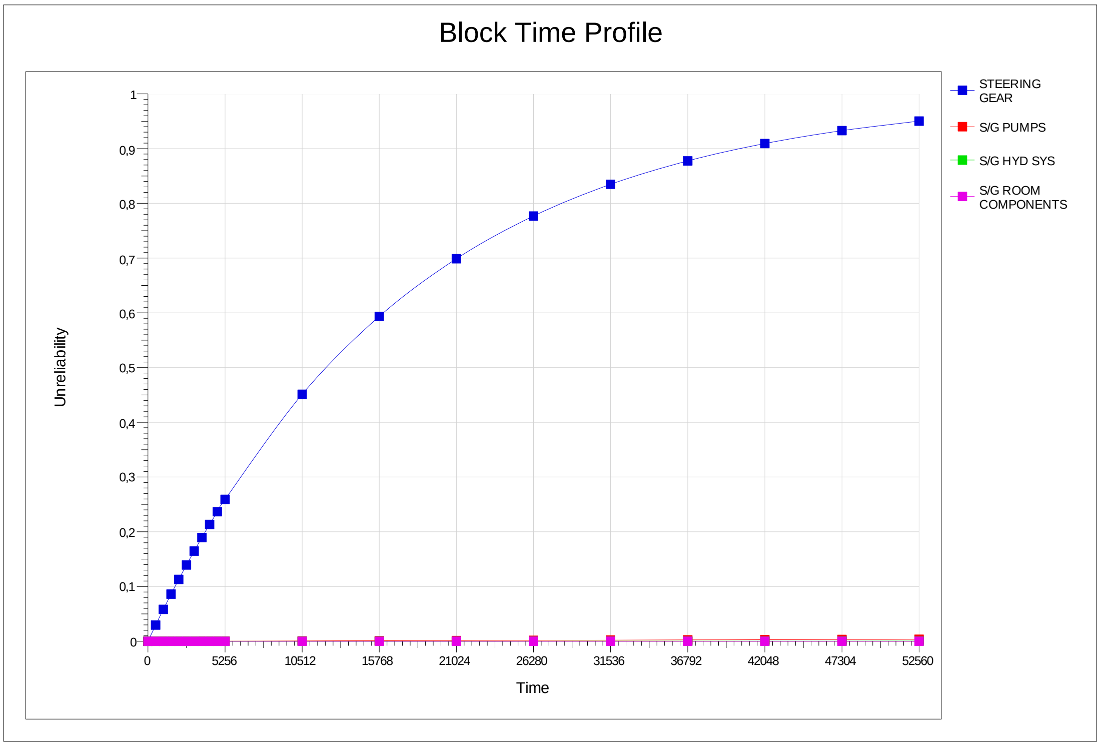

Figure 6.9 : Unreliability of steering gear sub-system.

6.3.3.3 Contribution of electric power sub-system

Result summary of RWB for electric power sub-system is shown on Table 6.3.

Table 6.3 : Electric power sub-system's result summary.

	Unavailability	Unreliability	No.of Expected Failures	TDT	MTTF	MTTR
Electric Power System	9,845E-05	0,9998	8,317	5,149	6316	0,622
GENSET No:1	0,0003842	1	34,98	20,09	1501	0,5773
GENSET No:2	0,008614	1	41,64	450,5	1251	10,87
Main Switchboard	3,805E-05	0,9933	5	1,99	1,051E+04	0,4
Section Boards	0,0001332	0,9997	7,999	6,964	6565	0,875
Emergency Power Supply	5,707E-05	0,9975	6	2,985	8754	0,5

Unavailabilities of electric power sub-systems are shown on Figure 6.11. Although unavailability of Genset No:2 is higher than other sub-systems, total unvailability is low, since Genset No:2 is connected to Genset No:1 in parallel.

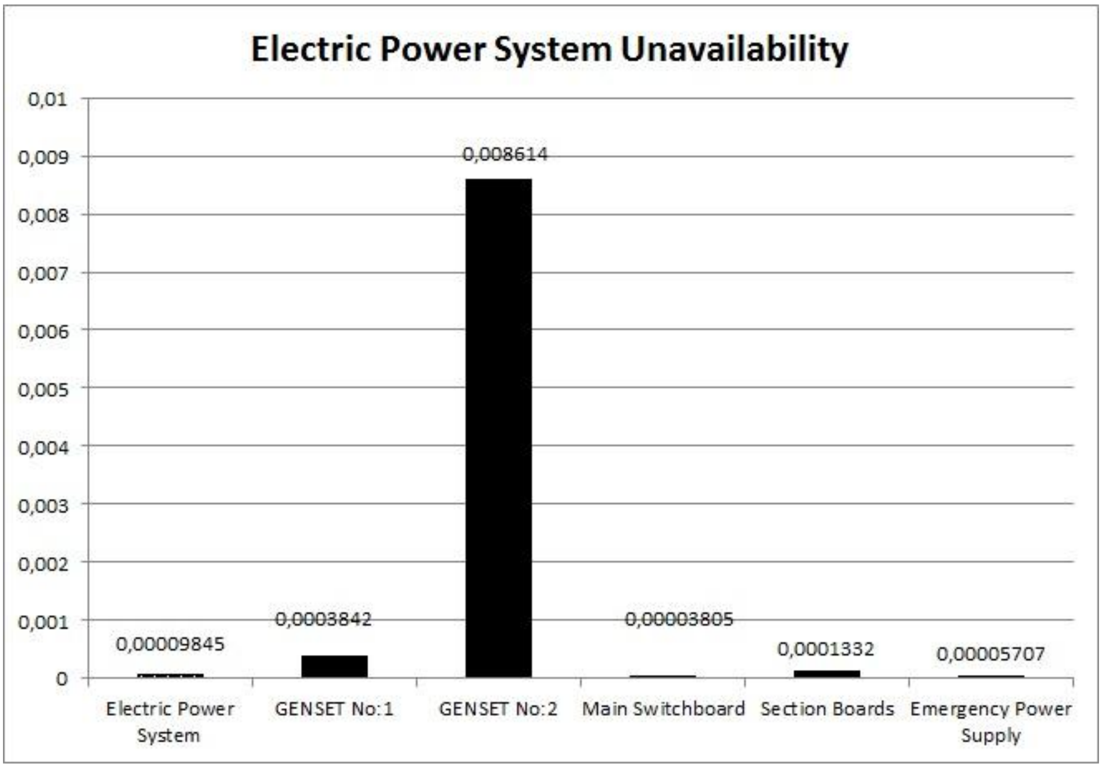

Figure 6.10 : Unavailabilities of electric power sub-systems.

Unreliabilities of electric power sub-systems are shown on Figure 6.12. Since Gensets have generators and diesel engines total reliabilities get higher with time and cut sets unreliabilities cause system unreliability to become high at the end of project time.

Unavailabilities and unreliabilities of Genset No:1 and No:2 are shown in Figures 6.13, 6.14, 6.15 and 6.16 respectively. Although unavailability of Gensets are low, unreliability values get higher with working hour. As indicated in description of reliability, reliability values represent the probability of failure occurance in system. Since availabilities are high, we may conclude that gensets are properly working in ship system. Because with a constant failure rate, it is normal to have lower reliabilities at the end of the project time.

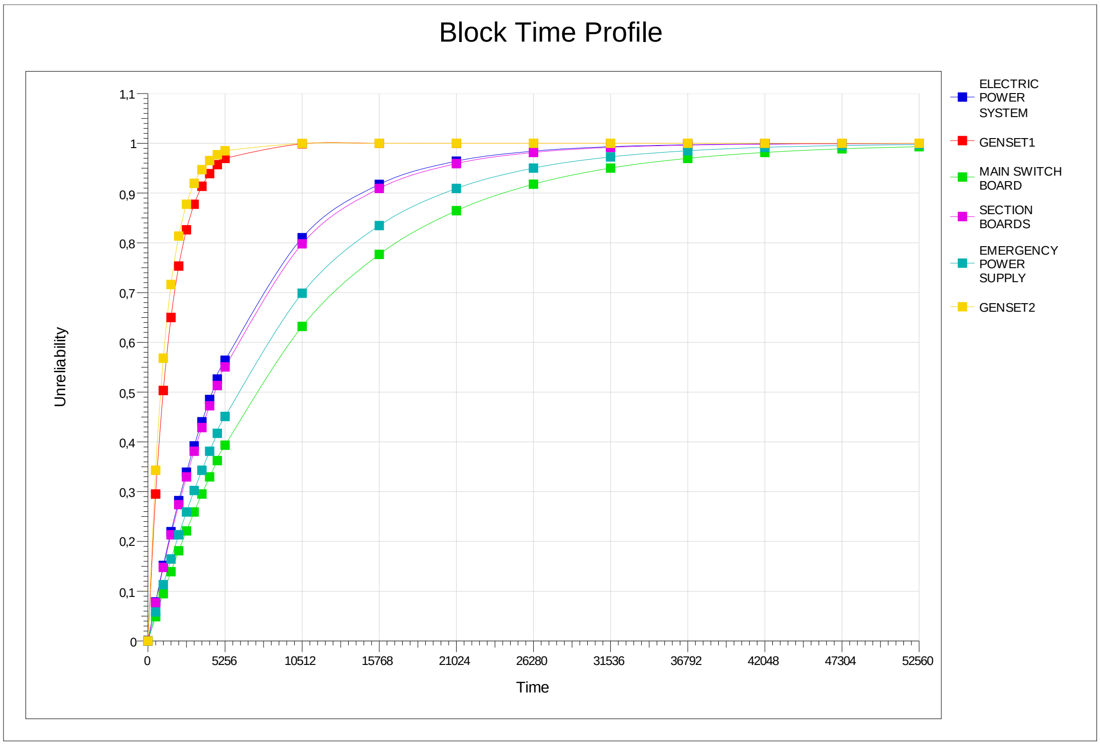

Figure 6.11 : Unreliabilities of electric power sub-systems.

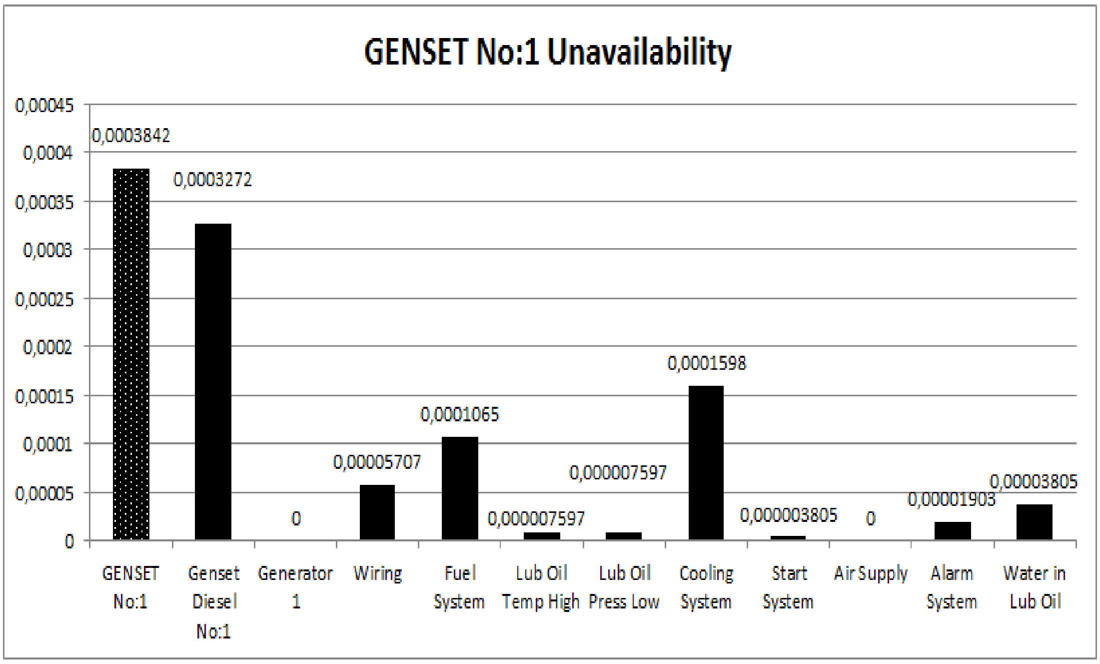

Figure 6.12 : GENSET No:1 unavailability.

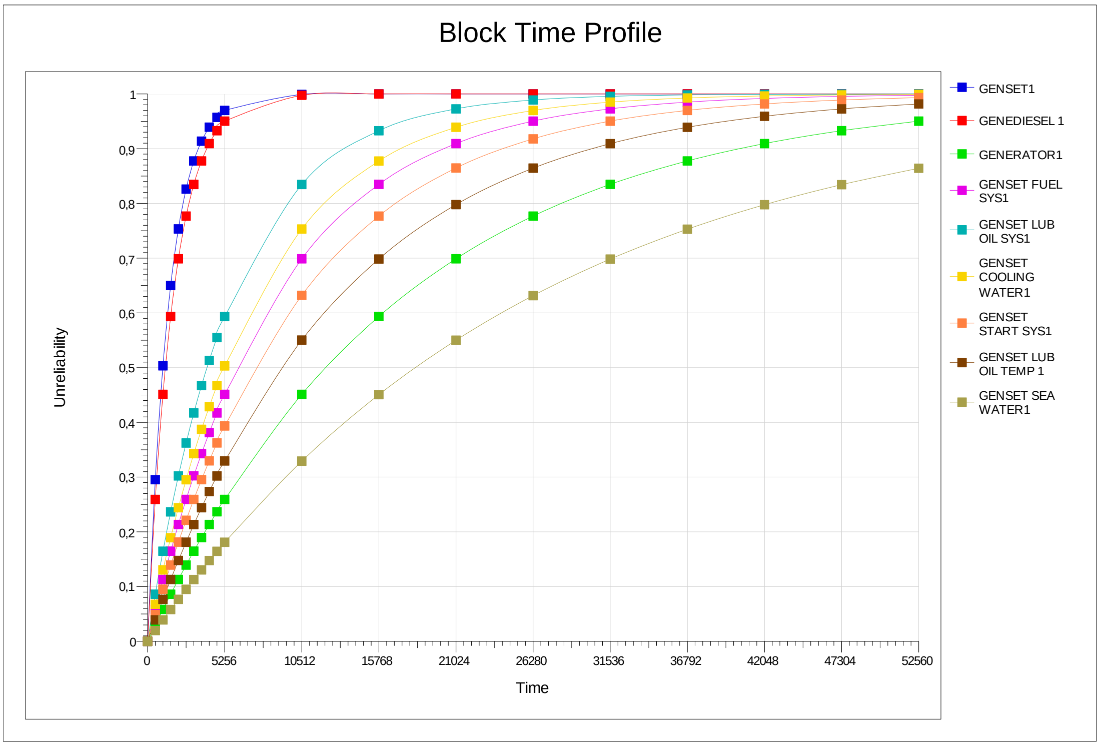

Figure 6.13 : GENSET No:1 unreliability.

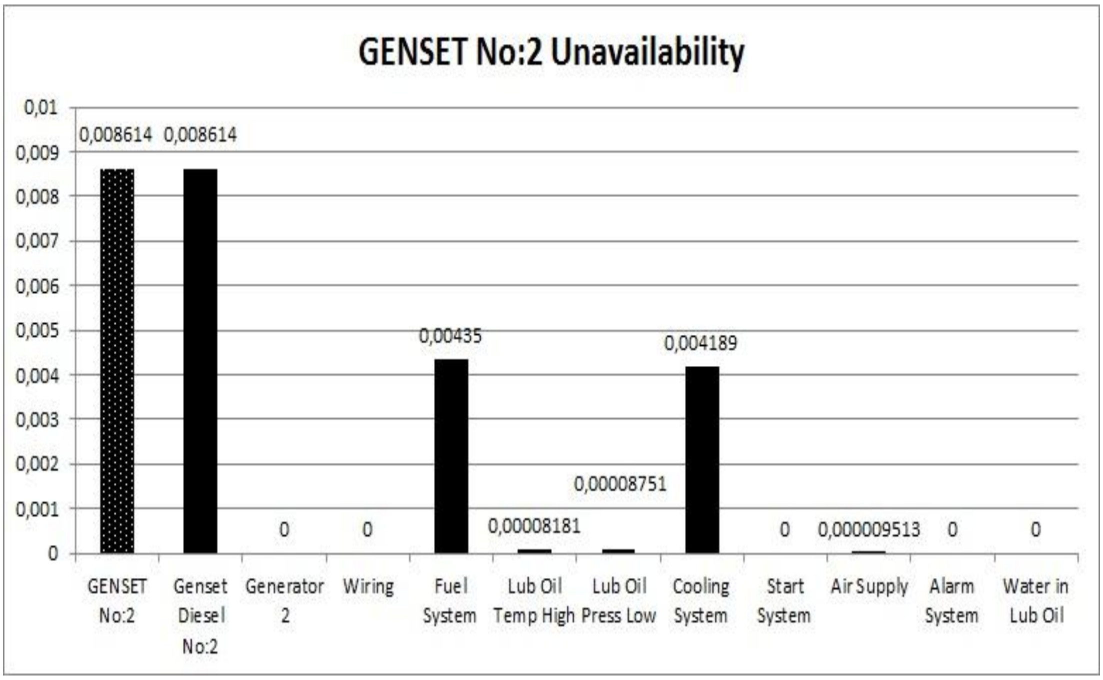

Figure 6.14 : GENSET No:2 unavailability.

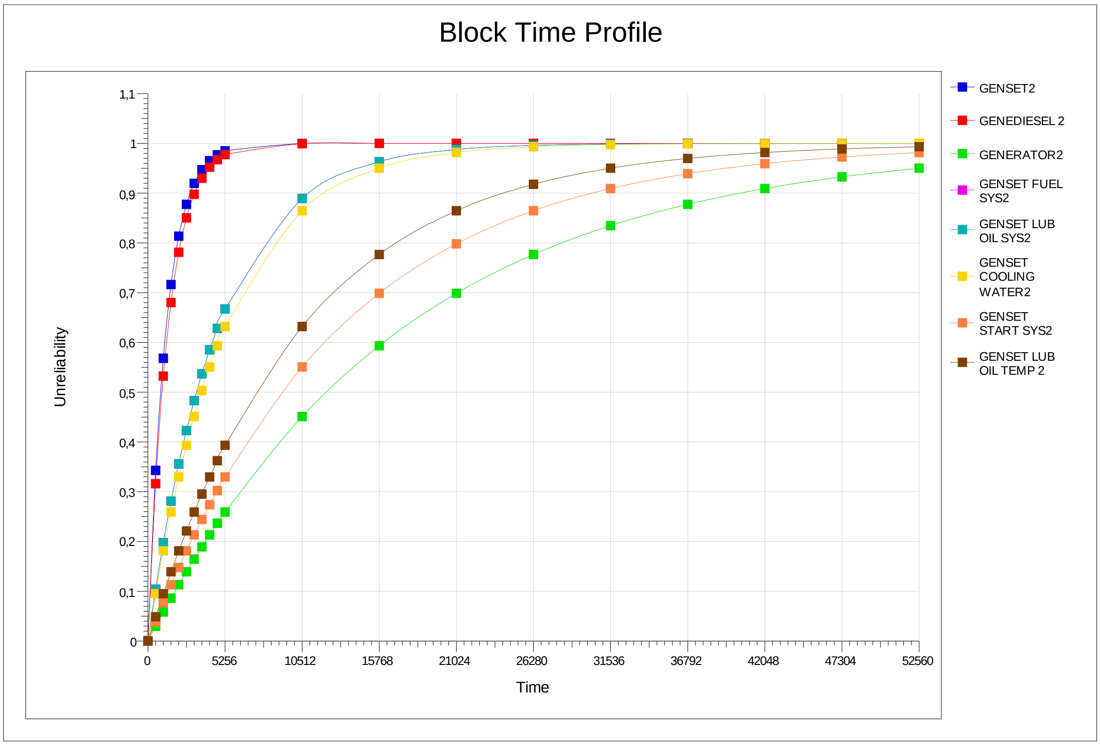

Figure 6.15 : GENSET No:2 unreliability.

