5)

No. 301
August 1986

RELIABILITY AND REPLACEMENT ANALYSIS OF MARINE DIESEL PROPULSION SYSTEMS: A REVIEW

Anastassios N. Perakis
Bahadir Inozu

THE UNIVERSITY OF MICHIGAN 1817

THE DEPARTMENT OF NAVAL ARCHITECTURE AND MARINE ENGINEERING

THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING

Perakis –
my copy.

No. 301
August 1986

Reliability and Replacement Analysis of Marine Diesel Propulsion Systems: A Review

by

Anastassios N. Perakis
Bahadir Inozu

Dept. of Naval Architecture
& Marine Engineering
College of Engineering
The University of Michigan
Ann Arbor, MI 48109

Abstract

The applicability of systems reliability and replacement analysis to the marine industry, in particular to marine diesel engines, is discussed, in a comprehensive survey of both the scholarly literature and industry practices. The paper begins with a discussion of reliability methodology and its vital contributions to failure made analysis. A review of general maintenance, repair and replacement models is then undertaken as a guide to potential adaptation to and/or development of such analyses for marine diesel engines. An overview of current maintenance, repair and replacement practices of several U.S. Great Lakes operators whose vessels are equipped with diesel engines is finally presented.

Table of Contents

1. Introduction

Reliability engineering was first introduced in non-marine fields, especially in the space program, beginning in the early 1950's. Maintainability engineering was introduced about ten years after reliability engineering. Reliability and maintainability theory and applications are widely used by the U.S. Air Force, Army and Navy, because of their significant impact on mission performance and safety.

Reliability and maintainability statistical techniques are widely applied in maintenance support and operations, such as in the determination of the time between overhauls and of the extent of overhauls of major aircraft assemblies by the Air Force. Major aircraft manufacturers have reliability and maintainability groups, which are responsible for reliability and maintainability prediction and assurance.

The Bureau of Ships and its successor, the Naval Ship Systems Command, have been applying formal reliability and maintainability requirements to electronic systems and equipment acquisitions since 1960. Commercial airlines have been using reliability and maintainability techniques for about twenty-five years [PANE 71].

Even though it has been long demonstrated that using the results of reliability analysis to optimize repair, maintenance and replacement decisions makes economic sense, merchant shipping operators have traditionally taken the above decisions in a rather arbitrary and at best empirical way.

2. Use of Reliability and Replacement Techniques in Marine Propulsion Systems.

There are several definitions of reliability, all containing the basic idea of the probability that a device will operate under the specified operating conditions and during a specific interval, or up to a certain time (instantaneous or interval reliability).

In recent years reliability analysis has been applied to problems in the marine industry because of rising operating costs and safety requirements [MANS 84], [HORI 79], [ZIGA 82]. Using the tools of reliability and replacement analysis, merchant vessel operators can improve their predictions on the frequency of failures and on the associated costs of repairs and inspections. Moreover, they can use this information to optimally schedule planned maintenance and replacement of worn-out parts. This may ultimately result in reductions in their total operating costs. Indirectly, it may also help them maintain their schedule and minimize turn-around times.

Traditionally, most operators schedule their maintenance periods to coincide with regulatory inspection periods, without considering any analytical techniques. Reliability and replacement analysis techniques have the potential to improve the prediction of maintenance and repair requirements and, ultimately, to improve the probability of mission success and/or to minimize total operating costs over the life of the vessel.

2.1 Reliability Methodology

It is very important to define both system and equipment failures accurately. Misinterpretation of failure definition may cause significant reliability data collection and processing problems.

As an example, one shipowner may replace seals periodically and consider them as a part of scheduled maintenance, while another owner may report a cracked seal, which is discovered during maintenance, as a failure [ARPI 79]. Actually a cracked seal is a failure, but the time to failure (TTF) is not synonymous with the time to discover (TTD) it. This has a crucial effect on the accuracy of failure rates, which are vital inputs in any reliability analysis. The risk assessment procedure is shown in figure 1, which is based on reference [NPRD 83].

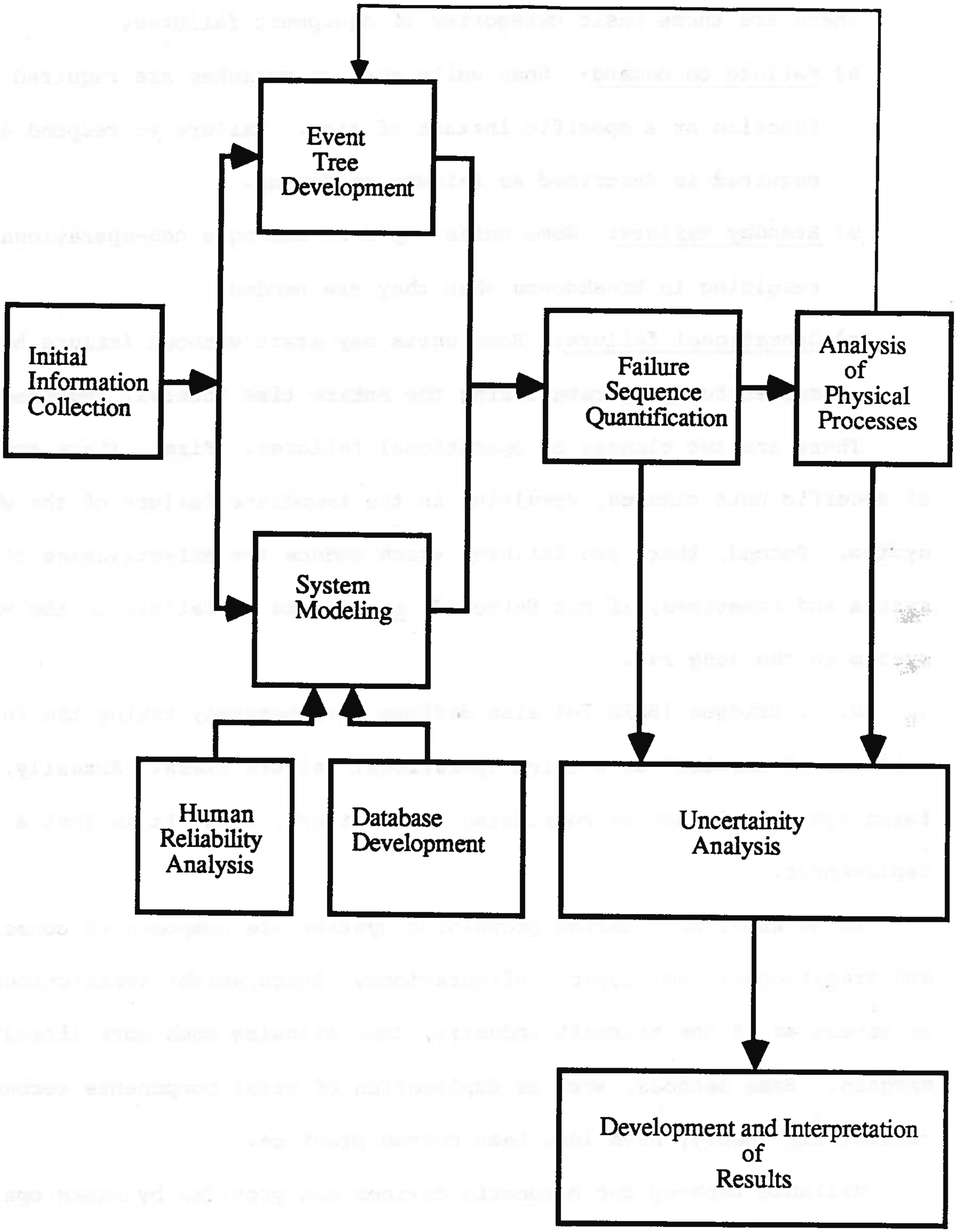

Figure 1: Risk assessment procedure
(Based on [NPRD 83])

There are three basic categories of equipment failures.

a) Failure on demand: Some units such as switches are required to function at a specific instant of time. Failure to respond as required is described as failure on demand.

b) Standby failure: Some units may fail during a non-operational period, resulting in breakdowns when they are needed.

c) Operational failure: Some units may start without failure but may not successfully operate during the entire time interval required.

There are two classes of operational failures. First, there are failures of specific unit classes, resulting in the immediate failure of the whole system. Second, there are failures which reduce the effectiveness of the system and sometimes, if not detected, might lead to failure of the whole system in the long run.

