A RELIABILITY, MAINTAINABILITY, SUPPORTABILITY AND AVAILABILITY ANALYSIS OF A SUBMARINE SONAR SYSTEM

by

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LIST OF ABBREVIATIONS

3-M	Maintenance and Material Management
ACT	Action Taken
AMT	Active Maintenance Time
A_o	Operational Availability
CAD	Corrective Action Date
CLASS	Classification Subsystem
CMPTR	Computer Subsystem
CORR	Correlation
DFR	Deferral Reason
DISP	Display Subsystem
DW	Durbin-Watson
JSN	Job Sequence Number
MHRE	Man Hours Expended
MNR	Mean Normal Residual
MSMT	Mean Scheduled Maintenance Time
MTBCM	Mean Time Between Corrective Maintenance
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
NARR	Narrative
PBB	Passive Broadband Subsystem
PMFL	Preventive Maintenance/Fault Logic

POWER	Power Distribution Subsystem
PREAMP	Preamplifier Subsystem
RECVR	Receiver Subsystem
REGRESS	Regression
SRC	Source Replacement Code
SUIC	Ships Unit Identification Code
TARR	Towed Array Subsystem
TINTERVAL	Student-t Test Interval
TRANS	Transmitter Subsystem
TTEST	Student-t Test
WDD	When Discovered Date
WDS	When Discovered Status
XDUCER	Transducer Subsystem

CHAPTER 1

INTRODUCTION

Objective

The objective of this study is to determine the Operational Availability (A_o) for a major sonar system installed in the U.S. Navy's nuclear submarine fleet based on data obtained from fleet operational submarines. Recent tests indicate that the system is not meeting the specified A_o of .95. This study analyzes the A_o to determine specific areas that are of concern and provides recommended actions for improving the A_o.

Operational Availability Definition

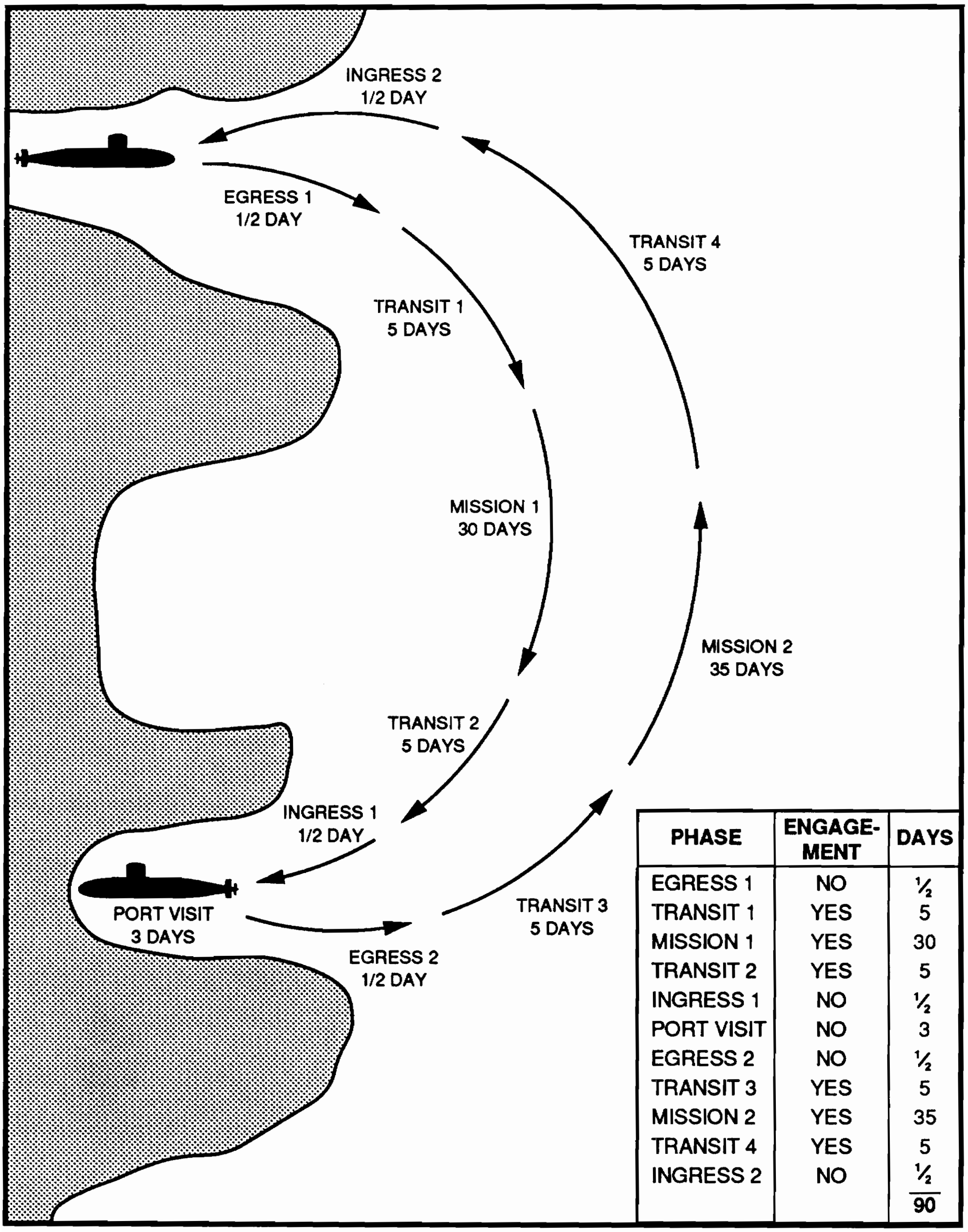
The Operational Availability is defined as the "probability that a system or piece of equipment, when used under stated conditions in an actual operating environment, will operate satisfactorily when called upon" [1]. The A_o calculation used by the Navy for evaluation purposes is as follows:

$$(1.1) \qquad A_o = \frac{MTBF}{MTBF + MTTR + DELAY} \qquad [2]$$

This equation will be utilized in this study so the calculation will be consistent with the Navy's. The A_o of the system must be evaluated in terms of the mission profile of the system. The availability of this system is evaluated based on the 90 day mission profile and engagement cycle shown in Figure 1. All subsystems must be available during the engagement period of mission.

Faults Versus Failures

It is very important to understand the difference between a fault and a failure as used in this study. A fault is defined as any item that malfunctions and does not affect the performance of the system. A malfunction in a redundant circuit would be classified as a fault. A failure is defined as any malfunction that causes the loss of system operation or results in a degraded mode of operation. The distinction between the two terms is very important. Faults are not counted against the Operational Availability of the system since the system is still will operate satisfactorily when called upon. Failures result in degraded or complete loss of operation which results in an unsatisfactory operating condition. The terms faults



PHASE	ENGAGE-MENT	DAYS
EGRESS 1	NO	½
TRANSIT 1	YES	5
MISSION 1	YES	30
TRANSIT 2	YES	5
INGRESS 1	NO	½
PORT VISIT	NO	3
EGRESS 2	NO	½
TRANSIT 3	YES	5
MISSION 2	YES	35
TRANSIT 4	YES	5
INGRESS 2	NO	½
		90

FIGURE 1. TYPICAL MISSION PROFILE

and failures will be used throughout this analysis.

Parameters Evaluated

The parameters that were calculated from the fleet data and how they are used in evaluating the system A_o are as follows:

Mean Time Between Corrective Maintenance (MTBCM): This is total number of operating hours between maintenance actions attributed to both faults and failures. It is used to determine the overall problems with part malfunctions and system reliability.

Mean Time Between Failures (MTBF): This is the total operating hours between maintenance actions attributed to failures only. This statistic is used in the A_o calculation and is used to identify specific design related problems in terms of reliability.

Mean Time To Repair (MTTR): This is the average time spent in returning the system to operational status because of a failure. Logistics and administrative delay times are not included. This is used in the A_o calculation and evaluation of maintainability problems.