6.3.3.4 Contribution of damage control sub-system

Damage control sub-system consist of components related with especially ship's floatability and preventive considerations against fire-fighting and water disharge systems. Other system is fuel transfer system which is necessary for ship's propulsion and electric power systems. RWB analze result summary is illustrated on Table 6.4.

Table 6.4 : Damage control sub-system result summary.

	Unavailability	Unreliability	No.of Expected Failures	TDT	MTTF	MTTR
Damage Control System	0,000236	1	16,03	12,34	3275	0,7739
Fire Fighting & Water Discharge System	4,858E-05	0,9822	4,028	2,54	1,304E+04	0,6338
Watertight Departments	7,229E-05	0,9999	8,999	3,781	5838	0,4222

Unavailabilities and unreliabilities of Damage Control Sub-systems are shown respectively on Figures 6.17 and 6.18.

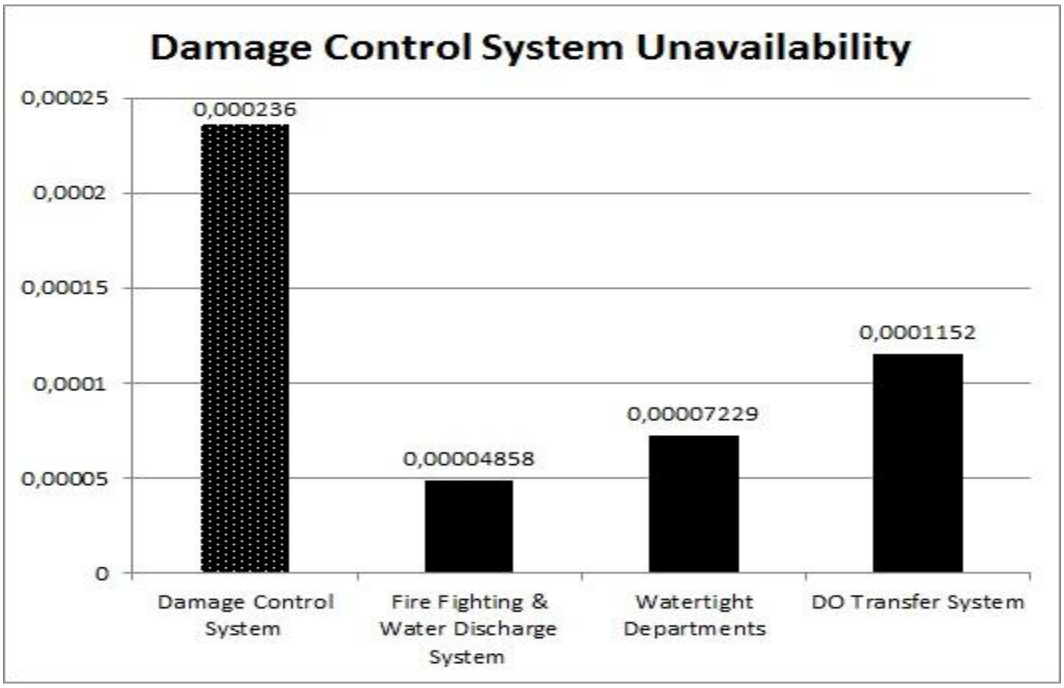

Figure 6.16 : Damage control unavailability.

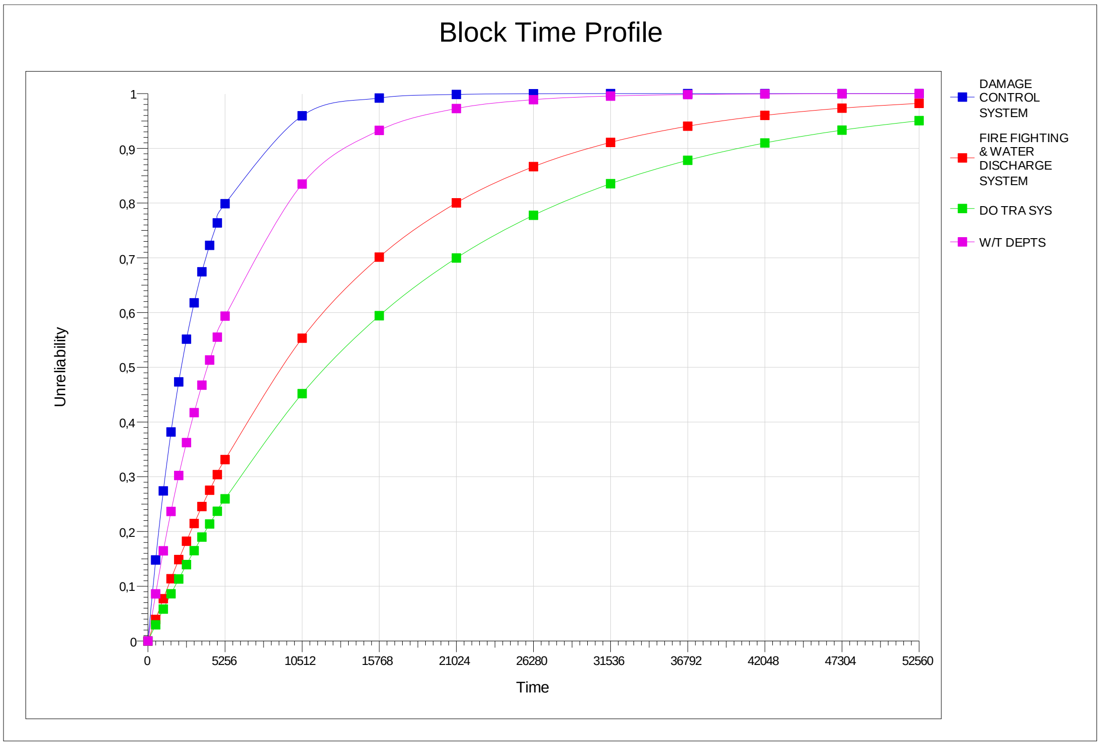

Figure 6.17 : Damage control unreliability.

7. FAULT TREE CONSTRUCTION

RWB Fault Tree analysis calculates unavailability, failure frequency and unreliability of project. RWB has facility to convert RBD to FT diagram. Since FT generated by RBD is difficult to follow in determining the reason of the failure in ship's main sub-systems, a simplified FT for the project has been prepared in RWB.

The simplified FT diagrams are shown in Appendix I. In construction process, logic of RBD has been used. Serially arranged events and systems are represented by OR gates and parallel arranged events and sub-systems are represented by AND gates. Top gate represents "ship cannot accomplish the mission" event. When ship cannot accomplish the mission, at least one of four sub-system may have failure. If FT is followed from top to bottom, failure causing the mission interrupt or making system unavailable may be determined.

An analysis has been carried out for the simplified FT and the results generated have been checked against the results of RBD as shown in Table 7.1. It is approved that the simplification of original FT converted from RBD is satisfactory..

Table 7.1 : RBD and FT analaysis results.

System	**Unavailability**		**Unreliability**		**No.of Expected Failures**	
RBD/ FT	**RBD**	**FT**	**RBD**	**FT**	**RBD**	**FT**
Total Ship	0,0003726	0,0003726	1	1	27,48	27,48
Propulsion System	3,87E-06	3,867E-06	0,1305	0,1302	0,1398	0,139
Steering Gear	3,425E-05	3,425E-05	0,9502	0,9502	3	3
Electric Power System	9,845E-05	9,844E-05	0,9998	0,9998	8,317	8,316
Damage Control	0,000236	0,000236	1	1	16,03	16,03

8. **CONCLUSIONS**

8.1 Unavailability Results

According to the analysis of the sample ship type chosen for the project, Ship has low unavailability value and number of expected failures calculated by RWB for total ship system is not high for the selected project time of six years. Low unavailability values may be interpreted that ship will be ready to accomplish the mission for most of the time through the period considered.

When the unavailabilities of the main systems are examined, it is obvious that damage control sub-system is most contributing one in increasing the unavailability of ship system. The reason of this contribution may be explained by checking the unavailabilities of damage control sub-systems. Water-tight compartments including hatchways and portholes have high number of failures. Even though these systems do not cause the mission interrupt directly, according to the regulations of naval ships, water-tigthness between compartments is necessary for a naval ship to be missioned. These kinds of failures are very important for the ship to go underway. Since in case of fire or water flooding, these failures may cause huge damages, ship with these kinds of failures is accepted as unavailable for the mission.

Ship propulsion system and steering gear system have 2500 working hours which are projected to 52560 hours. These systems have also low unavailability values for the selected project time. The reason for the low unavailability may be explained by the age of the ships. Project time, which has been selected, is the period after first overhaul of the ships.Systems are just at the beginning of the useful life described on **Figure 1.1** Bathtube curve. Probably low number of failures is due to the age of the systems. Number of failures and unavailability may increase proportionally as the system components age in future.

8.2 Unreliability Results

Unreliability values calculated by RWB show that unreliabilities of the sub-systems are increasing with time as expected. It is usual that unreliability of a system with contant failure rate, increases with working hours because of the definition of unreliability, Equation 6.1. Unreliability of propulsion system is so high, since one propulsion unit is accepted enough for accomplishing the mission. In case two propulsion unit was mandatory for the mission, the propulsion system should be constructed in a serial arrangement, and then unreliability of propulsion system would be higher.

8.3 Suggestions

In order to decrease unavailability of the ship, standby components can be designed for the components which decrease the availability of the sub-systems. As an example, additional submersible pump for water discharge system would increase the availability of damage control sub-system.

Another solution to increase availabilities of the sub-systems is to make additional preventive maintenance for the components which cause system failure. For instance, according to the results compiled by RWB, especially leakage problems cause unavailability increase. Preventive maintenance would decrease the number of failures occured in piping systems, so availability of the system increases.

Unreliability indicates a probability of failure for the systems. Since all the system components are repairable or replacable, maintainability of the system can be assured. Although reliability of the system decreases with time, availability is constant, because of constant failure rates. In order to increase reliability, the period between two overhaul can be decreased or maintenance procedures can be put into effect for the key components like engines, generators and steering gear components.

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APPENDICES

APPENDIX A: Failure Model List İncluding MTTF and MTTR Table on CD
APPENDIX B: Cut Sets Unavailability and Failure Frequency Table on CD
APPENDIX C: Events Generic Failure Models on CD
APPENDIX D: Events Failure Rate - MTTF – MTTR List on CD
APPENDIX E: Events MTTF List on CD
APPENDIX F: Events MTTR List on CD
APPENDIX G: Reliability Block Diagrams
APPENDIX H: RBD Time Profile on CD
APPENDİX I : Fault Tree Diagrams

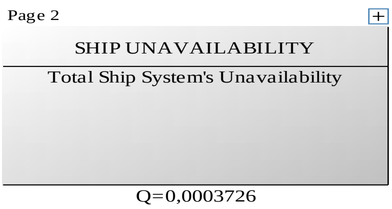
APPENDIX G

Reliability Block Diagrams

SHIP RELIABILITY

System SHIP RELIABILITY

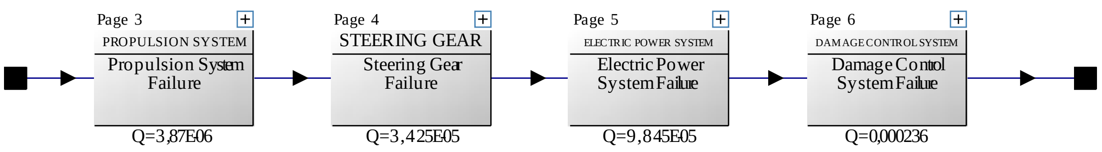
Page 1 of 49



Reliability Block Diagrams

SHIP RELIABILITY

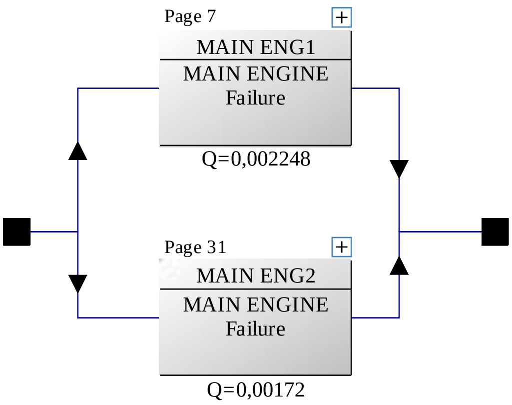
Sub-system SHIP UNAVAILABILITY See page 1



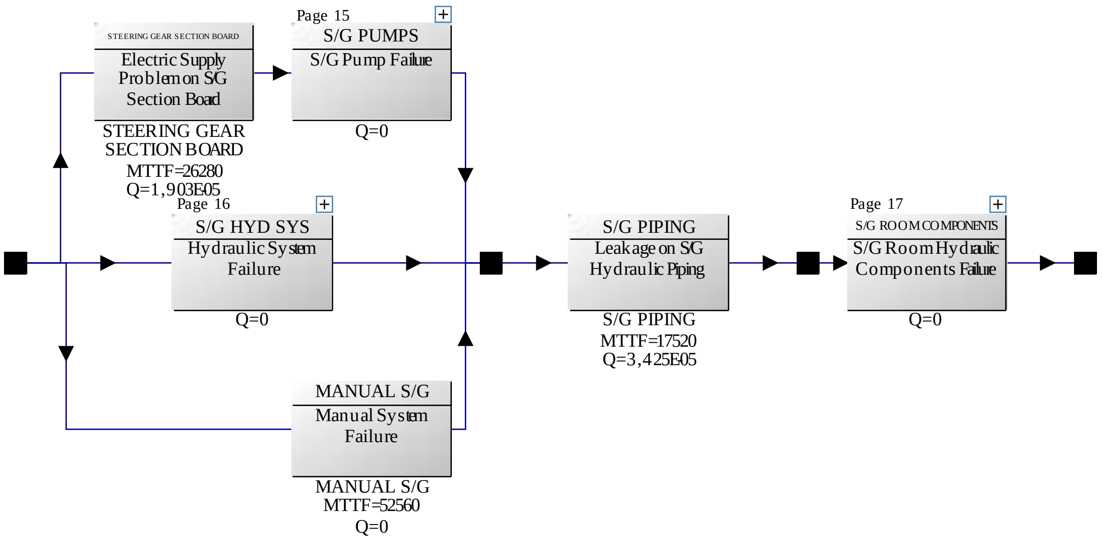
Reliability Block Diagrams

SHIP RELIABILITY

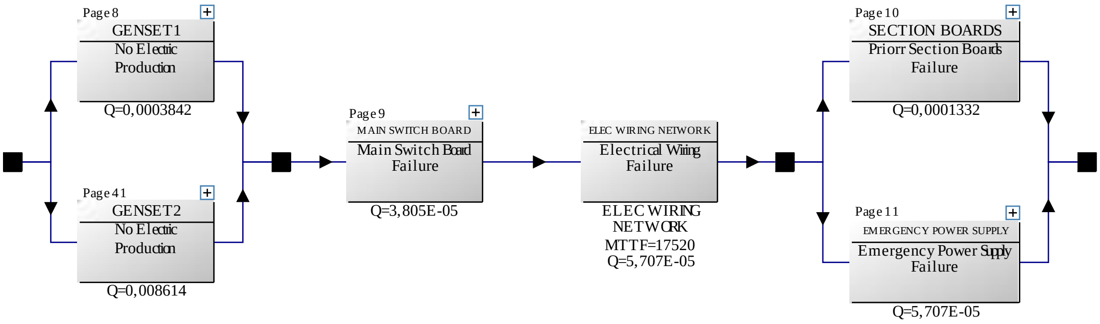
Sub-system PROPULSION SYSTEM See page 2



Sub-system STEERING GEAR See page 2



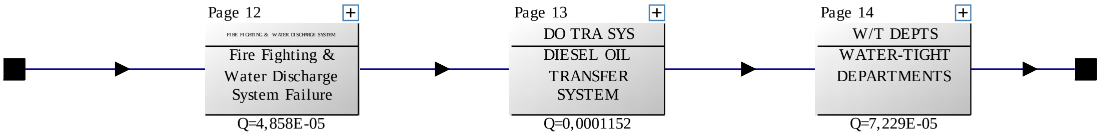
Sub-system ELECTRIC POWER SYSTEM See page 2



Reliability Block Diagrams

SHIP RELIABILITY

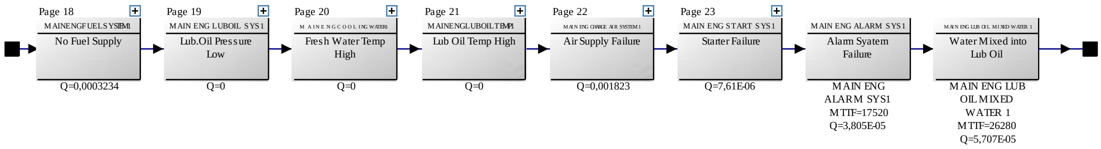
Sub-system DAMAGE CONTROL SYSTEM See page 2