D. C. Bridges [BRID 74] also defines "deliberately taking the functioning unit out of service" as a third operational failure class. Actually, this third type should not be considered as a failure, since it is just a replacement.

As we know, most marine propulsion systems are composed of conservatively and traditionally developed configurations. Space/weight restrictions are not as severe as in the aircraft industry, thus allowing much more liberal design margins. Some methods, such as duplication of vital components recommended by reliability theory, have long been common practice.

Reliable back-up for automatic devices are provided by human operators. Since human operators are constantly on duty, incipient failures may be detected and vital failures may be prevented before they occur. Replacement times and inspection times of marine propulsion systems are conservatively established [WOOD 63].

The above reasons make the reliability of marine propulsion plants very high. However, the acquisition costs of these plants are significantly higher than what they would be if they were not overdesigned.

To quantify and improve systems reliability, the following techniques have been developed:

Failure Modes and Effects Analysis (FMEA) helps to systematically analyze all contributing component failure modes and identify the resulting effects on the system. FMEA is frequently used at the first stage of an analysis, or when a detailed analysis involving fault trees and event trees (see below) is not required. To use this method, the analyst should assess the effect of any failure mode on the overall performance of the system. FMEA is an inductive approach. FMEA flow chart is shown in figure 2, which is based on [DHIL 81]. This method is simple to apply, providing an orderly examination of the hazard conditions in a system. FMEA considers only one failure at a time and not multiple or common cause failures. This fact, coupled with the inability to provide any quantitative information about the system and its failure rates, comprises the main disadvantage of this method [McCO 81]. FMEA is a useful tool for developing fault trees and for providing rough numerical estimates for a subsequent fault tree analysis [ALDW 82].

Event tree and Fault tree methods are the most frequently used failure analysis techniques [NPRD 83]. Fault trees include component failures as well as the effects of maintenance. Event trees are developed inductively. Event trees and fault trees are system models that are used to characterize the potential outcomes of postulated failure-initiating events.

An event tree consists of several system-accident sequences. These consist of initiating events and combinations of various system successes and failures that lead to an identifiable system state. A generalized process of event-tree development is shown in figure 3, which is based on reference [NPRD 83].

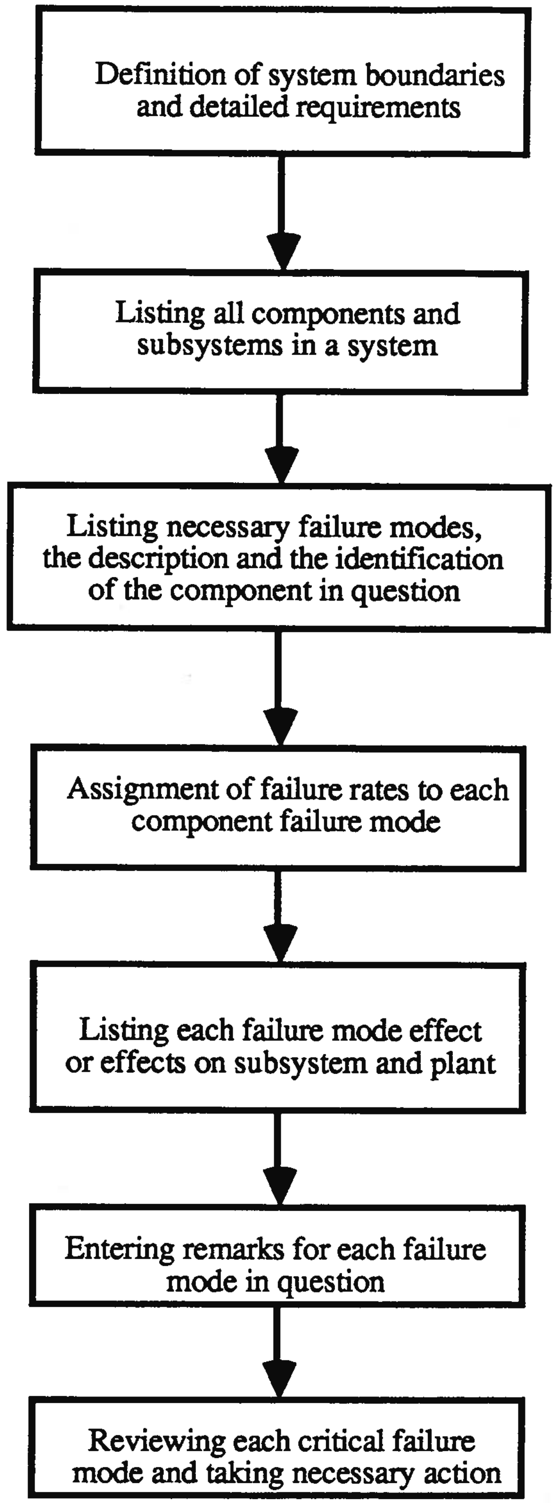

Figure 2: FMEA flow chart
(Based on [DHIL 81])

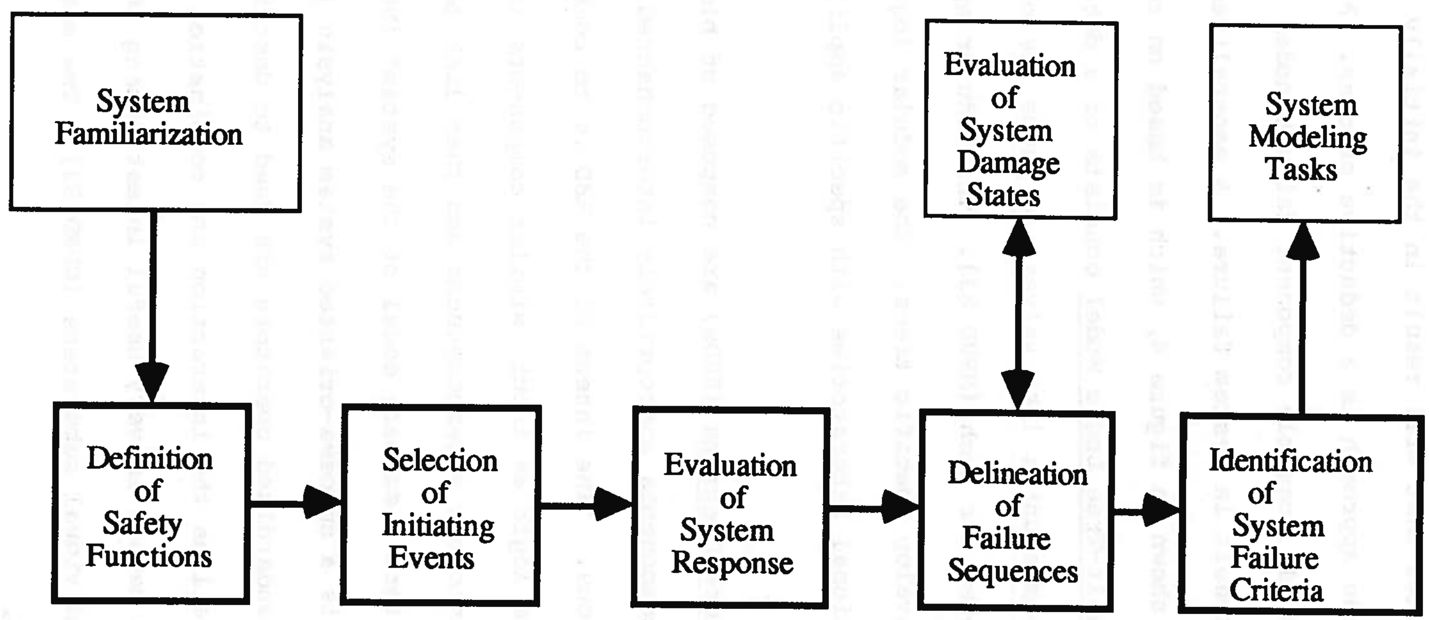

Figure 3: Generalized process of event-tree development
(Based on [NPRD 83])

In fault tree analysis, a failure event is first specified. The system is then analyzed to find all credible ways in which the failure can occur. The fault tree is a graphic model comprising the various parallel and sequential combinations of faults that will result in the initially specified failure event. The fault tree approach is a deductive process. A fault tree does not necessarily contain all possible component failure nodes or all possible fault events that could result in system failure. A generalized process of fault-tree system modeling is shown in figure 4, which is based on reference [NPRD 83].