Delay Times for Failure Items: This is the average administrative and logistic delay time associated with the correction of failures. This is used in the A_o calculation and the evaluation of supportability related problems.

Parts Available for Failures: This is a measure of the number of parts available on the submarine to correct failures. This statistic is used to evaluate the system sparing of critical parts which directly affects the delay times.

Parts Available for Faults: This is a measure of the number of parts available on the submarine to correct faults. This statistic is used to evaluate the system sparing of noncritical parts. This will be used to determine if there is excessive sparing of parts that are not required to keep the system operational.

A trend analysis for the above parameters is performed to determine how the system parameters are behaving over time. The system level statistics are also allocated to the subsystem level to identify problem areas. Where problems are identified to a particular subsystem, recommendations are made to improve the Operational Availability of this system.

The ultimate goal of this analysis is to identify areas that are having a negative impact on the Operational Availability of the system. The statistics are analyzed individually and then conclusions and recommendations are made by looking at the statistics as a whole. Figure 2 depicts the process utilized in this analysis. The conclusions and recommendations are provided in Chapter 7.

System Description

Background

The system was developed from 1970 through 1974. The first system became operational in 1975. The system has gone through four major upgrades to improve the system operability, reliability, and maintainability. The fifth major upgrade is currently being developed. A time line depicting the system life cycle to date is shown in Figure