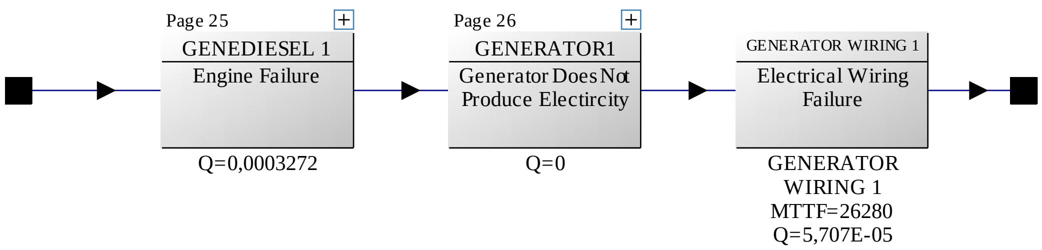
Reliability Block Diagrams

SHIP RELIABILITY

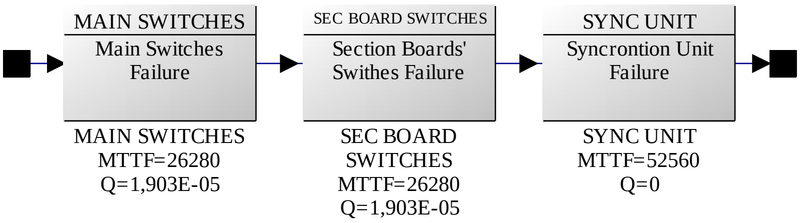
Sub-system MAIN ENG1 See page 3



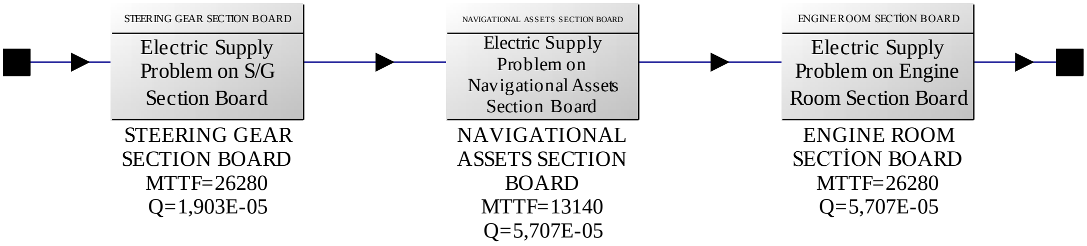
Sub-system GENSET1 See page 5



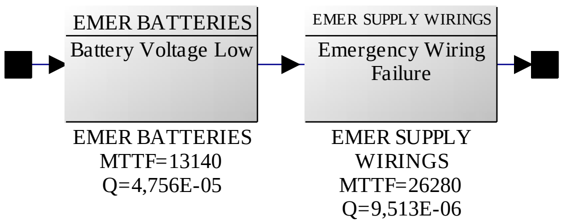
Sub-system MAIN SWITCH BOARD See page 5



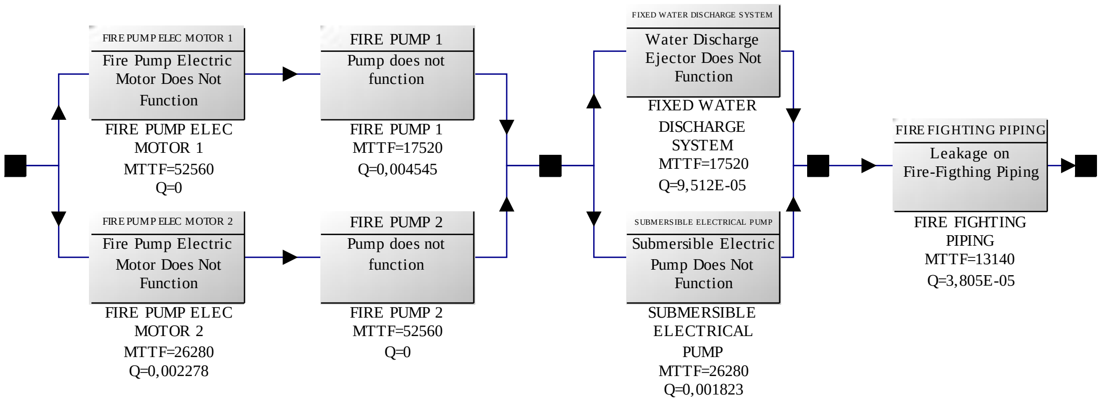
Sub-system SECTION BOARDS See page 5



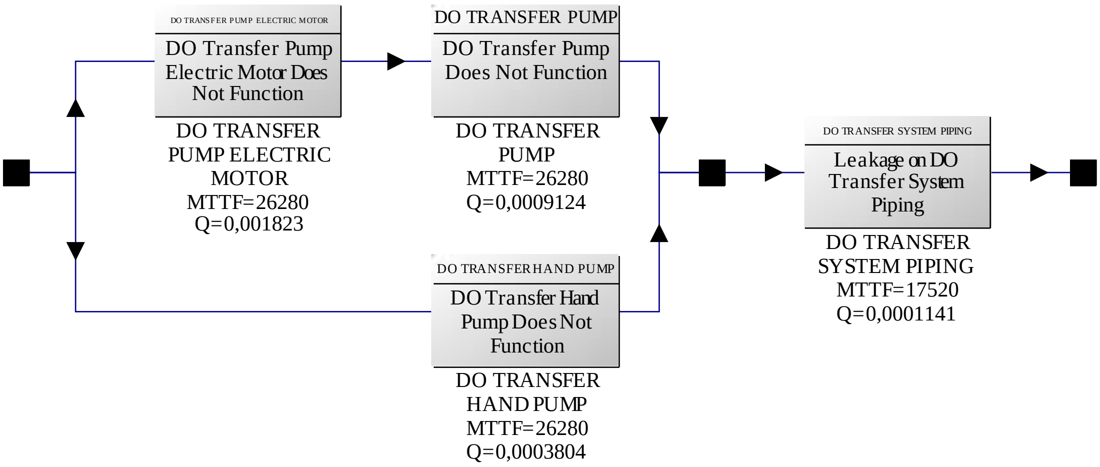
Sub-system EMERGENCY POWER SUPPLY See page 5



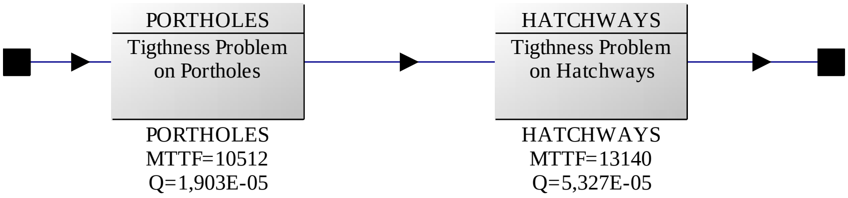
Sub-system FIRE FIGHTING & WATER DISCHARGE SYSTEM See page 6



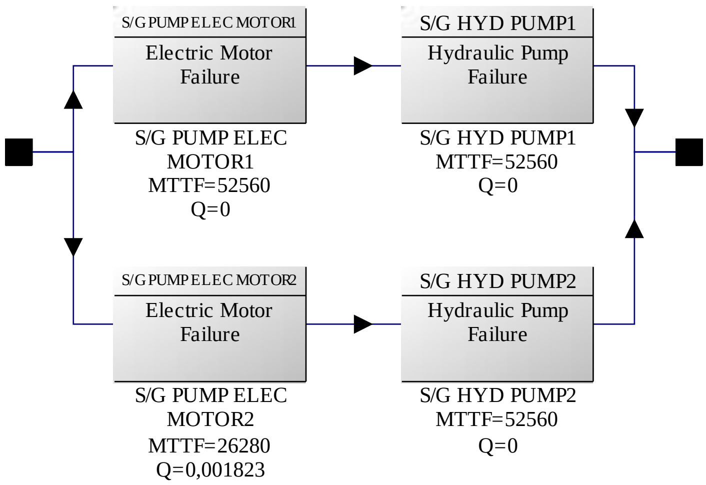
Sub-system DO TRA SYS See page 6



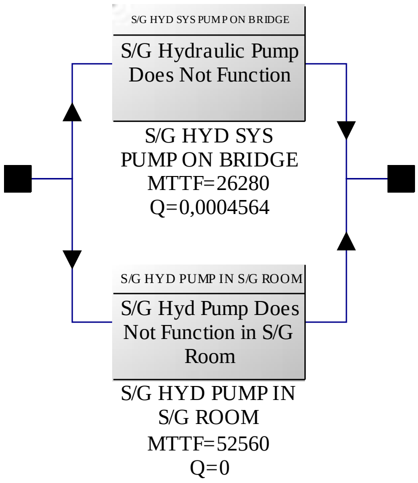
Sub-system W/T DEPTS See page 6



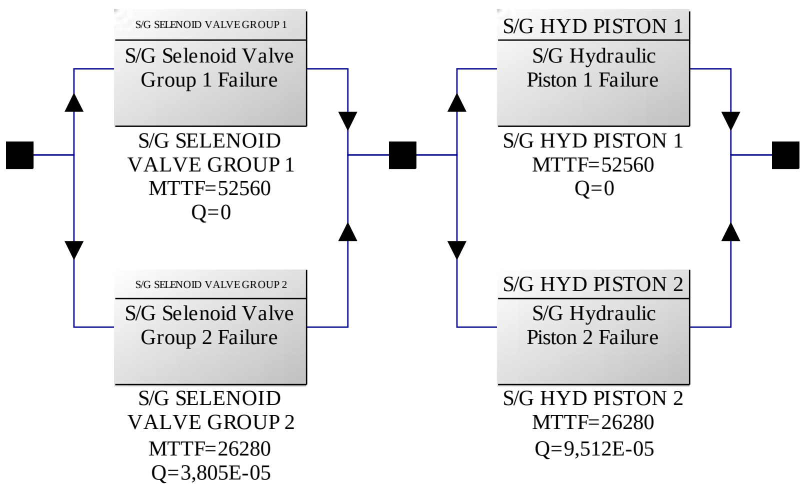
Sub-system S/G PUMPS See page 4



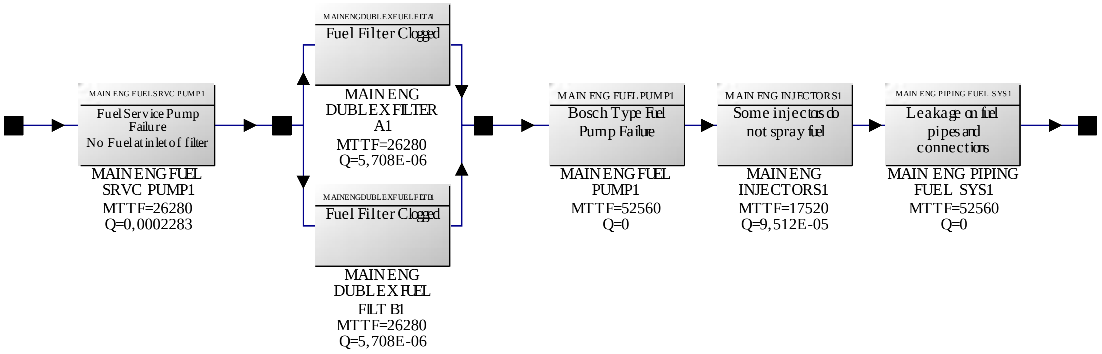
Sub-system S/G HYD SYS See page 4



Sub-system S/G ROOM COMPONENTS See page 4



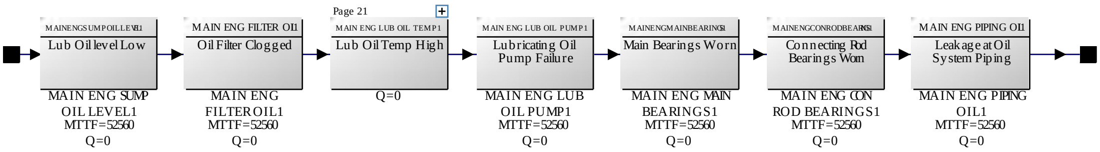
Sub-system MAIN ENG FUEL SYSTEM1 See page 7



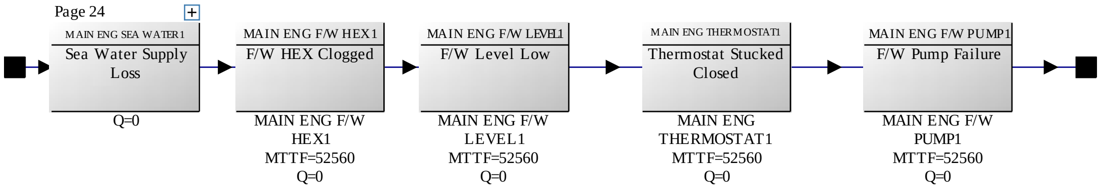
Reliability Block Diagrams

SHIP RELIABILITY

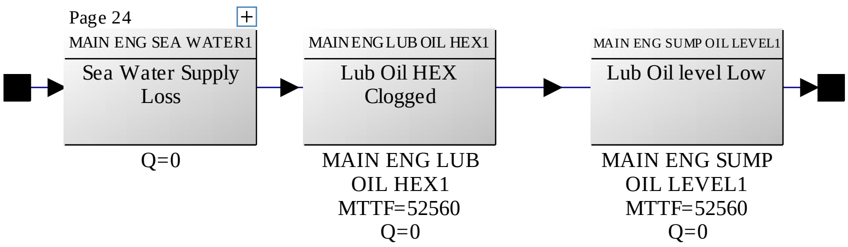
Sub-system MAIN ENG LUBOIL SYS1 See page 7



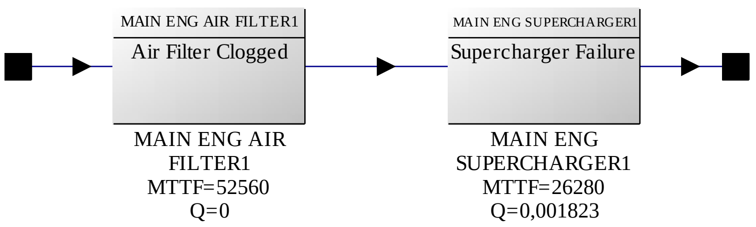
Sub-system MAIN ENG COOLING WATER1 See page 7



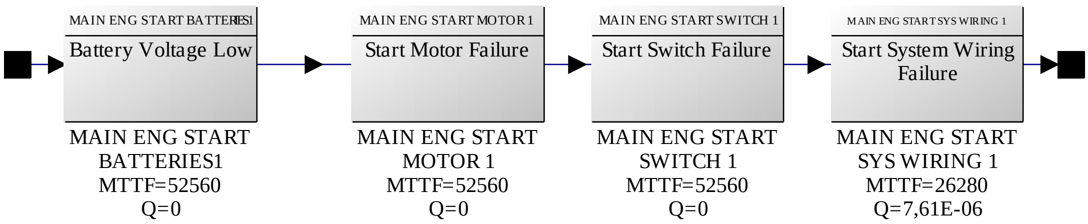
Sub-system MAIN ENG LUB OIL TEMP1 See pages 7,19



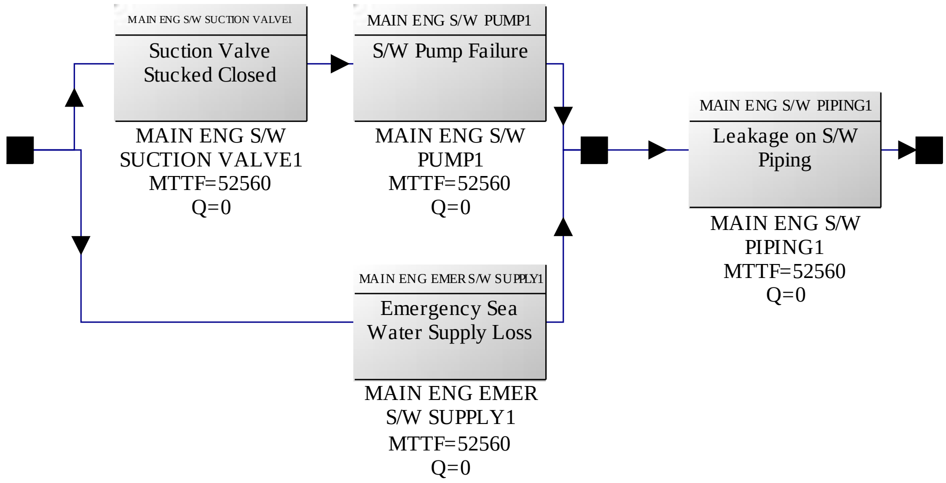
Sub-system MAIN ENG CHARGE AIR SYSTEM1 See page 7



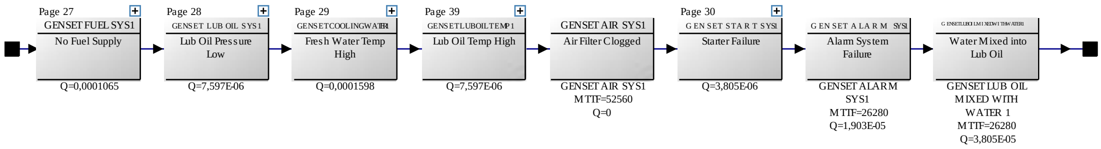
Sub-system MAIN ENG START SYS1 See page 7



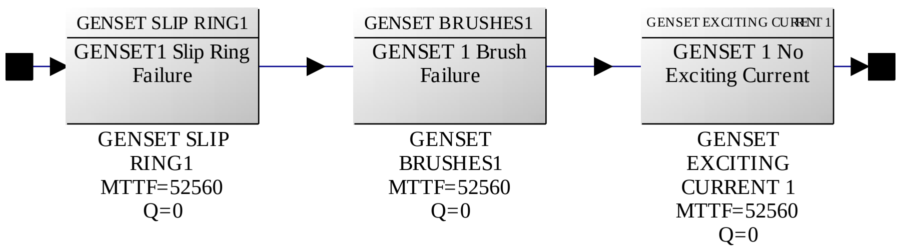
Sub-system MAIN ENG SEA WATER1 See pages 20,21



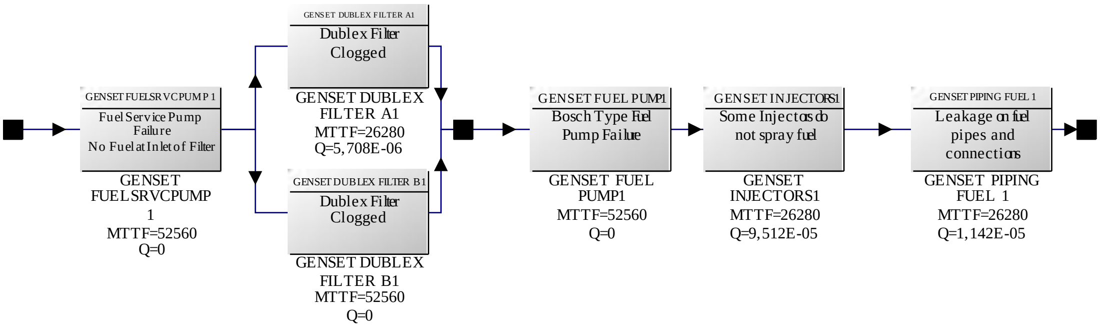
Sub-system GENEDIESEL 1 See page 8



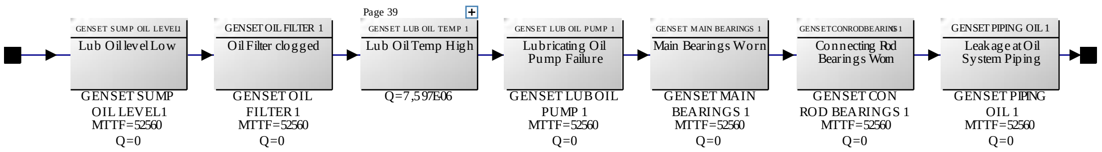
Sub-system GENERATOR1 See page 8



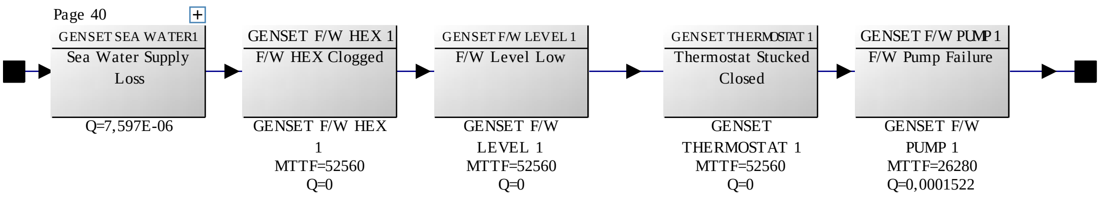
Sub-system GENSET FUEL SYS1 See page 25



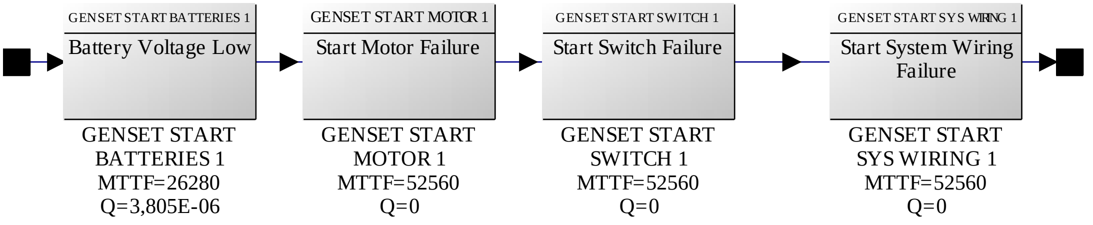
Sub-system GENSET LUB OIL SYS1 See page 25