The Modular Fault-Tree Logic Model consists of a detailed fault logic for each subsystem. Common units like valves and pumps are classified by type and subtrees are developed for each [NPRD 83]. The modular approach reduces the time required to develop specific trees. The modular logic was recently developed at Sandia National Laboratories with specific application to nuclear plants.

Reliability Block Diagrams (RBDs) are composed of blocks which represent distinct units or components appropriately interconnected in series, parallel or standby configurations. "The intent of the RBD is to combine, either directly or using the fault-tree logic as input, similar components that are in series in each system train into one supercomponent and then link together parallel supercomponents to form a summary model of the system" [NPRD 83].

The GO method is a success-oriented system analysis technique. In this method, a set of standardized operators are used to describe both the logic of the operation, as well as the interaction and combination of various system components. The GO method is very useful in estimating the success or failure probabilities of individual subsystems [NPRD 83]. The method is not appropriate for complex systems.

Markov modeling can be applied to the random behavior of systems that vary discretely or continuously with respect to time and space. To be able to

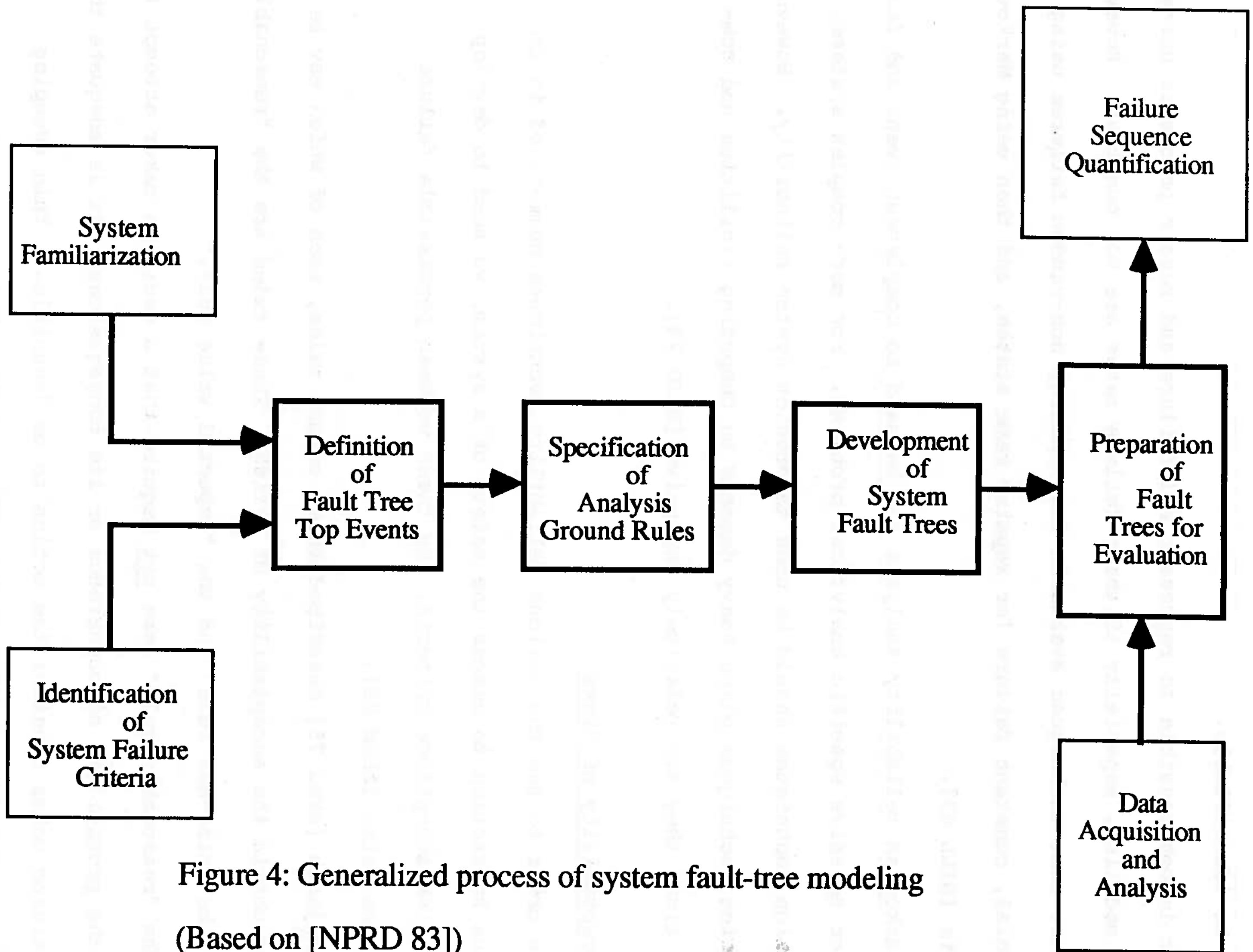

Figure 4: Generalized process of system fault-tree modeling

(Based on [NPRD 83])

apply Markov analysis, the behavior of the system should be memoryless. This means that the future states of a system should be independent of all past states except the immediately preceding one. Also, the states of the system should be identifiable.

It is not possible to represent all failure and repair processes using Markov modeling, especially if their failure rates are not constant. However, there are some techniques available for modeling non-random failures using artificial, constant failure (or repair) rate states, and then using Markov analysis [BILL 83].

Markovian reliability analysis may be used to complement event and fault trees or to solve specific analytical problems. For more complex systems, simulation techniques should be used to predict system reliability. However, simulation techniques place heavy demands on computing facilities and computing time, they are relatively expensive [BRID 74].

2.2 Acceptability of Risks

In order to use the various reliability techniques summarized in the previous subsection to assess the safety of a system, we need to develop proper risk acceptance criteria. By these we mean permissible failure occurrence rates [ALDW 82].

Benjamin [BENJ 75] described three common rules, each of which may be used to obtain the acceptability of a risk. These rules are the "reasonable rule," the "mini-max rule" and the "expected value rule."

The "reasonable rule" does not require that a decision maker attempt to study the probability of occurrence or its consequences. It is adequate that the decision maker consider the action to be "sensible." This sweeping approach is mostly used by governments and legislators.

The "mini-max" rule assumes that the worst ("max") possible accident will occur in the long run and suggests that a decision maker must try to minimize ("min") the risk.

The "expected value rule" is a more rational approach than the previous ones because it considers the probability of a failure and its possible consequences from a mathematical standpoint. It could be applied as a minimization of total expected costs or of the probability of system failure, or of some other system performance index.

2.3 General Maintenance, Repair and Replacement Models

Mathematical analysis helps planners to determine the maintenance and inspection requirements of repairable items and to make effective logistics decisions.

There is considerable literature on machine repair, maintenance and replacement problems. Sherif and Smith [SHER 81] have given a rather comprehensive list of references until 1981, classified in various sub-categories.

Pack [PACK 71] developed an "Extended Replacement Model," which is not stochastic, for ships and marine engines. This consists of two mathematical models: one for the optimal "challenger," i.e. new equipment that may replace the old or ("defender"), and the other for the optimal replacement year selection. Pack developed an optimization method using a transformation of the objective function that converts a problem with constraints to an unconstrained one. To solve the latter, a sequential unconstrained minimization technique was then used.

This transformation involves the following penalty function:

$$P(X_1, \ldots , X_n, r_k) = F(X_1, \ldots , X_n) + r_k \sum_{i=1}^{j} \frac{1}{g_i (X_1, \ldots , X_n)}$$

where

F = a given objective function

g_i = the equality or inequality constraints

X_i = the decision variables , $i=1, .., n$

r_k = the controlling multiplier which is repeatedly reduced.

J = the number of inequality constraints

Optimal Replacement Year Selection: In his model, the two decision variables are the defender's life and the challenger's life. Here the defender represents the ship currently in service, whereas the challenger represents a brand-new ship. From a network of possible "paths" of ship replacements the optimal path can be obtained using the following expression:

$$f_n = \underset{k=n+1,\ldots,N}{\text{maximum}} \quad [C_{nk} + f_k]$$

for $n = N-1, N-2, \ldots , 1$

and $F_N = 0$,

where:

C_{ij} = the NPVI value of the optimal challenger purchased at 1 and kept for j years (Each value C_{ij} is calculated by the optimal challenger selection model, except that in some cases the procedure has been NPVI is the net present value index. It is defined as the ratio of NPV over P, where P is the investment and NPV is its net present value.