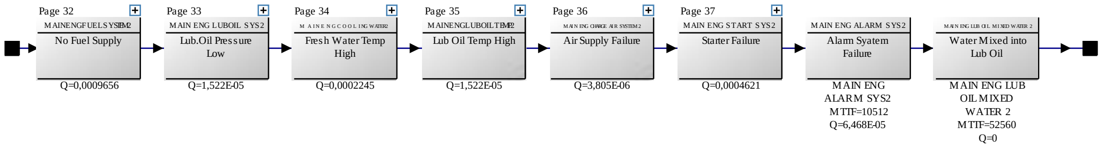
Sub-system GENSET COOLING WATER1 See page 25



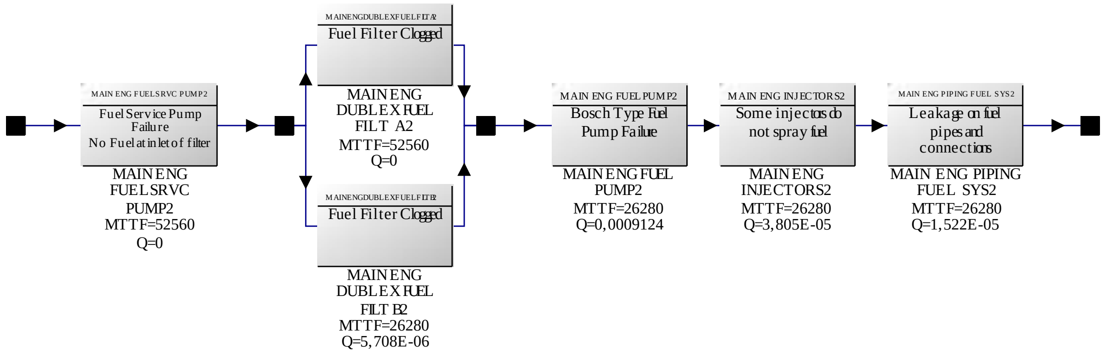
Sub-system GENSET START SYS1 See page 25



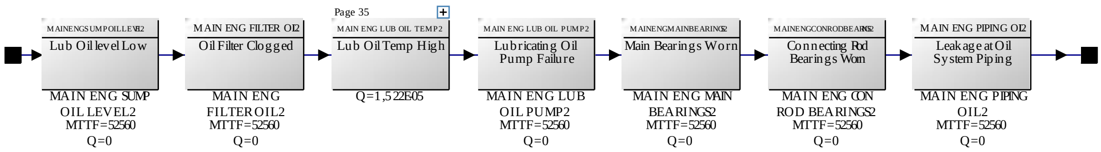
Sub-system MAIN ENG2 See page 3



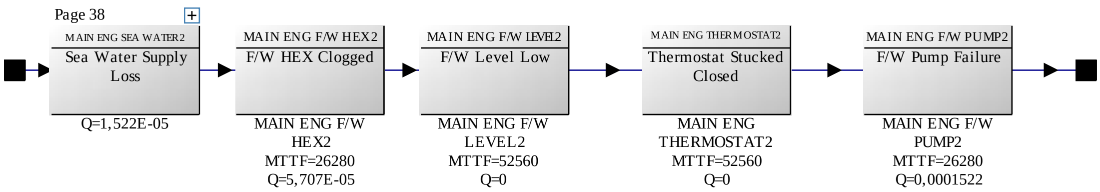
Sub-system MAIN ENG FUEL SYSTEM2 See page 31



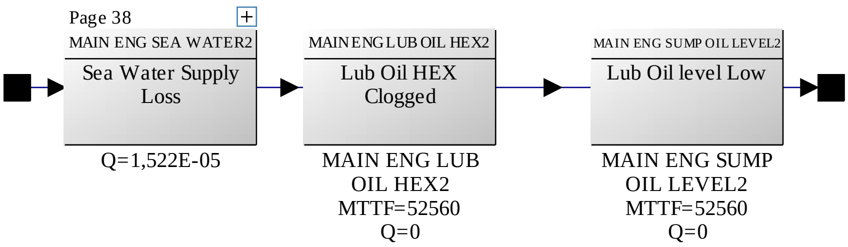
Sub-system MAIN ENG LUBOIL SYS2 See page 31



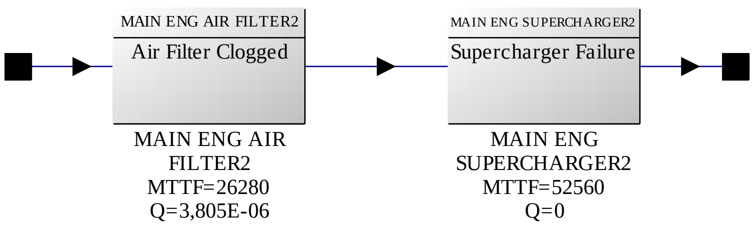
Sub-system MAIN ENG COOLING WATER2 See page 31



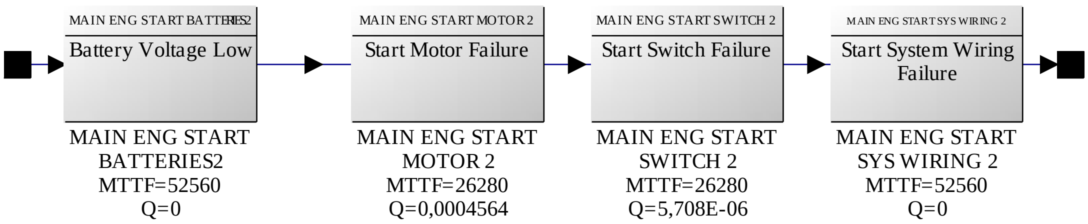
Sub-system MAIN ENG LUB OIL TEMP2 See pages 31,33



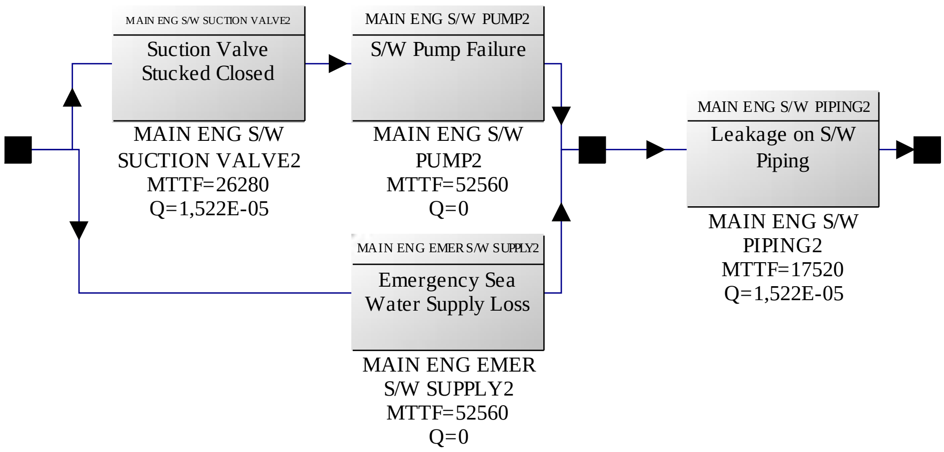
Sub-system MAIN ENG CHARGE AIR SYSTEM2 See page 31



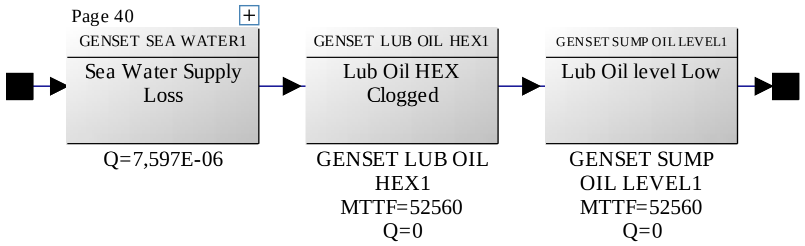
Sub-system MAIN ENG START SYS2 See page 31



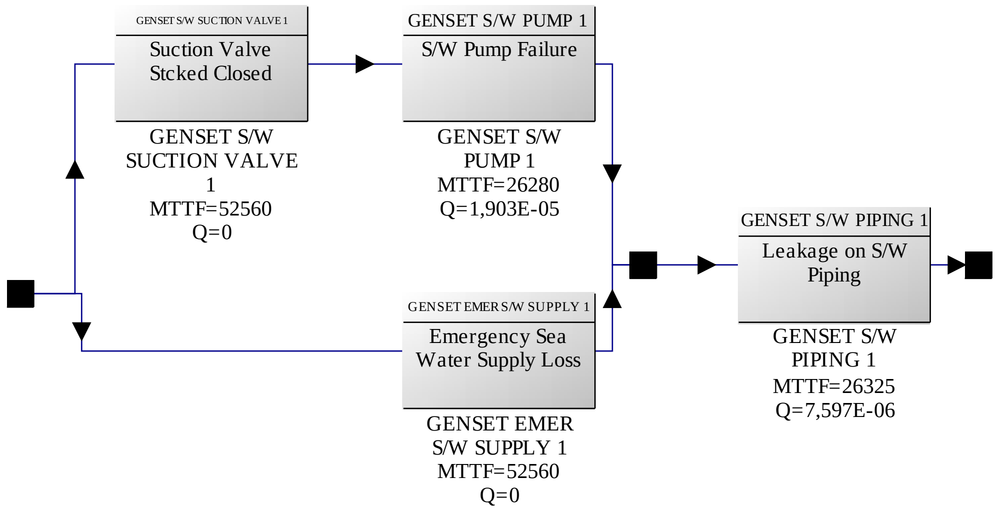
Sub-system MAIN ENG SEA WATER2 See pages 34,35



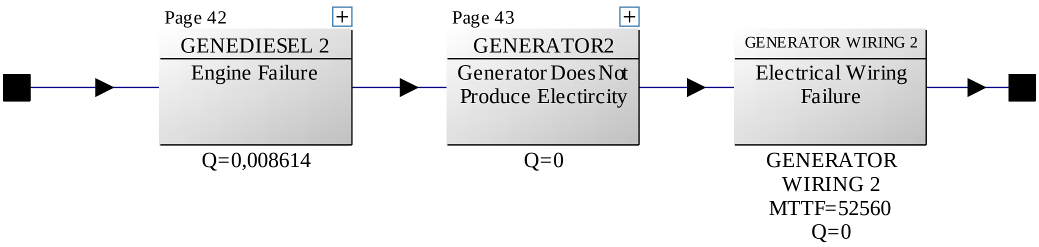
Sub-system GENSET LUB OIL TEMP 1 See pages 25,28



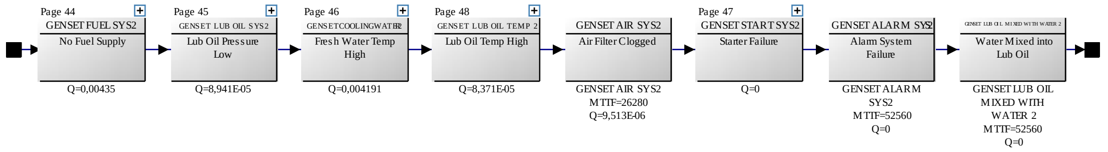
Sub-system GENSET SEA WATER1 See pages 29,39



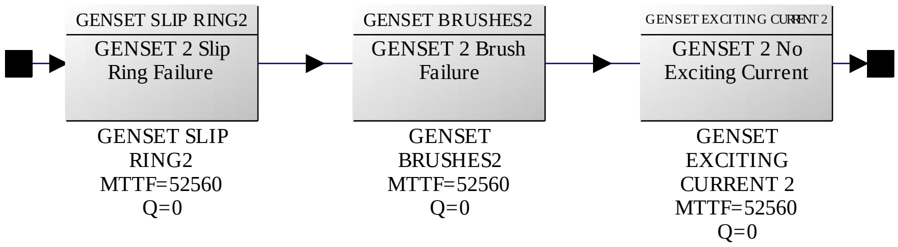
Sub-system GENSET2 See page 5



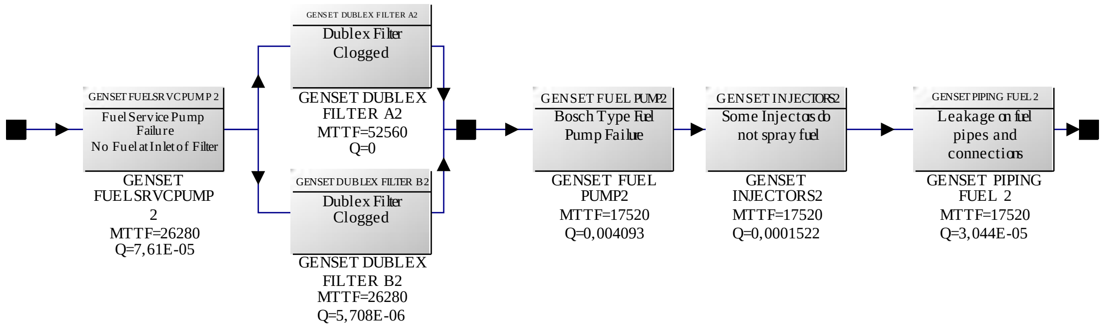
Sub-system GENEDIESEL 2 See page 41



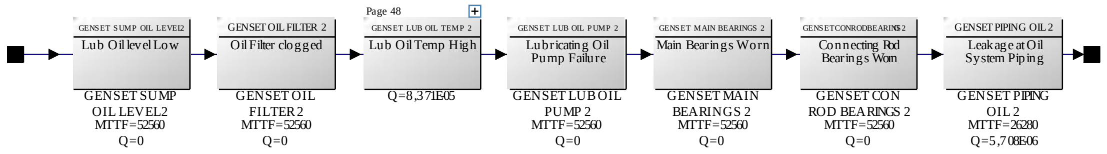
Sub-system GENERATOR2 See page 41



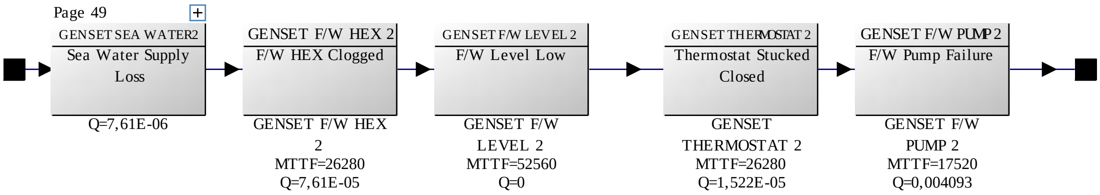
Sub-system GENSET FUEL SYS2 See page 42



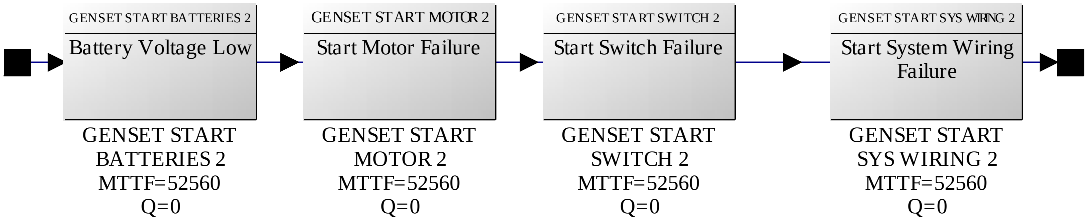
Sub-system GENSET LUB OIL SYS2 See page 42



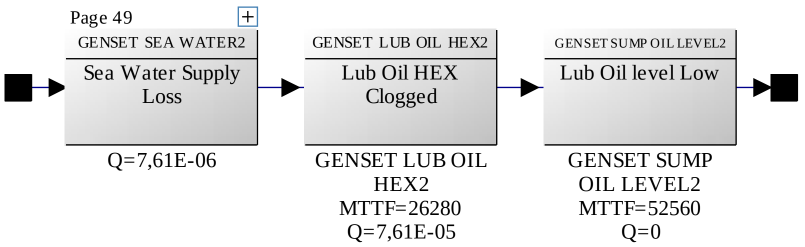
Sub-system GENSET COOLING WATER2 See page 42



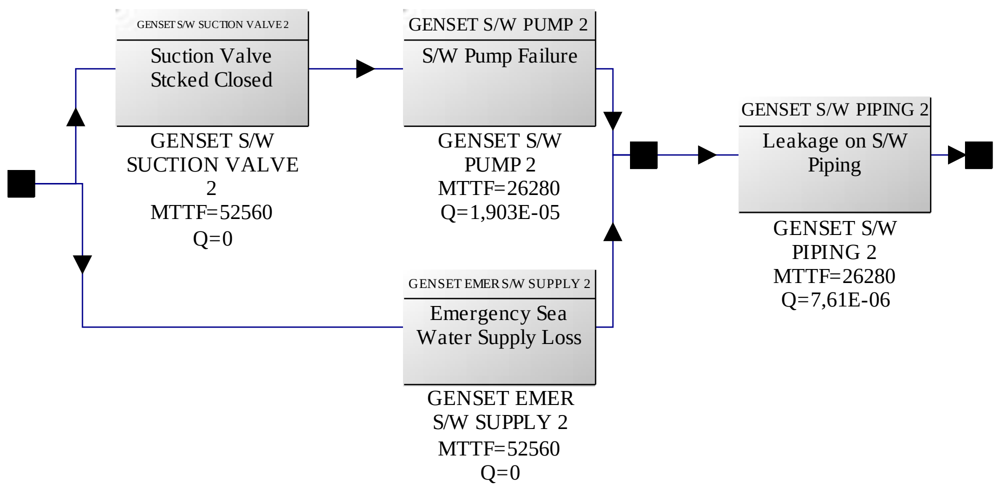
Sub-system GENSET START SYS2 See page 42



Sub-system GENSET LUB OIL TEMP 2 See pages 42,45



Sub-system GENSET SEA WATER2 See pages 46,48

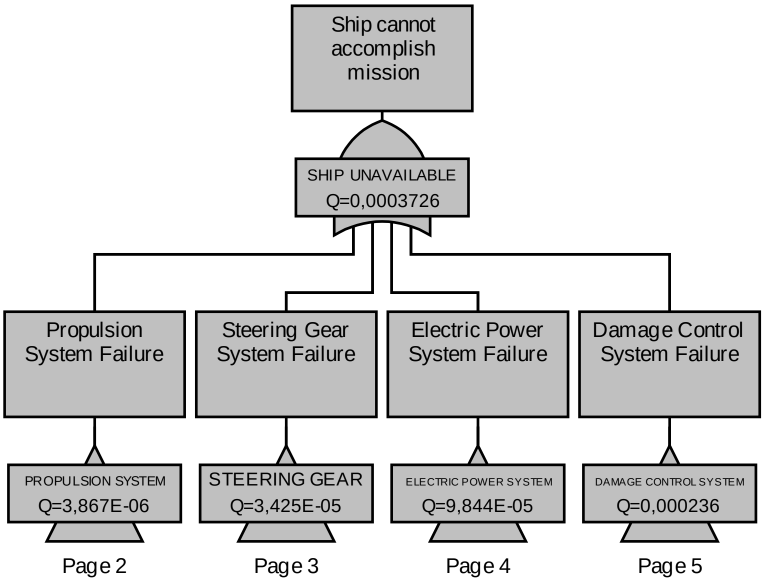


APPENDIX I

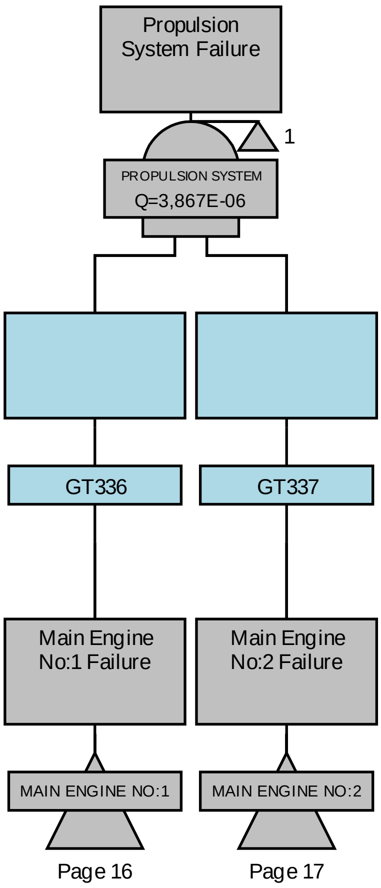
Fault Tree Diagrams

SHIP RELIABILITY

1



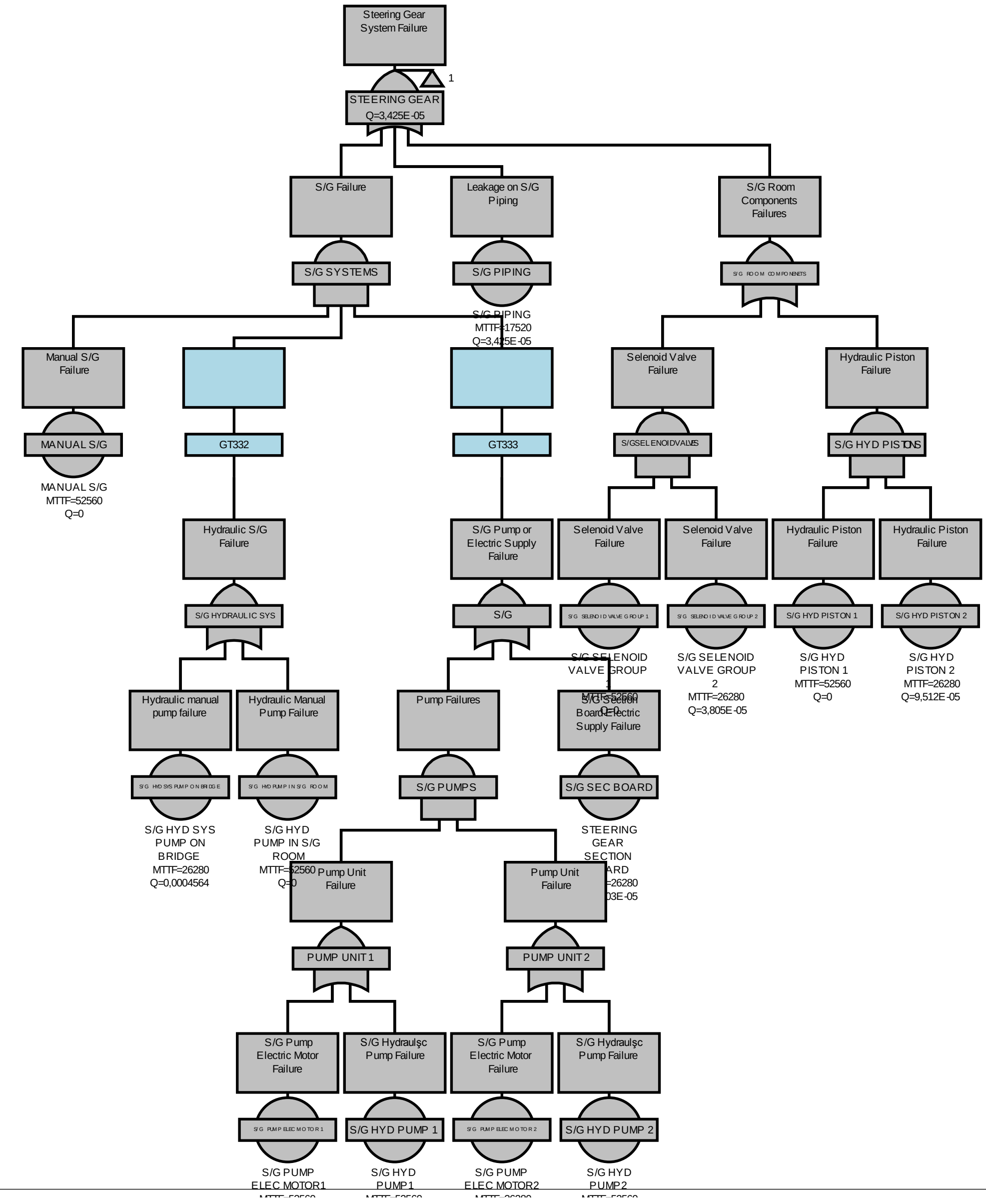
2


Propulsion System Failure
1
PROPULSION SYSTEM
Q=3,867E-06
GT336
GT337
Main Engine No:1 Failure
Main Engine No:2 Failure
MAIN ENGINE NO:1
MAIN ENGINE NO:2
Page 16
Page 17

<u>Fault Tree Diagrams</u>

SHIP RELIABILITY

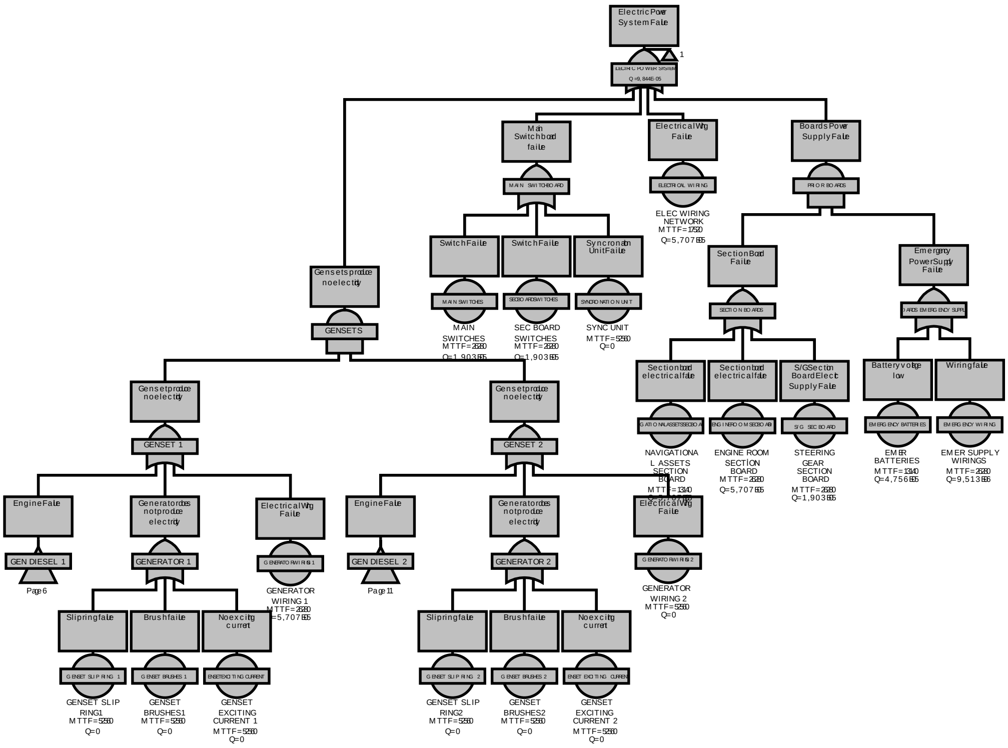
3



Fault Tree Diagrams

SHIP RELIABILITY

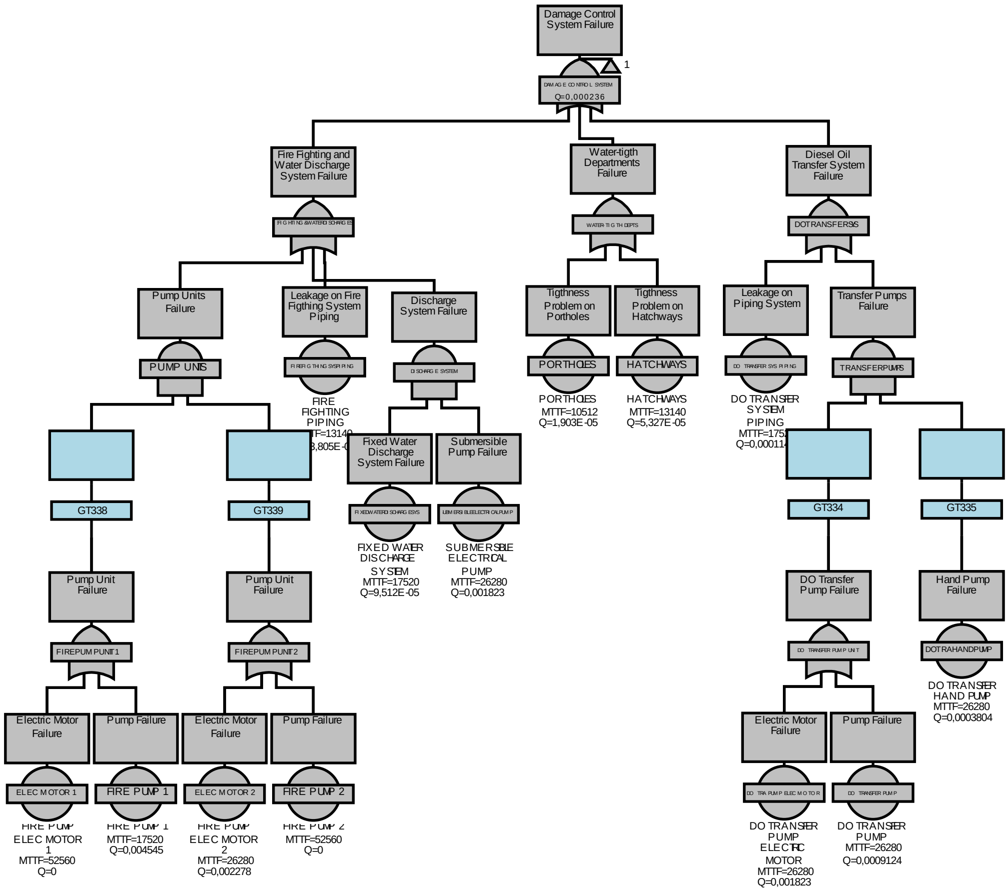
4



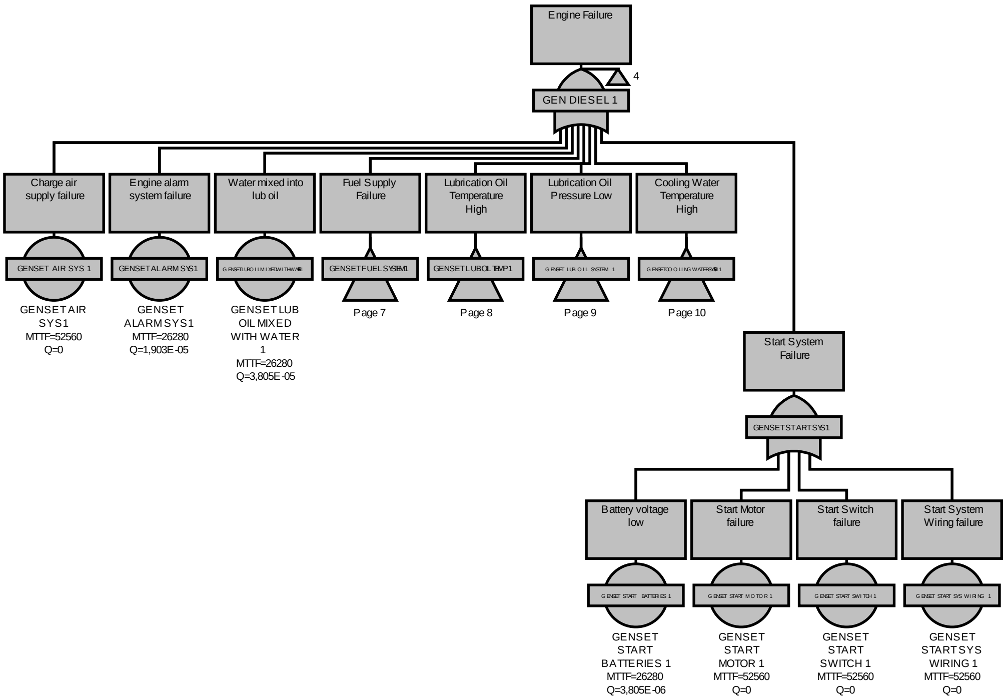
Fault Tree Diagrams

SHIP RELIABILITY

5



6

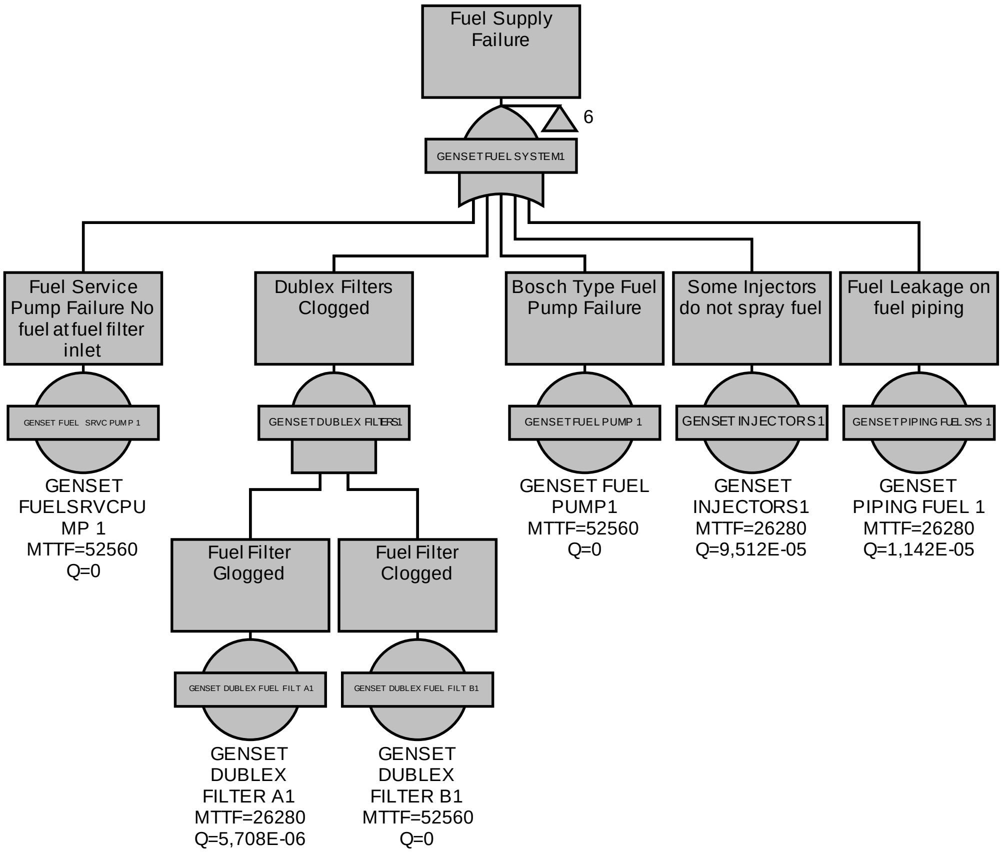


Engine Failure
4
GEN DIESEL 1
Charge air supply failure
Engine alarm system failure
Water mixed into lub oil
Fuel Supply Failure
Lubrication Oil Temperature High
Lubrication Oil Pressure Low
Cooling Water Temperature High
GENSET AIR SYS 1
GENSET ALARM SYS 1
GENSET AIR SYS1 MTTF=52560 Q=0
GENSET ALARM SYS1 MTTF=26280 Q=1,903E-05
GENSET LUB OIL MIXED WITH WATER 1 MTTF=26280 Q=3,805E-05
Page 7
Page 8
Page 9
Page 10
Start System Failure
GENSET START SYS1
Battery voltage low
Start Motor failure
Start Switch failure
Start System Wiring failure
GENSET START BATTERIES 1 MTTF=26280 Q=3,805E-06
GENSET START MOTOR 1 MTTF=52560 Q=0
GENSET START SWITCH 1 MTTF=52560 Q=0
GENSET START SYS WIRING 1 MTTF=52560 Q=0