N = the final time period in the planning horizon

$n = N-1, N-2, N-3, \ldots, 1$

f_n = the sum of all C_{ij} along the combination of paths leading from N to n which maximizes the total NPVI value

P_{mj} = the defender's NPVI value at m years of age if it is kept j more years before it is replaced.

Using a sensitivity analysis, Pack determined the importance of parameters for the optimal replacement year. The cargo forecast is the most important parameter, followed by the obsolescence rate (including capacity obsolescence) and the interest rate of return. The rate of deterioration, initial cost and salvage value were found to have smaller effects than the above three parameters. Inflation was found to have a very small effect.

Pack's conclusion was that missing the optimal year by a year or two in either direction may result in a relatively small cost increase.

A policy of periodic replacement with minimal repair at failure was first introduced by Barlow and Hunter [BARL 60]. Their model assumes that the failure rate of the system is independent of the failure and subsequent repair of the system. Boland and Proschan [BOLA 82a] generalized the Barlow and Hunter model by assuming increasing minimal repair costs. Their assumptions are the following:

1) Replacements or complete overhauls are made at times T, 2T, 3T, ... If the system fails at any time other than the multiples of T, minimal repair will be performed. Time to repair is neglected. After repair, the system failure rate does not change.
2) Replacements or complete overhauls do not take place in the time interval (0,s). The number of breakdowns obeys a Poisson distribution with parameter R(s).
3) System has a continuous life distribution (F), where $F(0) = 0$.
4) It is assumed that c_k (cost of minimal repair on the kth breakdown since the last replacement) is of the form $c_k = a + kc$, where a and c are constants and $a > 0$, $c \geq 0$. c is the cost of each additional repair, and c_0 is the cost of a replacement (or of a complete overhaul),

and $c_k^* = c_1 + c_2 + \dots + c_k$. For optimal periodic replacements over a finite time horizon, C(T) is defined as the expected cost over the interval (0,t), and is given by:

$$C(T) = \begin{cases} kc_0 + (k+1)\sum_{j=1}^{\infty}(R^j(T)/j!)e^{-R(T)}c_j^*, & \text{if } y = T \\ kc_0 + k\sum_{j=1}^{\infty}(R^j(T)/j!)\,e^{-RT}c_T^* \\ \quad + \sum_{j-1}^{\infty}(R^j(t-kT)/j!)e^{-R(t-kT)}c_j^*, & \text{if } y < T. \end{cases}$$

where $0 < T < t$,

$t = kT + y$

$0 < y < T$

By assuming that the jth minimal repair cost to the system is of the form $c_j = a+jc$, for $j = 1,2,3, \dots$, one obtains

$$c_j^* = ja + (j(j+1)/2)c$$

C(T), which is evaluated on the set {t, t/2, t/3, ...}, is minimized at $T_0=t$. This shows that the optimal policy is one of no planned replacements (overhauls).

For optimal periodic replacement over an infinite time horizon, the average long run cost per unit time is given by:

$$\bar{C}(T) = \left(\sum_{k=1}^{\infty}(R^k(T)/k!)e^{-R(T)}c_k^* + c_0\right)/T.$$

The period $T=T_0$ which optimizes expected costs per unit time can be found from the following equation:

$$(a + c)\left[Tr(T) - R(T)\right] + c\left[Tr(T)R(T) = R^2(T)/2\right] = c_0$$

Boland [BOLA 82a] derived the following expression for the expected minimal repair cost in an interval in terms of the cost function and the failure rate of the system.

$$E_{N_t}(E(C(t_1) + \ldots + C(t_k)/N_t=k)) = \int_0^{R(T)} CR^{-1}(t)dt ,$$

where $R(t)$ is the hazard function of the system, and N_t is the random variable which denotes the number of minimal repairs performed on the system in the age interval [0, T]. N_t has a Poisson distribution with parameter $R(T)$.

Most ship operators use age replacement policies. Some ships are not in operation throughout the entire year (e.g. Great Lakes ships.) Therefore, it is advantageous to consider no demand periods for the purpose of preventive replacements.

For intermittently demanded units, their operational age (rather than their chronological age) determines the time to failure, whereas for continuously operating units, calendar time determines the time to failure. Therefore, the age replacement policy should be modified for intermittently demanded units.

Berg [BERG 84] proposes a "Modified Age Replacement Policy" (MARP), obtained by making the following assumptions:

1) The demand process is an alternating renewal process of demand periods and no-demand periods.
2) A unit can fail only during operation, and its failure rate only depends on the operational time and the demand process.
3) The time to failure of a unit is random and is not a function of the operational time and demand process.
4) Expectations are positive and finite.

The optimal critical operational age d^* of a unit can be found by using the following [BERG 82]:

Only $d=d^*$ satisfies $C(d) = \eta(d)$, where

$$C(d) = (c_1\bar{G}(d) + c_2\bar{G}(d)) \Big/ \left(\int_0^d \bar{G}(u)du + \bar{F}_o{}^*(\alpha) \right), \quad d > 0, \text{ and where}$$

$\eta(d)$ = the marginal cost of a preventive replacement at age d

$$\eta(d) = (c_1 - c_2)\, h\,(d) \qquad d > 0$$

$h(d)$ = the hazard function of the demanded unit

c_1 = the replacement cost of a unit after its failure

c_2 = the replacement cost of a unit when it reaches age d

$C(d)$ = the expected cost per unit of time,

$\bar{G}\,(\cdot)$= survival function of a positive r.v. Y, which is the lifetime of a continuously demanded unit. $F_Z\,(\cdot)$ denotes the cumulative distribution function of a random variable Z. Also, $\bar{F}_Z\,(\cdot) = 1 - F_Z\,(\cdot)$, and $\bar{F}_Z^*\,(\cdot)$ denotes the Laplace Transform of $\bar{F}_Z\,(\cdot)$.

Bean, Lohmann and Smith [BEAN 83] proposed a "deterministic dynamic infinite horizon replacement economy decision" model. Their model includes the effects of technological changes in future challengers. Their conclusion is that "the traditional assumption of repeatability may lead to a significant number of uneconomical decisions and a correspondent long-run economic loss when the future challengers do not repeat themselves." They also observed that the equivalent finite horizon time was frequently just beyond the economic service life of the optimal current decision.

Oakford, Lohmann and Salazar [OAKF 84] generalized Wagner's dynamic programming model for the replacement economy decision problem. Their model allowed the decision maker to specify the cash flows without reformulating the dynamic program for each replacement problem.

Lohmann [LOHM 84] presented a Stochastic Replacement Economy Decision Model. This model allows the cash flows to be a random variable. ...

M. H. Agee [AGEE 86] described a microcomputer-based decision support system to determine and evaluate maintenance requirements of repairable item populations. In the following, a brief description of the model will be presented. The model can generate maintenance requirements of repairable items, which operate under steady-state or unsteady-state conditions for their total life cycle. It is assumed that an "end item" is composed of a group of components, which can have their own independent rates of failure. An end item represents a sub-system which can cause a fatal failure of the whole system. Component cumulative failure probabilities may follow any general distribution. Failure rates of components may vary at different stages of their life cycle.

The model is implemented on a microcomputer. When the user inputs the data, the model generates the maintenance requirements for end items, then sums the results and finally generates maintenance requirements for the entire population of repairable items. The cost of the associated logistics policy and the availability of the population of the end items are also calculated in the process. If the decision maker has no control over an input variable, it will be considered as a parameter. The model is very helpful to produce trustworthy maintenance requirements output.

2.4 Brief Review of Reliability Applications in Marine Engineering

While the other industries are increasingly utilizing probabilistic methods for the rational assessment of reliability and safety, rising operating costs and the current poor shape of shipping are forcing the marine industry to adopt these methods and, in parallel, to start developing its own methods of dealing with its unique reliability and maintainability requirements.

One of the earliest steps in that direction was the Conference on Advanced Marine Engineering Concepts of Increased Reliability, jointly sponsored by the

Office of Naval Research and the University of Michigan, held in February, 1963. The importance of the conference was that for the first time representatives from all segments of the Marine Industry were brought together with reliability experts from other industries to present and discuss various means of improving the reliability of ships. However, the conference did not stimulate any major use of reliability engineering by the Marine Industry. It did create a general awareness of the available techniques, and it helped to focus attention on the limitations, particularly the lack of data.