Fault Tree Diagrams

SHIP RELIABILITY

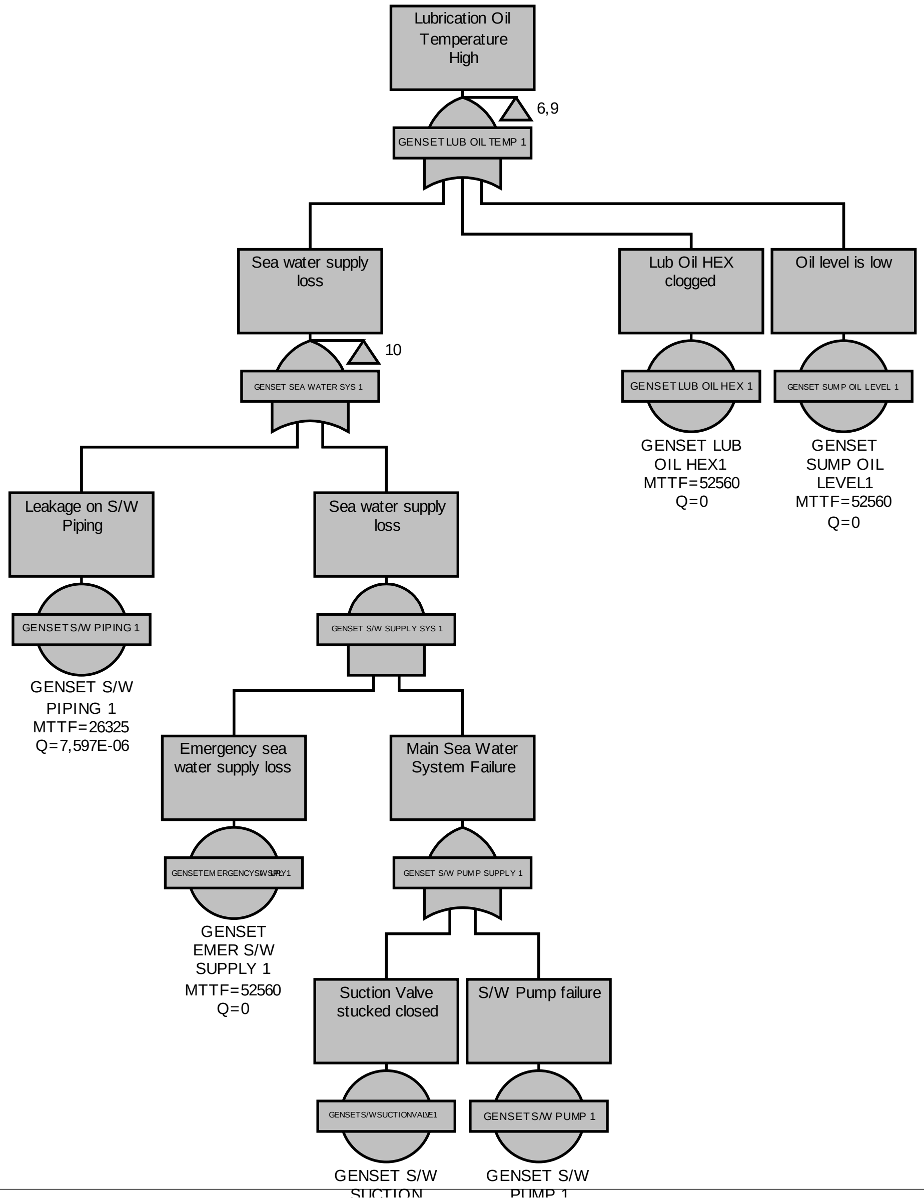
7



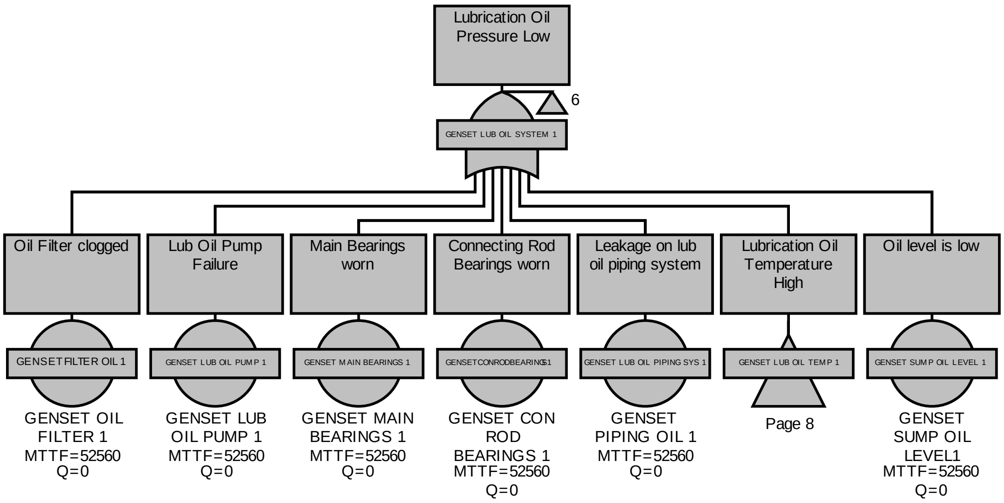
Fault Tree Diagrams

SHIP RELIABILITY

8



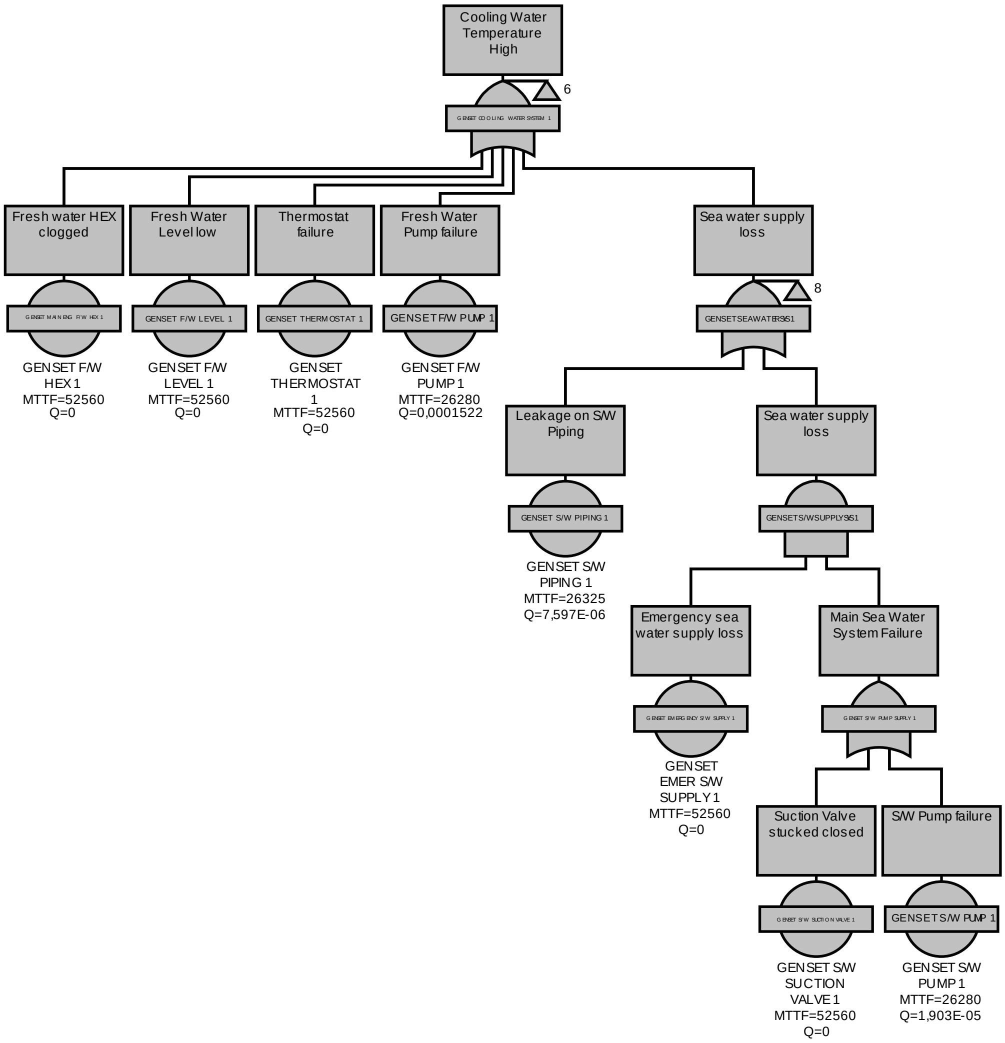
9


Lubrication Oil Pressure Low
6
GENSET LUB OIL SYSTEM 1
Oil Filter clogged
Lub Oil Pump Failure
Main Bearings worn
Connecting Rod Bearings worn
Leakage on lub oil piping system
Lubrication Oil Temperature High
Oil level is low
GENSET FILTER OIL 1
GENSET LUB OIL PUMP 1
GENSET MAIN BEARINGS 1
GENSET CON ROD BEARINGS 1
GENSET LUB OIL PIPING SYS 1
GENSET LUB OIL TEMP 1
GENSET SUMP OIL LEVEL 1
GENSET OIL FILTER 1
MTTF=52560
Q=0
GENSET LUB OIL PUMP 1
MTTF=52560
Q=0
GENSET MAIN BEARINGS 1
MTTF=52560
Q=0
GENSET CON ROD BEARINGS 1
MTTF=52560
Q=0
GENSET PIPING OIL 1
MTTF=52560
Q=0
Page 8
GENSET SUMP OIL LEVEL1
MTTF=52560
Q=0

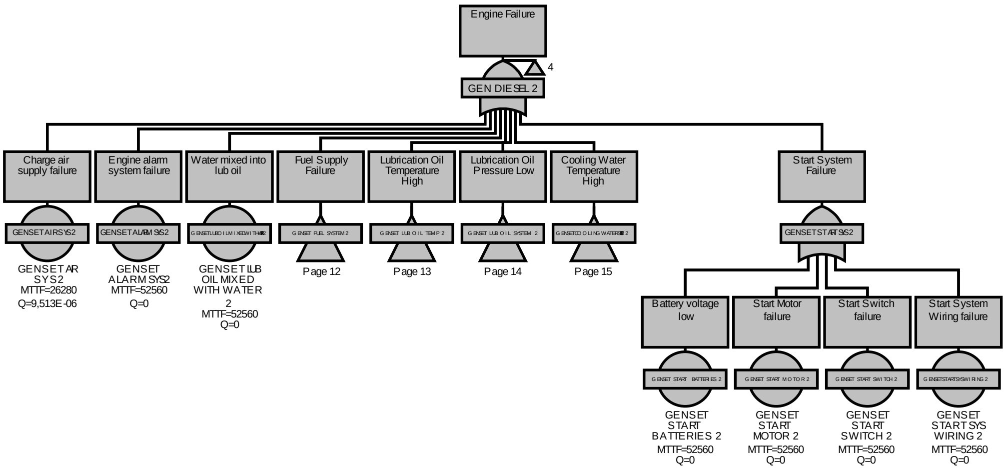
Fault Tree Diagrams

SHIP RELIABILITY

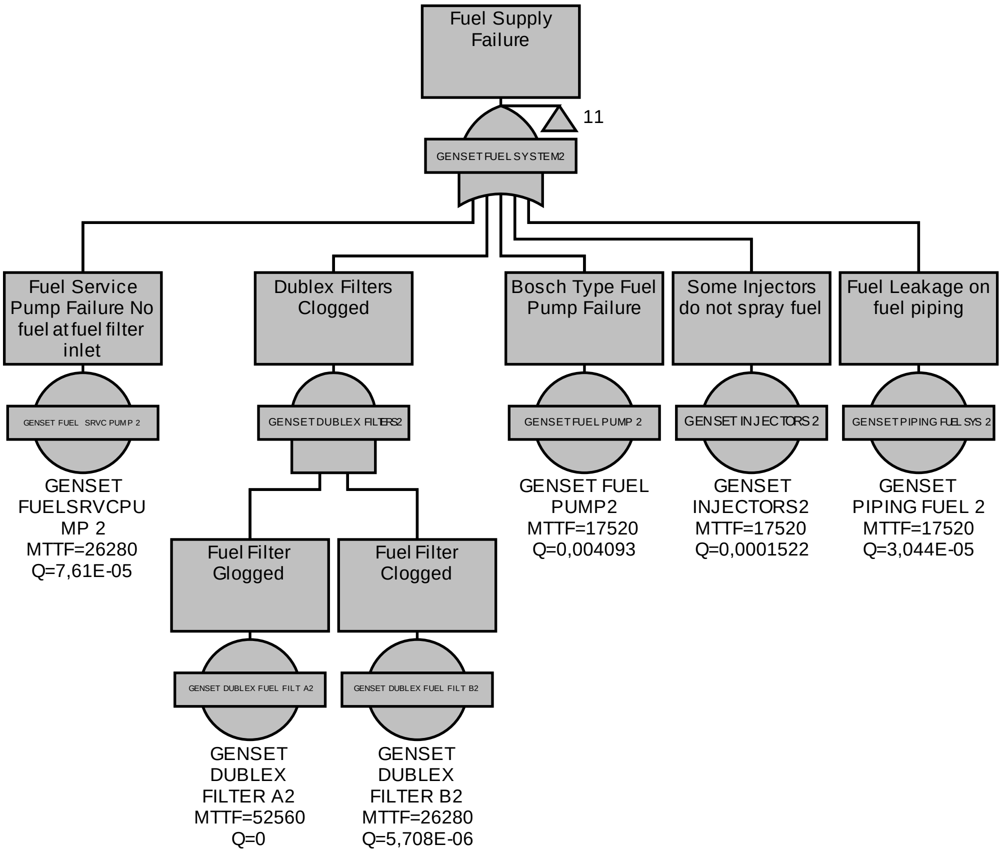
10



11


Engine Failure
4
GEN DIESEL 2
Charge air supply failure
Engine alarm system failure
Water mixed into lub oil
Fuel Supply Failure
Lubrication Oil Temperature High
Lubrication Oil Pressure Low
Cooling Water Temperature High
Start System Failure
GENSET AIR SYS2
GENSET ALARM SYS2
GENSET AIR SYS2 MTTF=26280 Q=9,513E-06
GENSET ALARM SYS2 MTTF=52560 Q=0
GENSET LUB OIL MIXED WITH WATER 2 MTTF=52560 Q=0
Page 12
Page 13
Page 14
Page 15
GENSET START SYS2
Battery voltage low
Start Motor failure
Start Switch failure
Start System Wiring failure
GENSET START BATTERIES 2 MTTF=52560 Q=0
GENSET START MOTOR 2 MTTF=52560 Q=0
GENSET START SWITCH 2 MTTF=52560 Q=0
GENSET START SYS WIRING 2 MTTF=52560 Q=0

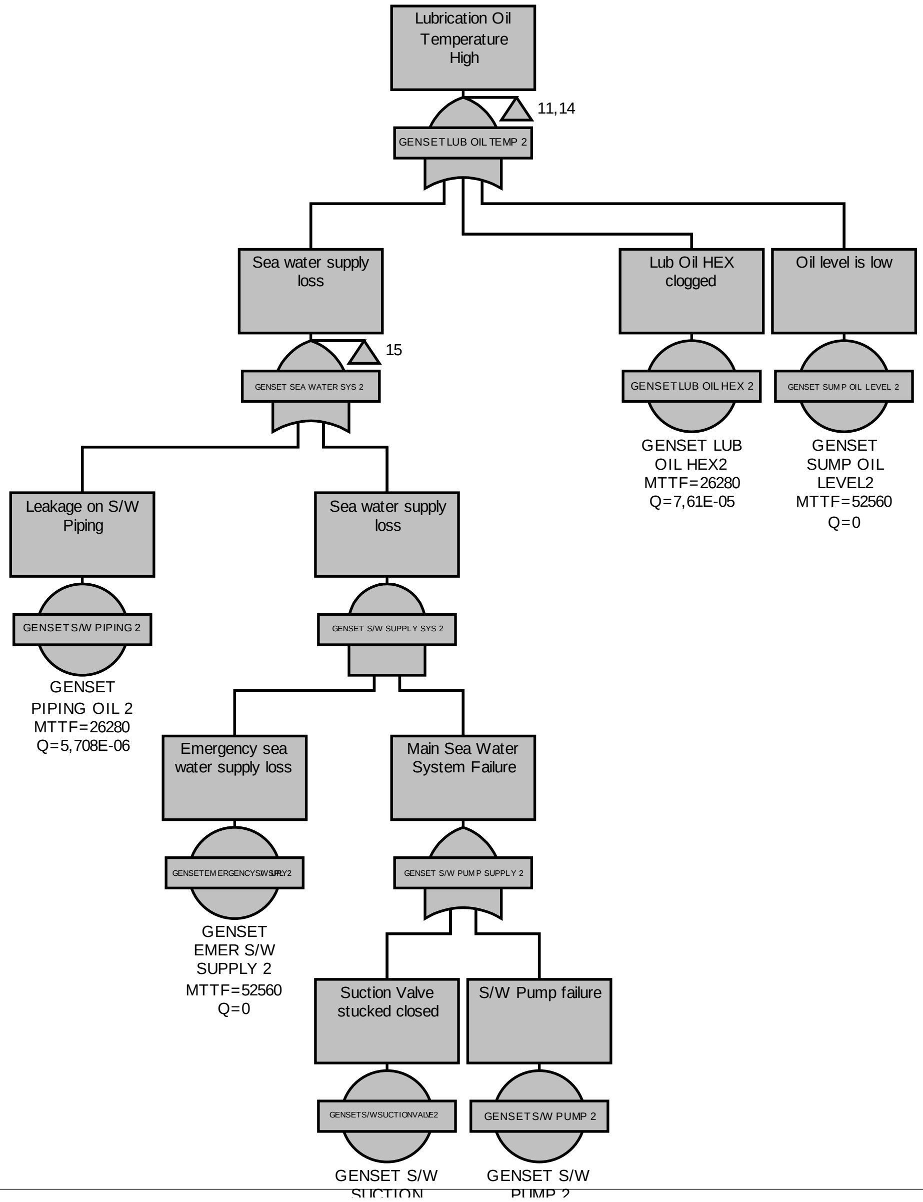
12


Fuel Supply Failure
11
GENSET FUEL SYSTEM2
Fuel Service Pump Failure No fuel at fuel filter inlet
Dublex Filters Clogged
Bosch Type Fuel Pump Failure
Some Injectors do not spray fuel
Fuel Leakage on fuel piping
GENSET FUEL SRVC PUMP 2
GENSET DUBLEX FILTERS2
GENSET FUEL PUMP 2
GENSET INJECTORS 2
GENSET PIPING FUEL SYS 2
GENSET FUELSRVCPUMP 2
MTTF=26280
Q=7,61E-05
GENSET FUEL PUMP2
MTTF=17520
Q=0,004093
GENSET INJECTORS2
MTTF=17520
Q=0,0001522
GENSET PIPING FUEL 2
MTTF=17520
Q=3,044E-05
Fuel Filter Glogged
Fuel Filter Clogged
GENSET DUBLEX FUEL FILT A2
GENSET DUBLEX FUEL FILT B2
GENSET DUBLEX FILTER A2
MTTF=52560
Q=0
GENSET DUBLEX FILTER B2
MTTF=26280
Q=5,708E-06

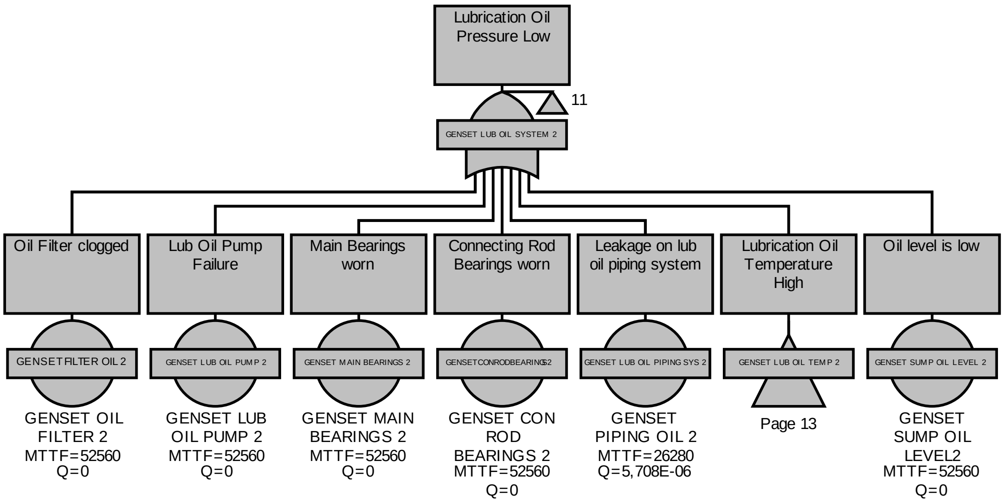
Fault Tree Diagrams

SHIP RELIABILITY

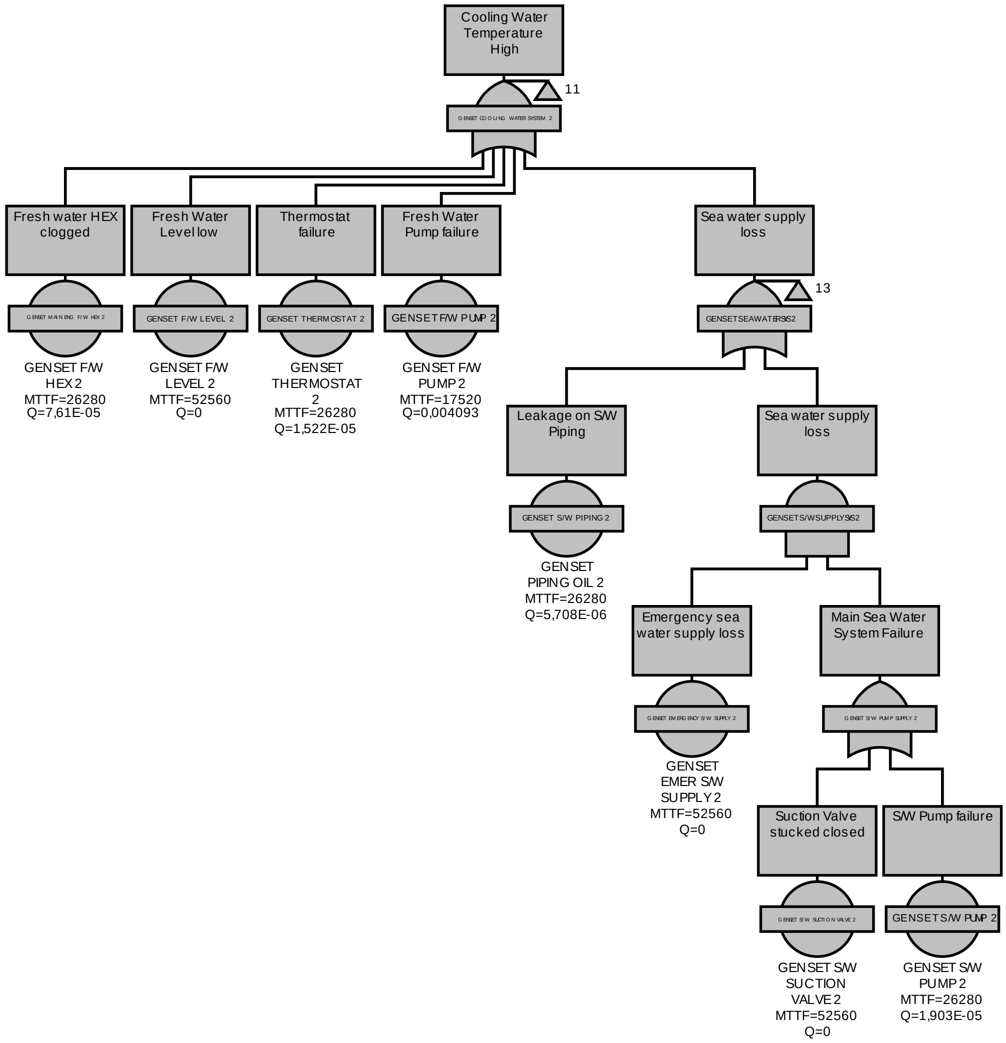
13



14


Lubrication Oil Pressure Low
11
GENSET LUB OIL SYSTEM 2
Oil Filter clogged
Lub Oil Pump Failure
Main Bearings worn
Connecting Rod Bearings worn
Leakage on lub oil piping system
Lubrication Oil Temperature High
Oil level is low
GENSET FILTER OIL 2
GENSET LUB OIL PUMP 2
GENSET MAIN BEARINGS 2
GENSET CONRODBEARINGS2
GENSET LUB OIL PIPING SYS 2
GENSET LUB OIL TEMP 2
GENSET SUMP OIL LEVEL 2
GENSET OIL FILTER 2
MTTF=52560
Q=0
GENSET LUB OIL PUMP 2
MTTF=52560
Q=0
GENSET MAIN BEARINGS 2
MTTF=52560
Q=0
GENSET CON ROD BEARINGS 2
MTTF=52560
Q=0
GENSET PIPING OIL 2
MTTF=26280
Q=5,708E-06
Page 13
GENSET SUMP OIL LEVEL2
MTTF=52560
Q=0

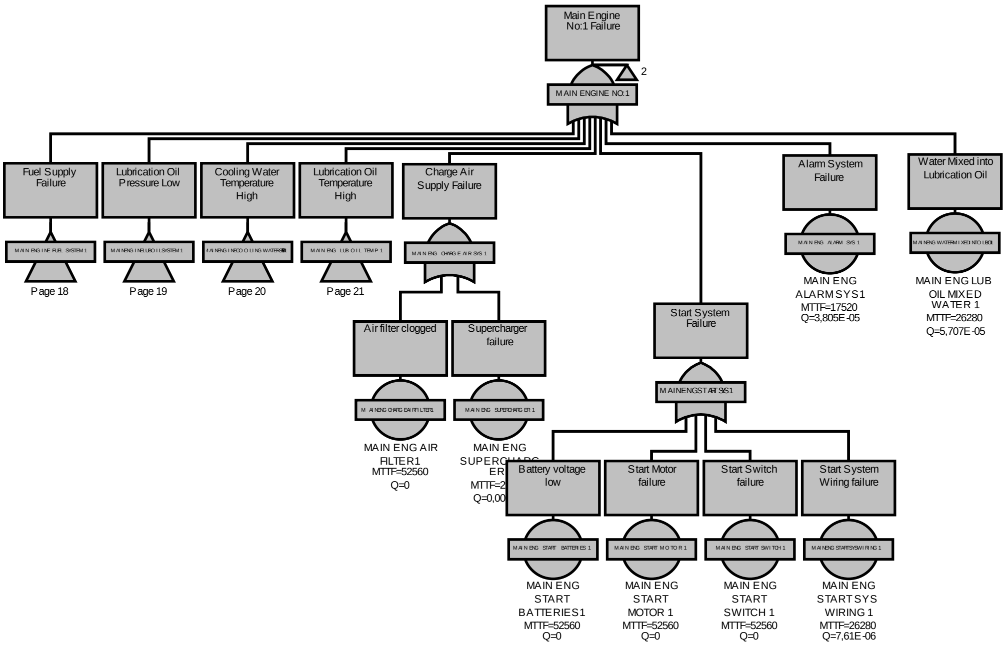
15


Cooling Water Temperature High
11
Fresh water HEX clogged
Fresh Water Level low
Thermostat failure
Fresh Water Pump failure
Sea water supply loss
GENSET F/W LEVEL 2
GENSET THERMOSTAT 2
GENSET F/W PUMP 2
13
GENSET F/W HEX 2 MTTF=26280 Q=7,61E-05
GENSET F/W LEVEL 2 MTTF=52560 Q=0
GENSET THERMOSTAT 2 MTTF=26280 Q=1,522E-05
GENSET F/W PUMP 2 MTTF=17520 Q=0,004093
Leakage on S/W Piping
Sea water supply loss
GENSET S/W PIPING 2
GENSET PIPING OIL 2 MTTF=26280 Q=5,708E-06
Emergency sea water supply loss
Main Sea Water System Failure
GENSET EMER S/W SUPPLY 2 MTTF=52560 Q=0
Suction Valve stucked closed
S/W Pump failure
GENSET S/W PUMP 2
GENSET S/W SUCTION VALVE 2 MTTF=52560 Q=0
GENSET S/W PUMP 2 MTTF=26280 Q=1,903E-05

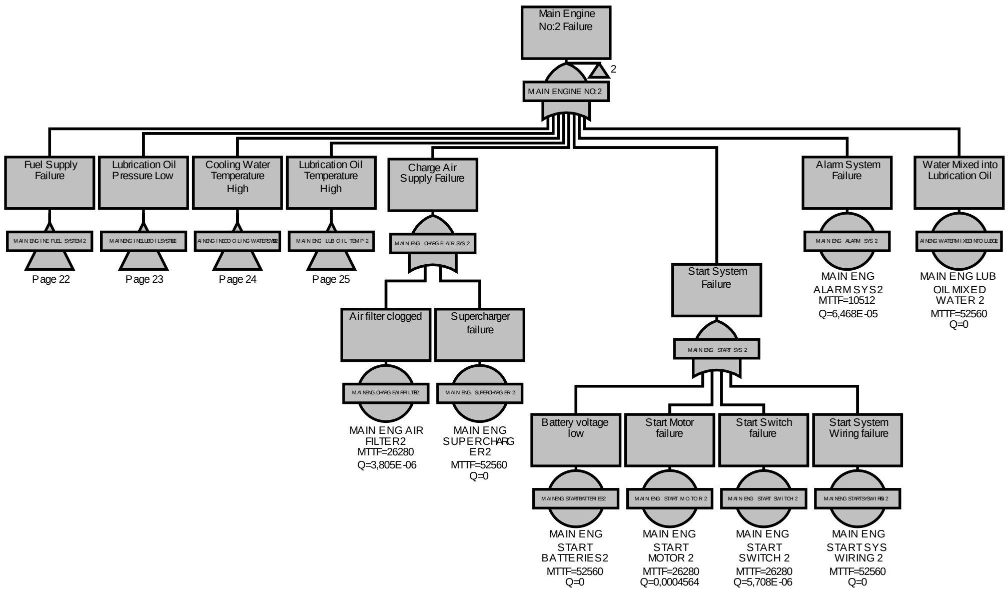
Fault Tree Diagrams

SHIP RELIABILITY

16

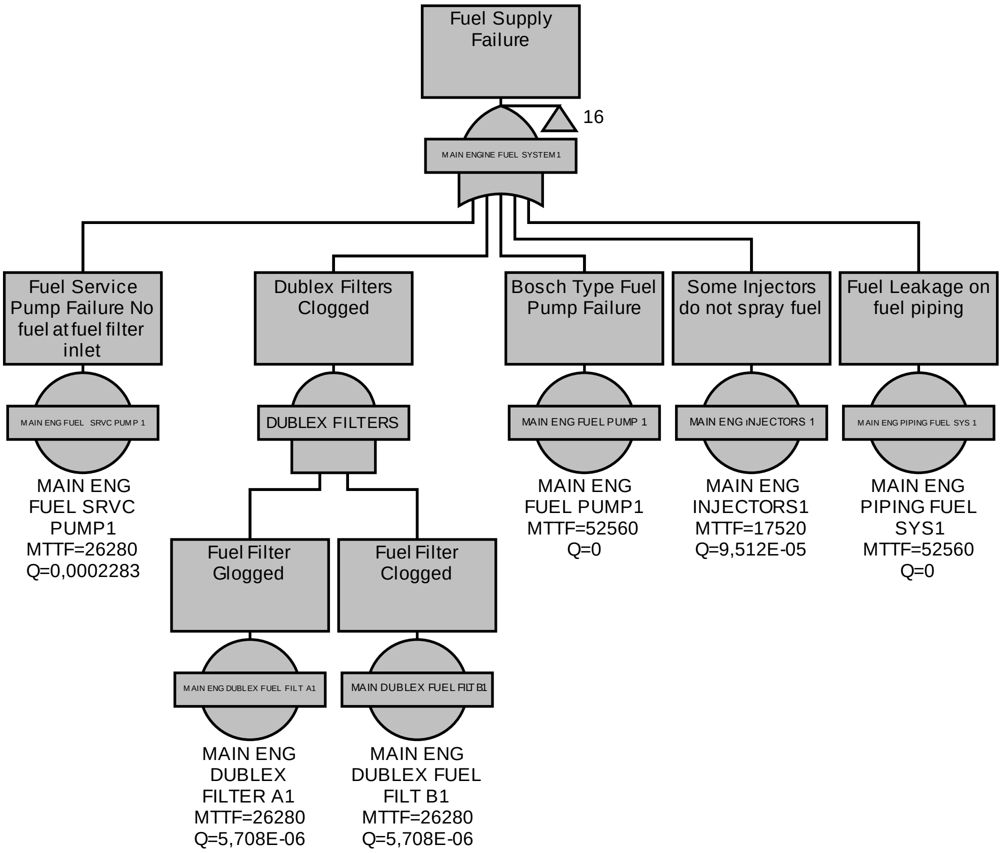


17

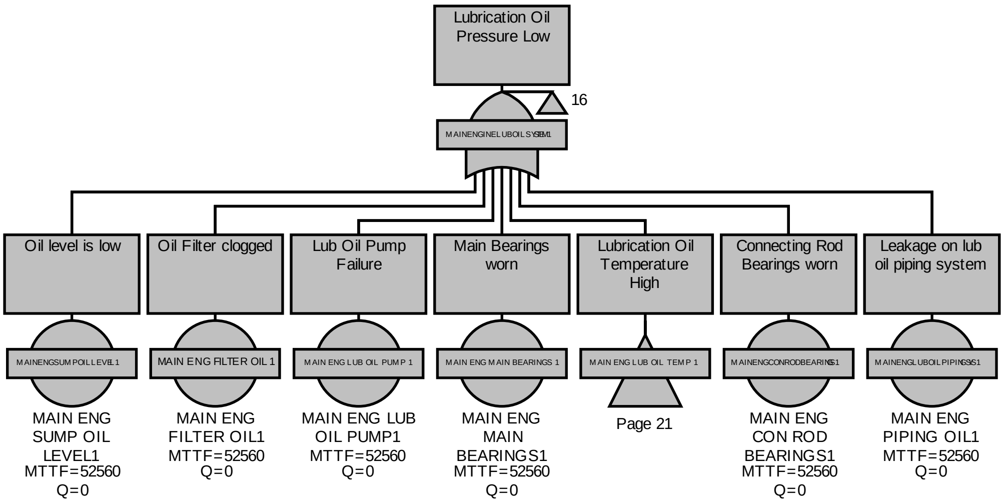


Main Engine No:2 Failure
2
MAIN ENGINE NO:2
Fuel Supply Failure
Lubrication Oil Pressure Low
Cooling Water Temperature High
Lubrication Oil Temperature High
Charge Air Supply Failure
Alarm System Failure
Water Mixed into Lubrication Oil
Page 22
Page 23
Page 24
Page 25
MAIN ENG ALARM SYS2
MTTF=10512
Q=6,468E-05
MAIN ENG LUB OIL MIXED WATER 2
MTTF=52560
Q=0
Start System Failure
Air filter clogged
Supercharger failure
MAIN ENG AIR FILTER2
MTTF=26280
Q=3,805E-06
MAIN ENG SUPERCHARG ER2
MTTF=52560
Q=0
Battery voltage low
Start Motor failure
Start Switch failure
Start System Wiring failure
MAIN ENG START BATTERIES2
MTTF=52560
Q=0
MAIN ENG START MOTOR 2
MTTF=26280
Q=0,0004564
MAIN ENG START SWITCH 2
MTTF=26280
Q=5,708E-06
MAIN ENG START SYS WIRING 2
MTTF=52560
Q=0

18

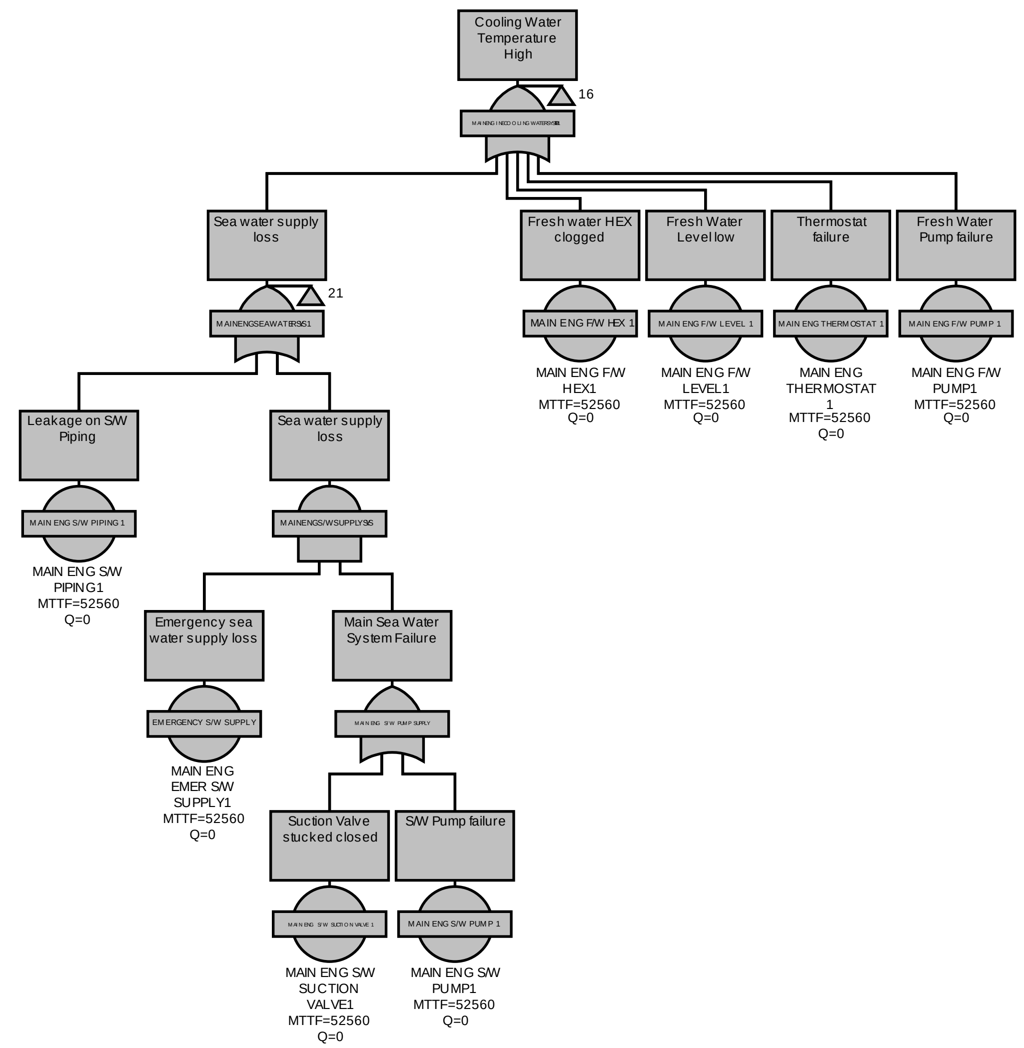

Fuel Supply Failure
16
MAIN ENGINE FUEL SYSTEM1
Fuel Service Pump Failure No fuel at fuel filter inlet
MAIN ENG FUEL SRVC PUMP 1
MAIN ENG FUEL SRVC PUMP1
MTTF=26280
Q=0,0002283
Dublex Filters Clogged
DUBLEX FILTERS
Fuel Filter Glogged
MAIN ENG DUBLEX FUEL FILT A1
MAIN ENG DUBLEX FILTER A1
MTTF=26280
Q=5,708E-06
Fuel Filter Clogged
MAIN DUBLEX FUEL FILT B1
MAIN ENG DUBLEX FUEL FILT B1
MTTF=26280
Q=5,708E-06
Bosch Type Fuel Pump Failure
MAIN ENG FUEL PUMP 1
MAIN ENG FUEL PUMP1
MTTF=52560
Q=0
Some Injectors do not spray fuel
MAIN ENG INJECTORS 1
MAIN ENG INJECTORS1
MTTF=17520
Q=9,512E-05
Fuel Leakage on fuel piping
MAIN ENG PIPING FUEL SYS 1
MAIN ENG PIPING FUEL SYS1
MTTF=52560
Q=0

19



Lubrication Oil Pressure Low
16
Oil level is low
Oil Filter clogged
Lub Oil Pump Failure
Main Bearings worn
Lubrication Oil Temperature High
Connecting Rod Bearings worn
Leakage on lub oil piping system
MAIN ENG FILTER OIL 1
MAIN ENG LUB OIL PUMP 1
MAIN ENG MAIN BEARINGS 1
MAIN ENG LUB OIL TEMP 1
MAIN ENG SUMP OIL LEVEL1 MTTF=52560 Q=0
MAIN ENG FILTER OIL1 MTTF=52560 Q=0
MAIN ENG LUB OIL PUMP1 MTTF=52560 Q=0
MAIN ENG MAIN BEARINGS1 MTTF=52560 Q=0
Page 21
MAIN ENG CON ROD BEARINGS1 MTTF=52560 Q=0
MAIN ENG PIPING OIL1 MTTF=52560 Q=0