Recently, the American Bureau of Shipping (ABS) and CONOCO joined forces with the industry and started an intensive effort to develop a reliability-based design criterion for tension-leg platforms (TLP's) [MANS 84]. The U.S. Navy has also been using reliability techniques to evaluate maintenance, repair and replacement requirements of steam turbines.

The development of marine reliability and maintainability will inevitably follow along the lines of past non-marine activity in the field. "Thus blind alleys can be avoided and reliability-maintainability costs minimized if rigorous study is given to lessons learned from past events in the non-marine field." [PANE 71].

2.5 Reliability Applications in Marine Diesel Propulsion Systems.

The failure rate data of components are essential in applying the reliability techniques to the evaluation of maintenance, repair and replacement requirements.

Failure rate data available for the hull are different in nature from those for machinery. The hull is a structure which is composed of a complex, highly redundant arrangement of standard structural elements. With the exception of corrosion, the hull structure does not generally exhibit "wearout" characteristics. Marine propulsion systems are composed of many components that are integrated into systems with some redundancy, exhibiting both random and wearout failures. The failure pattern of these systems is a function of maintenance and operational strategies [ALDW 82]. The remainder of this paper will be focused on marine propulsion systems, in particular Marine Diesel Engines.

T. Hashimoto and K. Ishizuko [HASH 73] obtained failure rates for several marine propulsion subsystems. Their findings are summarized below. The first figures show the probability that a specific machinery type will fail during the initial failure period of the first twelve months. The second figures show the probability that a specific machinery type will fail during the random failure period of twenty-five months after the initial twelve-month operation.

Main Engine:	20.9/36.2%
Deck Machinery:	28.6/26.0%
Automation Equipment:	27.1/10.2%
Generator:	5.4/9.9%
Auxiliaries:	8.5/9.9%
Electrical:	3.1/5.1%
Instrument and tank:	0.8/1.3%
Piping and valves:	0.8/1.3%

The survey shows that the main engine is one of the most troublesome units.

The recent dramatic increases in various ship operating costs, and the effect of the overall economic situation, as well as some new trends, such as the use of low-grade fuels has been to worsen the reliability of marine diesel engines significantly [BOHM 79].

In the case of four-stroke engines, the burning of heavy fuel oil made exhaust valves, injection valves pistons and piston rings very critical. In the case of two stroke engines, the exhaust valves became the most critical [BOHM 79]. The wear of cylinder liners and the piston rings of two-stroke engines also needs critical attention. Wear rates of piston rings (especially the top one) have drastically increased, with a reported increase in such failures up to 100%.

According to the survey made by Y. Okamoto [OKAM 77], the most common failures of the main engine components are the following:

Cylinder covers and liners: Most of the failures of the fire contact surface of the cylinder cover are cracks which occur on the edge of each valve hole. Failures of the cooled sides of the cylinder covers are mainly circumferential cracks.

Pistons: Cracks on the piston top and the rib root constitute a large portion of the failures of the cooled surface of the piston.

Cross pins, piston pins, crankshafts and bearings: The failure rates of the four-stroke engine components around the combustion chamber are smaller than those of two-stroke engines. Furthermore, the failure rates of the components which are under the influence of the lubricant are higher than those affected by thermal stress.

Cams and cam drive systems: The failures include wear and breakage of cam parts, and breakage of cam shaft drive unit teeth.

Base plates, columns, tension bolts and foundation bolts: Most of the failures of plates and columns are cracks.

Supercharger: Supercharger failures are caused by corrosion and the wear of casing.

To improve the reliability and to reduce the maintenance, repair and replacement costs of various components, several engineering design equipment and materials changes have been attempted.

For example, the coating of normal grey cast-iron rings with special chromium carbides, combined with molybdenum and perhaps nickel, has already reduced the wear rates of four-stroke piston rings to about 50 percent in standard operation [BOHM 79]. The coating is applied with the aid of a plasma jet, which compared with normal flame spraying, results in far higher compaction.

Beyond these improvements, computer-aided fault diagnosis methods, are becoming quite popular [ZIGN 85]. Vibration monitoring is an example of a recently developed method to diagnose deviations from normal conditions. However, in order to locate and identify these failures, vibration monitoring should be combined with overall performance monitoring [WHIT 84].

3. Current Industry Practices (Great Lakes Shipping)

3.1 General

In this section, we will present a summary and a discussion of the information obtained from an informal survey of the maintenance, repair and replacement practices of several (almost all) U.S. Great Lakes operators whose vessels are equipped with Diesel Engines. This survey is part of an ongoing research project funded by the National and Michigan Sea Grant Programs, directed by the first author.

The Great Lakes Shipping maintenance/repair/replacement problem is quite different from the similar problem for oceangoing ships in more than one respect. First and foremost, the existence of the winter lay-up in Great Lakes shipping allows operators to do most of their maintenance work during that non-operating season, and minimize failures, repairs, and maintenance that may lead to significant time losses during the operating season. Second, Great Lakes ships almost always move in restricted waters close to major equipment supply centers, and may reach several such ports-centers every day.

Therefore, it is much easier for them to order and receive spare parts (especially if they use Detroit Diesel or EMD engines) than, for example, to a tanker routinely traveling between the Persian Gulf and Japan. Despite this convenience, Great Lakes vessels routinely carry (on board) significant numbers of spare parts. It seems to us that current practices are perhaps too conservative and should be revised. The result of fewer parts is not only a small reduction in ship weight and associated fuel costs, but, much more importantly, a substantial decrease of the "inventory value" of those spare parts, i.e. a reduction in the money tied-up in the purchase and storage of those parts for months (or years) before they will be needed.

Normally, winter lay-up is utilized for performing major repair and conversion work, such as main bearing renewals. The type and number of Diesel Engines aboard a vessel will have a significant impact on the extent of the winter maintenance and replacements. For example, a vessel having four Electro Motive Diesel (EMD) engines, of 20 cylinders each, will be able to operate even if a significant number of these (80) cylinders is not operating properly, and even if one turbocharger fails. Catastrophic failures are rare, and even if they occur, they could be fixed in a few hours at the next port of call (e.g. power pack failure and associated change). A vessel having a different type of engine (such as 2 Colt/Pielsticks with 16 cylinders each) may have more serious problems in this respect, and probably needs more extensive maintenance and replacement work during the winter.

3.2 Discussions with Great Lakes Shipping Engineers

In the following, summaries of the discussions of the first author with engineers from various Great Lakes shipping companies will be presented. In some cases, the discussions will be rather brief, to avoid repetition of points made in other parts of this section.

Cleveland Tankers, Inc. uses two-cycle and four-cycle, 16-cylinder, turbo-charged) EMD engines. Due to the ready parts availability, only a small number of spare parts is kept. The preventive maintenance system is mostly based on the engine manufacturer's recommendations. However, these are sometimes too conservative, since the part that should be replaced after 16,000 hours may still be in good operating shape after 24,000 hours. Moreover, the 5-year (2-year, for 15 days, for oceangoing ships) continuous machinery survey under ABS provides another opportunity for preventive maintenance ("since we have to take it apart, we might as well change (replace) some parts that would soon have to be replaced anyway").

Current economic difficulties in the region and consequently in its shipping, have made excessive replacement practices, however, quite unattractive. However, it is not obvious that, especially in the long run, the effects of a reduced preventive maintenance and replacement policy will produce lower overall operating costs.

Erie Sand Steamship has two small ships equipped with Detroit Diesel engines. An index card system for failures and major overhauls is kept. Manufacturer's recommendations are followed on most cases, and "seem to work out pretty well." Power packs, cylinder pistons, cylinder heads are replaced roughly every 12,000 hours of operation. No computerized data management in place.

Amoco Oil Company in Indiana also largely follows manufacturer's recommendations in maintenance and replacement procedures for its EMD 645 E-6 and V-71 series Detroit Diesels. Record keeping exists in a card file, where important failures and other data are transferred from the "shirt pocket" of the chief engineer. No computerized database management system exists.

Inland Steel Company engineers find manufacturer's recommendations rather conservative. Specific items as power packs and piston rings fail rather frequently, whereas others like valves are more reliable. Unusual failures also occur, such as a recent failure of the drive disk of the crankshaft, which took five days to fix. Engines are operated at a low RPM, both due to price considerations and also due to the existence of a critical speed level below which they have to operate to avoid excessive vibration. The use of performance monitoring devices is contemplated. No computerized database management system exists.

National Gypsum Company (Cement Division) follows the manufacturer's recommendations for the two EMD engines (low RPM, directly connected to the propeller). Checks are frequently made by taking off cylinder heads, and taking out the pistons, connecting rods, bearings and mains. In most cases, these are put back in without any repair or replacement. We were told that one of the ships, built in 1953, was never down during an operating season. Some non-critical maintenance work is done during the operating season, as cleaning parts from accumulated carbons in the 2-cycle engine and rebuilding fuel pumps. It was the estimate of the engineer we talked to that one more month of operating season wouldn't make any difference to the ships, who would still not have any major failures during the extended season. The company does not have any (computerized or not) database management system for maintenance and replacement work.

Bethlehem Steel Company also largely follows the manufacturer's suggested guidelines for the maintenance of its 2-cylinder, 3500 HP, 900 RPM EMD engines. Typical failures like turbocharger, liner, piston or piston ring failures, occur mostly due to wearout of these units. No card-based or computerized maintenance database.

Oglebay-Norton Company keeps two logs of failure and maintenance data, of which one log for maintenance on board the ship. Manufacturer's recommendations are followed for overhaul periods (e.g. 16-18,000 hours for bearings). Again, no computerized maintenance database system exists.

U.S. Steel Company has vessels with two types of engines, one burning light fuel and the other using heavier fuel with high sulfur et al content. Winter maintenance has to be thorough enough to guarantee 5000-6000 hours of trouble-free operation. Problems arise with several specific parts such as cylinder liners (lots of them replaced, mostly due to poor fit) and the maintenance of fuel systems on Pielstick engines and engines using heavy fuel. Normal maintenance hopefully allows 20,000 to 30,000 hours.

During each May/June, a list of winter maintenance work is put together before major overhauls. A total inspection of each ship is then done during each fall (while the ships are traveling). That enables the planner to lay out the winter work schedule and budget, including any major overhauls or inspections. A charging system aboard each ship, still in manual form, produces reports on each piece of equipment, the work done on it and the number of man-hours to be charged. A note explains if the item was removed (changed), repaired or left alone. For example, in Colt engines, new injectors are installed roughly every 1000 hours.

For preventive maintenance purposes, a "Logging Abstract" is kept and updated monthly. It contains readings at full power of all vital engine parameters. By comparing it to past records, trouble spots may be located and investigated. Contents of the Abstract include engine hours, various air pressures, exhaust gas temperatures, governor settings et al.-the list is quite long.

The company also maintains computerized Mechanical Report Forms, including checks and routine inspections, remarks, and several other details, as well as costs during the operating season and during the winter layup. Finally, fuel rates are controlled all the time, and the relevant data have been quite useful to the company. "Workbooks" for that purpose are kept on board all vessels.

From the above informal survey it becomes clear that of the dozen or so Great Lakes shipping companies utilizing marine diesel engines, several have no maintenance/repair records whatsoever, and are content to follow (in most cases) manufacturer's recommendations. Some other companies keep manual records of failures/repairs and replacements, and try to use them in subsequent decisions in a rather empirical way. Very few companies have tried using a computerized database management or decision support system. Along with U.S. Steel Shipping Company, American Steamship and Interlake Steamship Company, are the only Great Lakes Shipping Companies with any computerized maintenance database management system in operation or under construction to date. Interlake Steamship (Pickands-Mather & Company), for which a database management system was built in the summer of 1984 at the Department of Naval Architecture and Marine Engineering of the University of Michigan [NIKO 84a]. This system, utilizing the "Knowledgeman" database management software, has been in use since January 1985. However, the records developed also contain information obtained manually before that time. The data are for three 1000 foot vessels of the company and for Colt-Pielstick engines.

American Steamship Company is currently developing a computer program for the scheduling preventive maintenance work for its vessels. All its vessels have EMD (Electro-Motive Diesel) engines, which are quite different from the Colt-Pielstick engines of Interlake Steamship. The present manual preventive maintenance system at American Steamship was described as quite loose and very different from ship to ship. This latter difference, coupled with the fact that there are frequent and extensive crew movements (due to crew seniority considerations and other reasons) from ship to ship, provides substantial motivation for constructing a "universal" computerized maintenance system for the entire fleet. This way, a sailor moving from vessel A to vessel B will be already familiar with the maintenance records and management in the new ship.

Given the fact that personal computers are already quite inexpensive and are getting even less expensive and much more powerful with time, engineers at American Steamship are convinced that using a computerized system for preventive maintenance work can only help the company further reduce operating costs. The system developed will be capable of "calling up" the maintenance history for every machine on board any of the company's ships from any on-board terminal. However, as in the case of Interlake Steamship, the system will not perform any optimization of maintenance and replacement intervals to produce the lowest total operating costs.

The computerized system currently developed by American Steamship Company is an outgrowth of a 1980-82 project funded by the company and the U.S. Maritime Administration, titled "Computer-Aided Maintenance and Operations Management System" ([BASS 82], [BASS 83]). In our communications with company engineers, it became clear that the project was excessively complex, if it were to be of any value to shipboard personnel, and perhaps it should be used by shoreside office personnel. They also underlined that their maintenance and replacement procedures follow very closely those established by the manufacturers. In some cases, replacement or service schedules are altered whenever appropriate by the Chief Engineers to coincide with seasonal maintenance period (e.g. winter lay-up).

4. Concluding Remarks:

While other industries have been increasingly applying the results of reliability analysis to optimize their maintenance and replacement decisions, the marine industry has long been in a "wait and see" position.

Merchant vessel operators have been using manufacturer's recommendations, registers' requirements and empirical "rules-of-thumb" to make the above decisions. With the downturn in today's shipping markets, more rational maintenance, repair and replacement policies are needed to insure the shipping company's profitability.

Systems reliability and replacement analysis has the potential to help in minimizing ship operating costs. It may also enable the merchant ship operators to obtain lower insurance rates and longer regulatory inspection intervals.

None of the replacement models reviewed in this paper is, by itself, proper for modeling the maintenance, repair and replacement process for Great Lakes diesel-powered ships. A special stochastic replacement model will have to be developed, taking into account the pecularities of the operating conditions, such as the winter lay-up.

The National and Michigan Sea Grant Programs have recognized the need for this optimization, and have awarded the first author of this paper a three year sponsored research project (1986-1988). The aim of the project, as stated in its proposal, will be to develop optimal maintenance repair and replacement policies for Great Lake vessels, focusing on their main Diesel Engines and the auxiliaries necessary for their operations. The database developed on our department for Interlake Steamship [NIKO 84] will be used. Most or all of the work will be programmed on an IBM-PC (XT or AT).

5. References

Note: The following list does not include numerous papers from the IEEE Transactions on Reliability.

[AGEE 86] Marvin H. Agee, Thomas P. Moore, Kenneth W. Brammer, Walter J. Fabrycky and Charles J. Malmborg, "Predicting Life Cycle Costs and Maintenance Requirements." Blacksburg, Virginia, March, 1986.

[ALDW 82] D.S. Aldwinkle and R.V. Pomeroy, "A Rational Assessment of Ship Reliability and Safety," presented at RINA, October 7, 1982.

[ANDE 81] Anderson, M. "Monotone Optimal Preventive Maintenance Policies for Stochastically Failing Equipment." Nav. Res. Logist. Quart., Vol. 28, pp. 47-74, 1981.

[APOS 74] Apostolakis, G.E., "Mathematical Methods of Probabilistic Safety Analysis," U.C.L.A. Report UCLA-Eng.-7464, 1974.

[ARPI 79] Arpi, D.W., and Leo Winn, "A Statistical and Economic Evaluation of Stern-Tube Bearing and Seal Failures," SNAME Spring Meeting, April 1979, pp. 121-133.

[BARL 65] Barlow, R.E. and F. Prochan, "Mathematical Theory of Reliability," Wiley, New York, 1965.

[BARL 60] Barlow, R.E., and L.C. Hunter, "Optimum Preventive Maintenance Policies, Operations Research, Vol. 8, pp. 90-100, 1960.