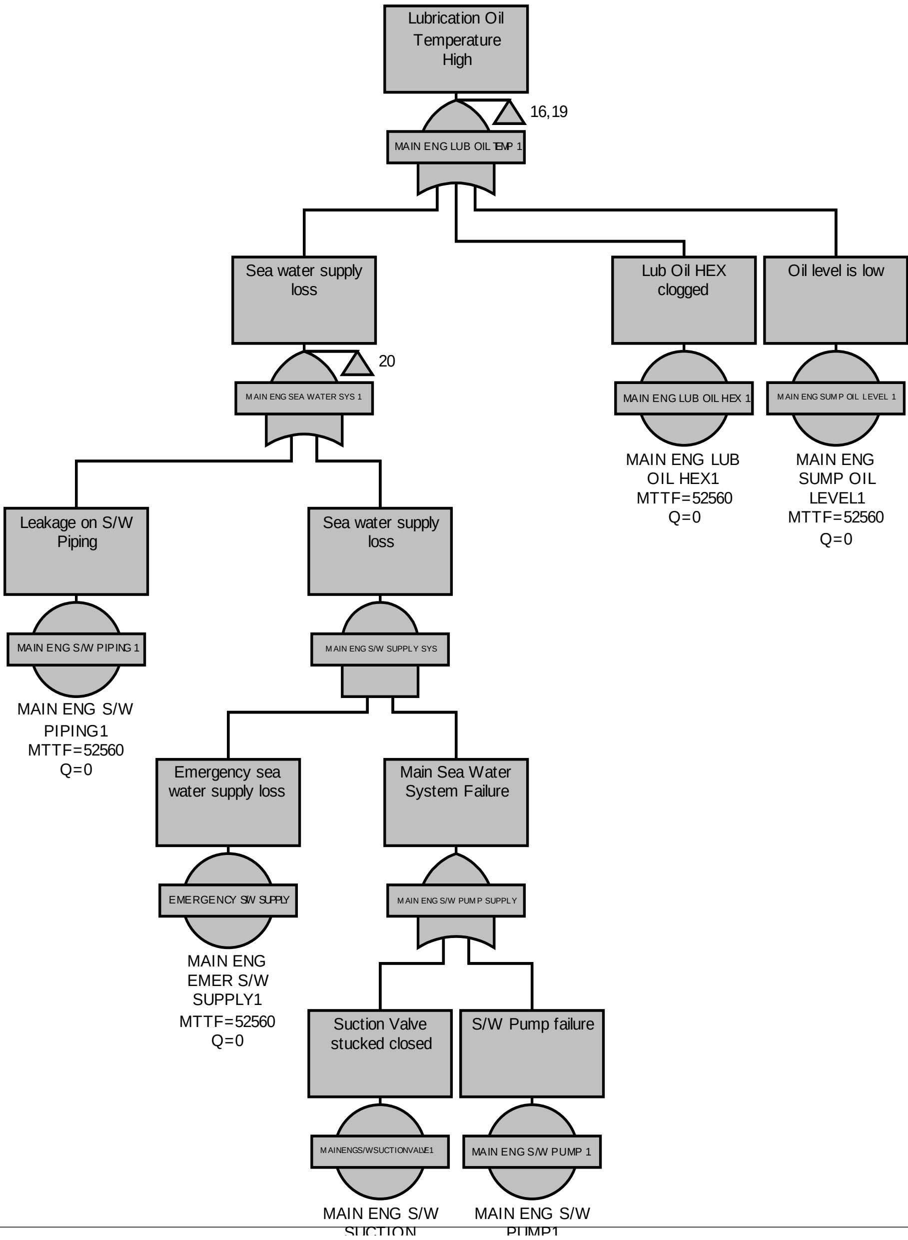
20


Cooling Water Temperature High
16
Sea water supply loss
21
Fresh water HEX clogged
Fresh Water Level low
Thermostat failure
Fresh Water Pump failure
MAIN ENG F/W HEX 1
MAIN ENG F/W LEVEL 1
MAIN ENG THERMOSTAT 1
MAIN ENG F/W PUMP 1
MAIN ENG F/W HEX1 MTTF=52560 Q=0
MAIN ENG F/W LEVEL1 MTTF=52560 Q=0
MAIN ENG THERMOSTAT 1 MTTF=52560 Q=0
MAIN ENG F/W PUMP1 MTTF=52560 Q=0
Leakage on S/W Piping
Sea water supply loss
MAIN ENG S/W PIPING 1
MAIN ENG S/W PIPING1 MTTF=52560 Q=0
Emergency sea water supply loss
Main Sea Water System Failure
EMERGENCY S/W SUPPLY
MAIN ENG EMER S/W SUPPLY1 MTTF=52560 Q=0
Suction Valve stucked closed
S/W Pump failure
MAIN ENG S/W PUMP 1
MAIN ENG S/W SUCTION VALVE1 MTTF=52560 Q=0
MAIN ENG S/W PUMP1 MTTF=52560 Q=0

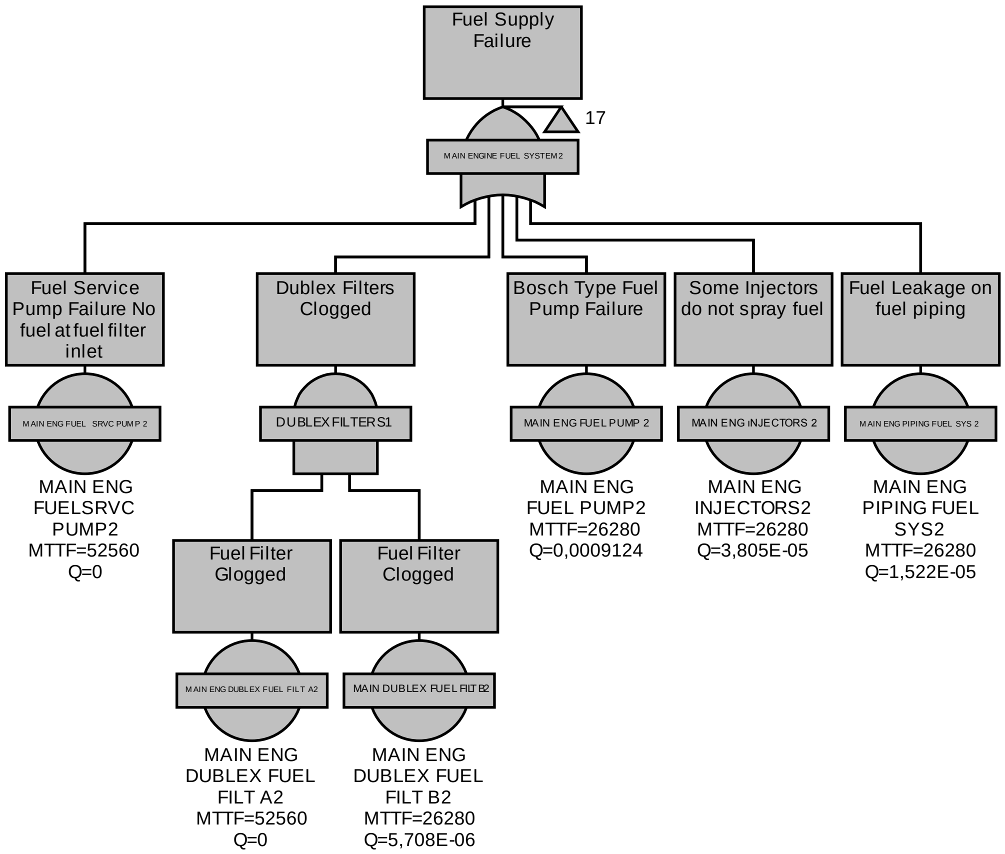
Fault Tree Diagrams

SHIP RELIABILITY

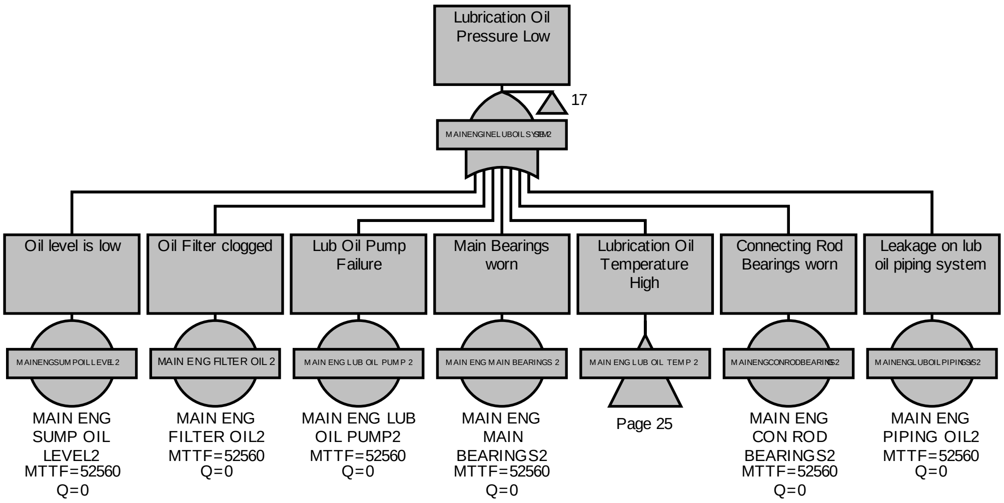
21



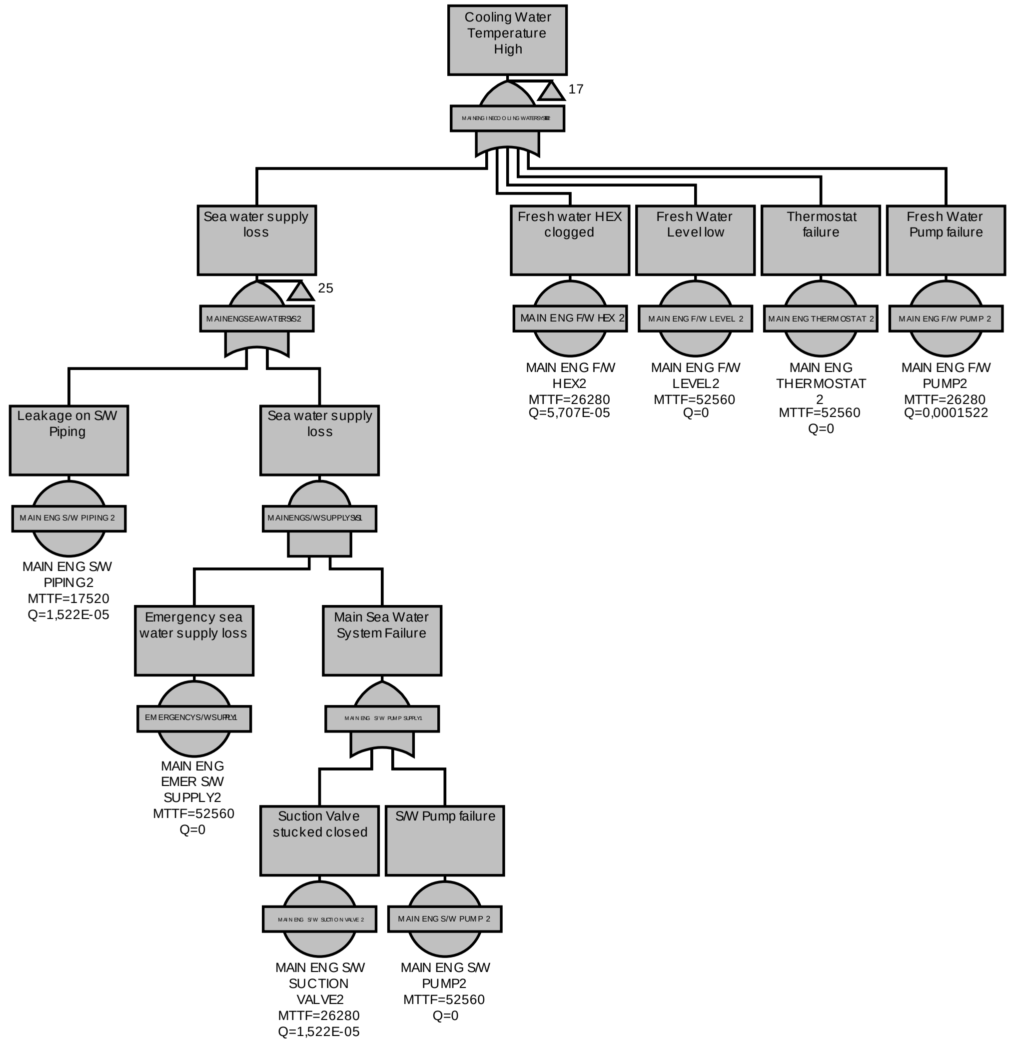
22



Fuel Supply Failure
17
MAIN ENGINE FUEL SYSTEM 2
Fuel Service Pump Failure No fuel at fuel filter inlet
MAIN ENG FUEL SRVC PUMP 2
MAIN ENG FUELSRVC PUMP2
MTTF=52560
Q=0
Dublex Filters Clogged
DUBLEX FILTERS1
Fuel Filter Glogged
MAIN ENG DUBLEX FUEL FILT A2
MAIN ENG DUBLEX FUEL FILT A2
MTTF=52560
Q=0
Fuel Filter Clogged
MAIN DUBLEX FUEL FILT B2
MAIN ENG DUBLEX FUEL FILT B2
MTTF=26280
Q=5,708E-06
Bosch Type Fuel Pump Failure
MAIN ENG FUEL PUMP 2
MAIN ENG FUEL PUMP2
MTTF=26280
Q=0,0009124
Some Injectors do not spray fuel
MAIN ENG INJECTORS 2
MAIN ENG INJECTORS2
MTTF=26280
Q=3,805E-05
Fuel Leakage on fuel piping
MAIN ENG PIPING FUEL SYS 2
MAIN ENG PIPING FUEL SYS2
MTTF=26280
Q=1,522E-05

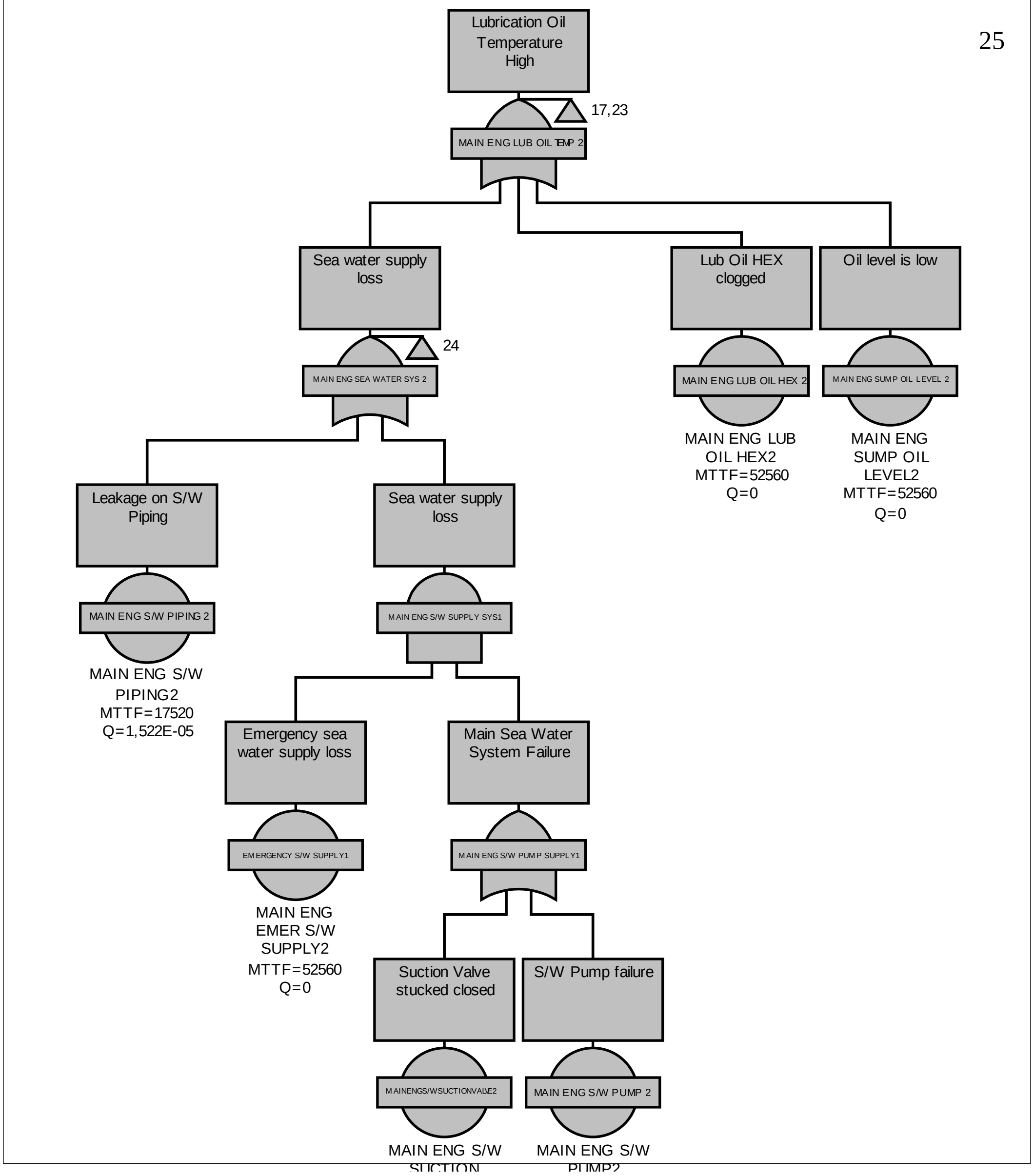

Lubrication Oil Pressure Low
17
Oil level is low
Oil Filter clogged
Lub Oil Pump Failure
Main Bearings worn
Lubrication Oil Temperature High
Connecting Rod Bearings worn
Leakage on lub oil piping system
MAIN ENG FILTER OIL 2
MAIN ENG LUB OIL PUMP 2
MAIN ENG MAIN BEARINGS 2
MAIN ENG LUB OIL TEMP 2
MAIN ENG SUMP OIL LEVEL2
MTTF=52560
Q=0
MAIN ENG FILTER OIL2
MTTF=52560
Q=0
MAIN ENG LUB OIL PUMP2
MTTF=52560
Q=0
MAIN ENG MAIN BEARINGS2
MTTF=52560
Q=0
Page 25
MAIN ENG CON ROD BEARINGS2
MTTF=52560
Q=0
MAIN ENG PIPING OIL2
MTTF=52560
Q=0

24



Cooling Water Temperature High
17
Sea water supply loss
25
Fresh water HEX clogged
Fresh Water Level low
Thermostat failure
Fresh Water Pump failure
MAIN ENG F/W HEX 2
MAIN ENG F/W HEX2 MTTF=26280 Q=5,707E-05
MAIN ENG F/W LEVEL2 MTTF=52560 Q=0
MAIN ENG THERMOSTAT 2 MTTF=52560 Q=0
MAIN ENG F/W PUMP2 MTTF=26280 Q=0,0001522
Leakage on S/W Piping
Sea water supply loss
MAIN ENG S/W PIPING2 MTTF=17520 Q=1,522E-05
Emergency sea water supply loss
Main Sea Water System Failure
MAIN ENG EMER S/W SUPPLY2 MTTF=52560 Q=0
Suction Valve stucked closed
S/W Pump failure
MAIN ENG S/W PUMP 2
MAIN ENG S/W SUCTION VALVE2 MTTF=26280 Q=1,522E-05
MAIN ENG S/W PUMP2 MTTF=52560 Q=0

25



Lubrication Oil Temperature High
17,23
MAIN ENG LUB OIL TEMP 2
Sea water supply loss
24
MAIN ENG SEA WATER SYS 2
Lub Oil HEX clogged
MAIN ENG LUB OIL HEX 2
MAIN ENG LUB OIL HEX2
MTTF=52560
Q=0
Oil level is low
MAIN ENG SUMP OIL LEVEL 2
MAIN ENG SUMP OIL LEVEL2
MTTF=52560
Q=0
Leakage on S/W Piping
MAIN ENG S/W PIPING 2
MAIN ENG S/W PIPING2
MTTF=17520
Q=1,522E-05
Sea water supply loss
MAIN ENG S/W SUPPLY SYS1
Emergency sea water supply loss
EMERGENCY S/W SUPPLY1
MAIN ENG EMER S/W SUPPLY2
MTTF=52560
Q=0
Main Sea Water System Failure
MAIN ENG S/W PUMP SUPPLY1
Suction Valve stucked closed
MAINENGS/WSUCTIONVALVE2
MAIN ENG S/W
S/W Pump failure
MAIN ENG S/W PUMP 2
MAIN ENG S/W

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List of Publications and Patents:

PUBLICATIONS/PRESENTATIONS ON THE THESIS

Akkaya O., SÖĞÜT O.S., 2012: Hata Ağacı Analizi İle Standby Sistemlerin Gemi Kullanılabilirliği Üzerine Etkisinin İncelenmesi. Gemi İnşaatı ve Deniz Teknolojisi Teknik Kongresi, Aralık 13-14, 2012 İstanbul, Türkiye.