[BASS 82] Basset, Noel L. and J.B. Rodgers, III, "Computer-Based Maintenance and Operations Management System: Final Report" Executive Summary, Contract #MA-80-8AC-01052, Office of Advanced Shiip Operations, Maritime Administration, U.S. Dept. of Transportation, September 1982.

[BASS 83] Basset, Noel L. and John B. Rodgers, III, "Recent Advances in Computer-Based Shipboard Maintenance and Operations Management," Proceedings, Spring Meeting/STAR Symposium, SNAME, April 1983.

[BAZO 61] Bazovsky, I., Reliability Theory and Practice, Prentice Hall, 1961.

[BEAN 84] Bean, J.C., Lohmann, J.R., and Smith, R.L., "A Dynamic Infinite Horizon Replacement Economy Decision Model," Technical Report 83-11, Department of Industrial and Operations Engineering, University of Michigan, 1983, Revised April 1984.

[BEND 85] Bendell, A. and Humble, S., "A Reliability Model with States of Partial Operation" Nav. Res. Logist. Quart., Vol. 32, pp. 509-535, 1985.

[BENF 72] Benford, H., "Optimal Life and Replacement Analysis for Ships and Shipyards," Transactions RINA, Vol. 1114, pp. 393-407, 1972.

[BENJ 75] Benjamin, J.R., Shinozuka, M. and Shah, H.C. "Acceptable Risk in Reactor Safety Studies," Transactions 3rd International Conference on Structural Mechanics in Reactor Technology, London 1975.

[BERG 84] Berg, Menachem, "A Preventive Replacement Policy for Units Subject to Intermittent Demand," Operations Research, Vol. 32, No. 3, pp. 584-595, 1984.

[BILL 83] Billinton, Roy and R.N. Allan, "Reliability Evaluation of Engineering Systems," Plenum, 1983.

[BLOC 83] Block, H.W., et al, "A General Minimal Repair Maintenance Model," TR No. 83-17, Univ. of Pittsburgh, Dept. of Mathematics and Statistics, 1983.

[BOE 74] Boe, C. and O. Treit, "Reliability Engineering and Safety at Sea," IEEE Transactions on Reliability Theory, August 1974.

[BOHM 79] Boehm, Folker and Joachim, Simon, "Diesel Propulsion Systems of the Future" SNAME Transactions, Vol. 87, 1979, pp. 383-403.

[BOLA 82a] Boland, P.J. and F. Proschan, "Periodic Replacement with Increasing Minimal Repair Costs of Failure," Opns. Res. 30, 1183-1189, 1982.

[BOLA 82b] Boland, Philip J., "Periodic Replacement when Minimal Repair Costs Vary with Time," Nav. Res. Logist. Quart., Vol. 29, No. 4, pp. 541-545.

[BOLA 83] Boland, P.J. and F. Proschan, "Optimum Replacement of a System Subject to Shocks," Opns. Res., 31, 697-704, 1983.

[BOUR 72] Bourne, A.J. and A.E. Green, Reliability Technology, Wiley, 1972.

[BRID 74] Bridges, D.C., "The Application of Reliability to the Design of Ships' Machinery," Transactions IME, Vol. 85, pp. 109-116, 1974.

[BROW 84] Brown, Mark, "On the Reliability of Repairable Systems," Operations Research, Vol. 32, No. 3, pp. 607-615, 1984.

[BUNN 73] Bunnis, J.B., "Optimizing Ship Repair and Maintenance Costs: A Systematic Approach," Transactions RINA, 1973.

[CALD 83] Caldwell, J.B., "Prospects for a "Rational" Approach to Marine Safety," Proceedings, Intl. Conf. on Marine Safety, Glasgow, 1983.

[CHAN 82] Chand, Suresh, and Sethi, Suresh, "Planning Horizon Procedures for Machine Replacement Models with Several Possible Replacement Alternatives," Nav. Res. Logist. Quart., Vol. 29, No. 3, pp. 483-493, 1982.

[COJE 83] Cojeen, H.P., "Automation for Safety Management," presented at seminar on Safety Management for Offshore Operations on the Canadian East Cost, June 1983.

[COLT 70] Colt Industries "Colt-Pielstick PC2 Diesel Engine Description," 1970.

[CORN 85] M. Elisabeth Pate - Cornell and Corazon Pe Benito - Claudos "Warning Systems for Nuclear Power Plants: Evaluation of Social vs. Technical Measures for Risk Reduction," October 1985, Stanford University.

[DERM 84] Derman, C. et al, "On the Use of Replacements to Extend System Life," Operations Research, Vol. 32, No. 3, pp. 626-627, 1984.

[DHIL 81] Dhillon, B.S., and Singh, C., Engineering Reliability: New Techniques and Applications, Wiley, 1981.

[DHIL 83] Dhillon, B.S., "Reliability Engineering in Systems Design and Operation," Van Nostrand, 1983.

[DURE 72] Duregger, R.A., et. al, "System Safety Analysis Techniques as Applied to Shipboard Systems," SNAME Spring Meeting, May 1972.

[EPST 82] Epstein, Sheldon and Yonah Wilamowsky, "A Replacement Schedule for Multicomponent Life-Limited Parts," Nav. Res. Logist. Quart., Vol. 29, No. 4, pp. 685-692, 1982.

[FAUL 79] Faulkner, D. and J.A. Sadden, "Toward a Unified Approach to Ship Structural Safety," Transactions RINA, 1979.

[FRAN 65] Frankel, E., "Complex System Reliability Analysis under Constraints: A Study in Dynamic Programming," International Shipbuilding Progress, Vol. 12, No. 135, pp. 429-436, November 1965.

[FREU 66] Freudenthal, A., "The Analysis of Structural Safety," Proceedings of the American Society of Civil Engineers, Vol. 92, 1966.

[GIDE 75] Gideon, D.N. et al, "Review of LNG Safety Research," Battele Laboratories, Columbus, Ohio, 1975.

[GOLD 81] Goldberg, H., "Extending the Limits of Reliability Theory," Wiley, 1981.

[GOOD 83] Goodman, R.A., "Lloyd's Register's Approach to Ship Safety," Proceedings, Intl. Conf. on Marine Safety, Glasgow, 1983.

[GROS 84] Gross, D., "On Some Common Interests Among Reliability, Inventory and Queuing," The George Washington University, GWU/IMSE/Serial T-491/84, 1984.

[GUMB 58] Gumbel, E.J., Statistics of Extremes, Columbia University Press, New York, 1966.

[GUPTA 85] Gupta, S.K., "Low-Grade Fuel Engines in the United States," Marine Technology, Vol. 22, No. 2, April 1985, pp. 179-187.

[HAHN 68] Hahn, G.H. and S.S. Shapiro, "Statistical Models in Engineering," Wiley, 1968.

[HARR 70] Harrington, R.L., Coats, J.W. and Farley, F.E., "Reliability and Maintainability Analysis of Shipboard Systems," Marine Technology, January 1970, p. 38-54.

[HASH 73] Hashimoto, T. and K. Ishizuka, "Consideration for the Initial Failure of Marine Engine," Bulletin of the Mar. Eng. Soc. of Japan, November 1973, pp. 57-68.

[HASH 81] Hashimoto, T., et al., "Evaluation of Reliability and Maintainability of Marine Engine Subsystems," Bulletin of the Mar. Eng. Soc. of Japan Vol. 9, No. 1, March 1981, pp. 52- .

[HELL 79] Heller, A. and J. Pegram, "Probabilistic Assessment of Collision Involving Seagoing Ships," I.E.E.E. Transactions on Reliability, Vol. R-28, No. 4, October 1979.

[HORI 77] Horigome, M., and S. Umemoto, "Valve Replacement on Marine Diesels," Bulletin of the Mar. Eng. Soc. of Japan, Vol. 5, No. 4, December 1977, pp. 320-328.

[HORI 78] Horigome, M. and M. Kasai, "Application of Autoregressive Model to Failure Data of Marine Mechanical Parts," Bulletin of the Mar. Eng. Soc. of Japan, Vol. 7, No. 1, March 1979.

[HORI 80] Horigome, M. and T. Nakamura, "On the Statistical Characteristics of Replacement Data of Fuel Valves of a Marine Diesel Engine," Bulletin of the Mar. Eng. Soc. of Japan, Vol. 8, No. 1, March 1980, pp. 20-26.

[HORI 83] Horigome, M. and I. Okawara, "Statistical Characteristics of Maintenance of Main Diesel Engine System," Bull. of the M.E.S. Japan, Vol. 11, No. 2, pp. 23-31, 1983.

[HUTH 81] Hutchinson, Bruce L., "Risk and Operability Analysis in the Marine Environment," Transactions SNAME, pp. 127-154, 1981.

[HUTH 85] Hutchison, Bruce L., "Application of Probabilistic Methods to Engineering Estimates of Speed, Power Weight and Cost," Marine Technology Vol. 22, No. 4, October 1985, pp. 358-372.

[JARD 73] Jardine, A.K.S., Maintenance, Replacement and Reliability, Wiley, 1973.

[KAUF 77] Kaufmann, A., et al., Mathematical Models for the Study of the Reliability of Systems, Academic Press, 1977.

[KUNR 82] Kunreuther, H.C., ed. "The Risk Analysis Controversy - An Institutional Perspective," Springer-Verlag 1983.

[LAMP 83] Lampkin, Harold and Winterbottom, Alan, "Approximate Bayesian Intervals for the Reliability of Series Systems from Mixed Subsystem Test Data," Nav. Res. Logist. Quart., Vol. 30, pp. 313-317, 1983.

[LEMO 85] Lemoine, Austine J. and Wenocut, Michael L., "On Failure Modeling," Nav. Res. Logist. Quart., Vol. 32, pp. 497-508, 1985.

[LIPS 73] Lipson, C., "Statistical Design and Analysis of Engineering Experiments," McGraw Hill, 1973.

[LOHM 84] Lohmann, Jack R., "A Stochastic Replacement Economy Decision Model," Technical Report 84-11, Department of Industrial and Operations Engineering, University of Michigan, 1984.

[MANN 74] Mann, N.R., et al, "Methods for Statistical Analysis of Reliability and Life Data," Wiley, 1974.

[MANS 72] Mansour, A., "Methods of Computing the Probability of Failure Under Extreme Values of Bending Moment," Journal of Ship Research, June 1972, pp. 113-123.

[MANS 72a] Mansour, A., "Probabilistic Design Concepts in Ship Structural Safety and Reliability," Transactions SNAME, 1982, pp. 64-97.

[MANS 73] Mansour, A. and D. Faulkner, "On Applying the Statistical Approach to Extreme Sea Loads and Ship Hull Strength," Transactions RINA, Vol. 115, 1973.

[MANS 74] Mansour, A., "Approximate Probabilistic Method of Calculating Ship Longitudinal Strength," Journal of Ship Research, Vol. 18, No. 3, p. 203, September 1974.

[MANS 84] Mansour, A.E., H.Y. Jan, C.I. Zigelman, Y.N. Chen, S.J. Harding, "Implementation of Reliability Methods to Marine Structures," SNAME Transactions, Vol. 92, 1984, pp. 353-382.

[MATS 76] Matsuka, Takeshi, "An Application of Reliability Analysis to the Emergency S.W. Cooling System of the Nuclear Ship Savannah," Bulletin of the Mar. Eng. Soc. of Japan.

[McCO 81] McCormick, Norman, Reliability and Risk Analysis, Academic Press, 1981.

[MEEK 83] Meek, M. et al, "A Shipbuilder's View of Safety," Proceedings, Intl. Conf. on Marine Safety, Glasgow, 1983.

[MILL 79] Miller, Robert H. "Great Lakes Thousand Footers," "Joint Meeting of the Eastern Canadian Section and Great Lakes & Great Rivers Section," SNAME, Toronto, Ontario CANADA, May 1979.

[NAKA 84] Toshio Nakagawa, "Periodic Inspection Policy with Preventive Maintenance," Nav. Res. Logist. Quart., Vol. 31, pp. 33-40, 1984.

[NIKO 85] Nikolaidis E., A.N. Perakis and M.G. Parsons "Structural Reliability of Marine Diesel Engine Propulsion Shafting Systems," SNAME Transactions, Vol. 93, 1985.

[NIKO 84] Nikolaidis E., A.N. Perakis, "Propulsion Shafting Systems Design and Torsional Vibration, A Survey of Methods and Problems," Proceedings, 3rd International Congress on Maritime Technology, Athens, Greece, June 1984.

[NIKO 84a] Nikolaidis, E. and M. G. Parsons, "Marine Diesel Engine Maintenance Data Management System for the Interlake Steamship Company," Report, Department of NA&ME, The University of Michigan, 1984.

[NPRD 83] PRA Procedures Guide, U. S. Nuclear Regulatory Commission, January, 1983.

[OAKF 84] Oakford, R.V., Lohmann, J.R., Salazar, A., "A Dynamic Equipment Replacement Model, IIE Transactions, March 1984.

[OCHI 69] Ochi, M. and E. Motter, "Predictions of Extreme Values of Impact Pressure Associated with Ship Slamming," Journal of Ship Research, June 1969.

[OKAM 78] Okamoto, Z. (Chairman), Symposium Proceedings on "Extension of Time Interval for Periodical Ship Survey," May 1977, Bulletin of Mar. Eng. Soc. of Japan, Vol. 6, No. 3, 1978.

[PACK 71] Pack, Han W., "Mathematical Fleet Replacement Model for General Cargo Liners," Ph.D. Thesis, Department of Naval Architecture and Marine Engineering, University of Michigan, 1971.

[PANE 71] Panel M-22 (Reliability and Maintainability) of the Ships' Machinery Committee, SNAME, "Reliability and Maintainability Engineering in the Marine Industry," Technical and Research Bulletin No. 3-22, SNAME, New York, N.Y., July, 1971.

[RAUS 83] Rausand, M. and G. Engen, "Reliability Studies of Downhold Safety Valves," Norwegian Maritime Research, No. 3, 1983, pp. 23-33.

[REICH 59] Reich, W.H., L.P. Ackermann, C.N. Guckert, B.W. Lockett, H.M. Tiedeman, J.H. Weiner, C.W. Woodal, H. Hostrup, "Ship Maintenance and Repair," SNAME Transactions, Vol. 67, 1959.

[ROLA 83] Roland, H.E. and B. Moriarty, "System Safety Engineering and Management," Wiley, 1983.

[SAMP 82] Sampson, A.R. and R.L. Smith, "Assessing Risks Through the Determination of Rare Event Probabilities," Operations Research, Vol. 30, No. 5, Sept.-Oct. 1982.

[SHER 81] Sherif, Y.S., Smith, M.L., "Optimal Maintenance Models for Systems Subject to Failure a Review," Nav. Res. Logist. Quart., Vol. 28, pp. 47-74, 1981.

[SHOO 68] Shooman, M.L., Probabilistic Reliability: An Engineering Approach, McGraw-Hill, 1968.

[SLOG 83] Slogget, J.E., LNG Carriers-Safety in Operation," Proceedings, Intl. Conf. on Marine Safety, Glasgow, 1983.

[SMIT 76] Smith, C.O., Introduction to Reliability in Design, McGraw-Hill, 1976.

[TANA 83] Tanaka, Y. and K. Sasaki, "An Approach to Economic Analysis of Machinery on Board," Bull. of the M.E.S. Japan, Vol. 11, No. 2, pp. 32-40, 1983.

[THOM 80] Thomas, B.E.M., "Management of Shipboard Maintenance," Sheridan House Inc., White Plains, NY, 1980.

[THOM 84] Thompson, W.A., "Some Reliability Models for Safety Assessment," Operations Research, Vol. 32, No. 3, pp. 559-565, 1984.

[STIA 80] Stiansen, S.G., et al., "Reliability Methods in Ship Structures," Transactions RINA, 1980, p. 381.

[WOOD 63] Woodward, John B., Reliability Theory in Marine Engineering, SNAME GL&GR Section, February 1963.

[ZACK 84] Zacks, S., "Estimating the Shift to Wear-out Systems Having Exponential-Weibull Life Distributions," Operations Research, Vol. 32, No. 3, pp. 741-749, 1984.

[ZIGA 82] Zigang, Li, "Reliability Analysis of Ship Navigation Systems," Annals of the CSNAME, Vol. 1, 1982, pp. 185-196.

[ZIGN 85] Zigan, D., "Computer Aided Fault Diagnosis," Motor Ship, March, 1985.