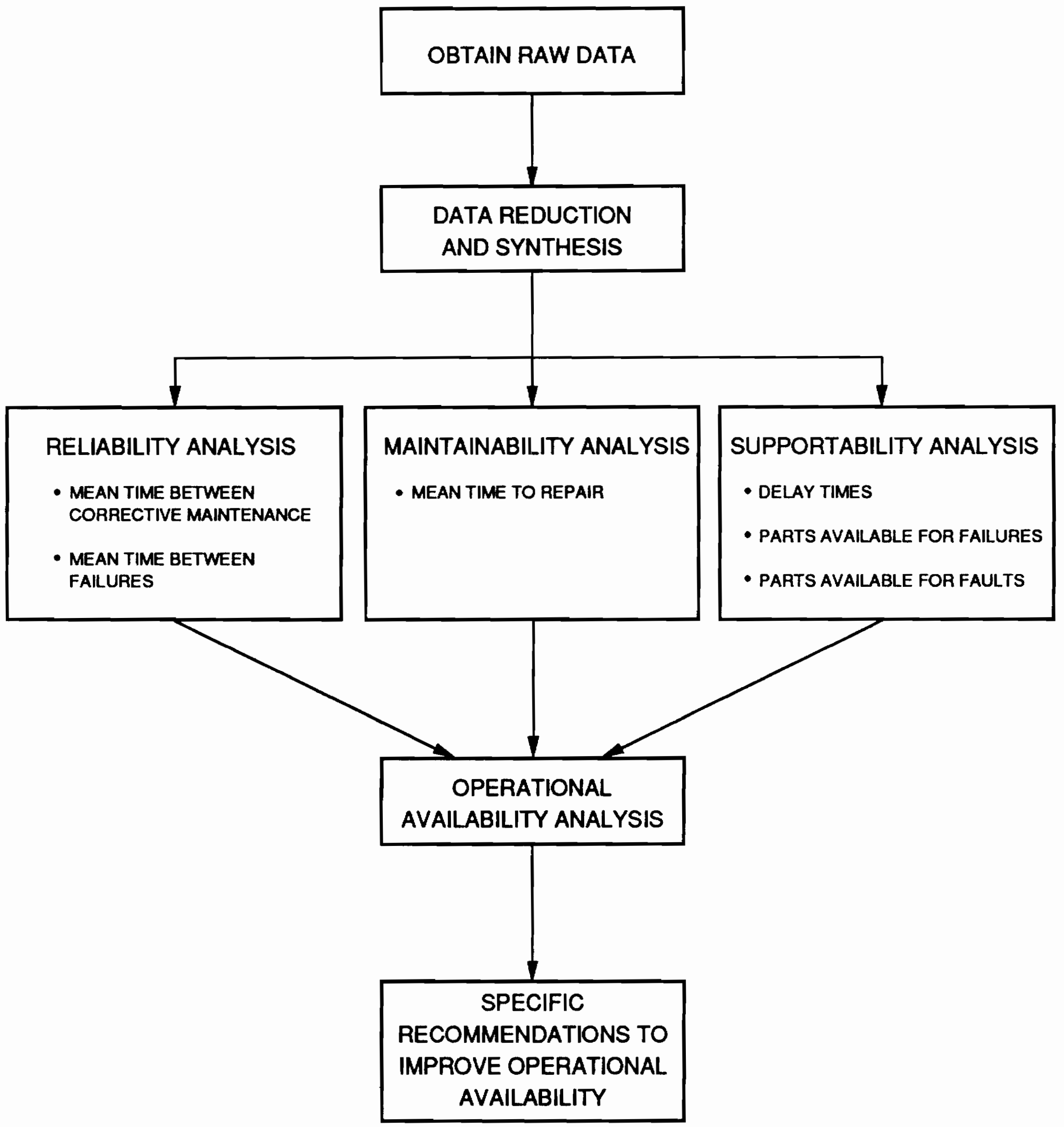


FIGURE 2. THE ANALYSIS PROCESS

3. Figure 3 also shows the time period analyzed for this study.

Description

The system analyzed is the primary sonar system in the U.S. Navy's nuclear submarine fleet. The system consists of eleven major subsystems. Figure 4 is a top level block diagram of the major subsystems and how they interrelate. The abbreviations for each subsystem shown in Figure 4 are used in tables and graphs throughout the rest of this study.

The system performs both active and passive sonar functions. The active functions of the system are performed by the Active Transmit, Transducer, Preamplifier and Active Receive Subsystems. The Active Transmit Subsystem generates the signal that is to be transmitted. The energy enters the water via the Transducer Subsystem. After the energy enters the water and gets reflected off a target, the Transducer Subsystem absorbs the energy which is then amplified by the Preamplifier Subsystem. The signal is then sent to the Active Receive Subsystem for processing. The operator selects active functions and observes the active returns from the Display Subsystem. The entire sequence is controlled by the Computer

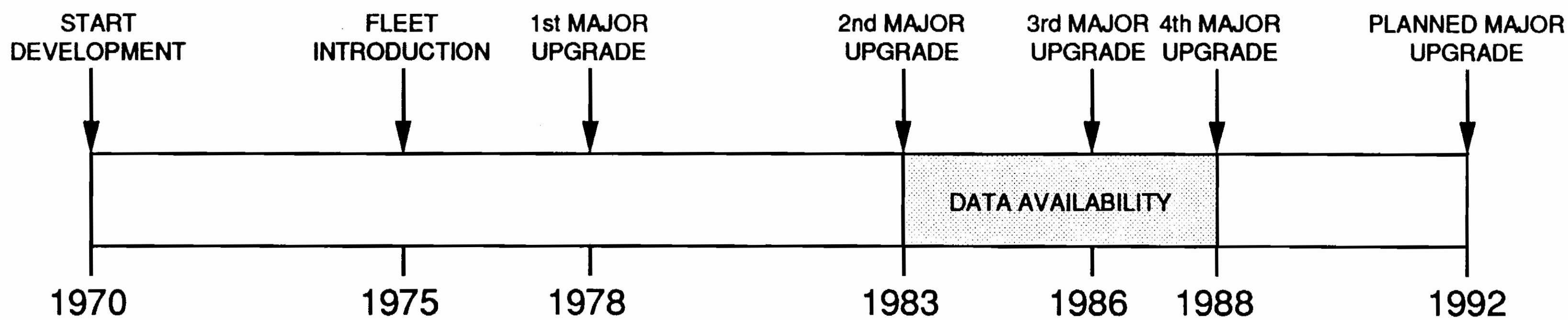


FIGURE 3. SYSTEM EVOLUTION TIME LINE

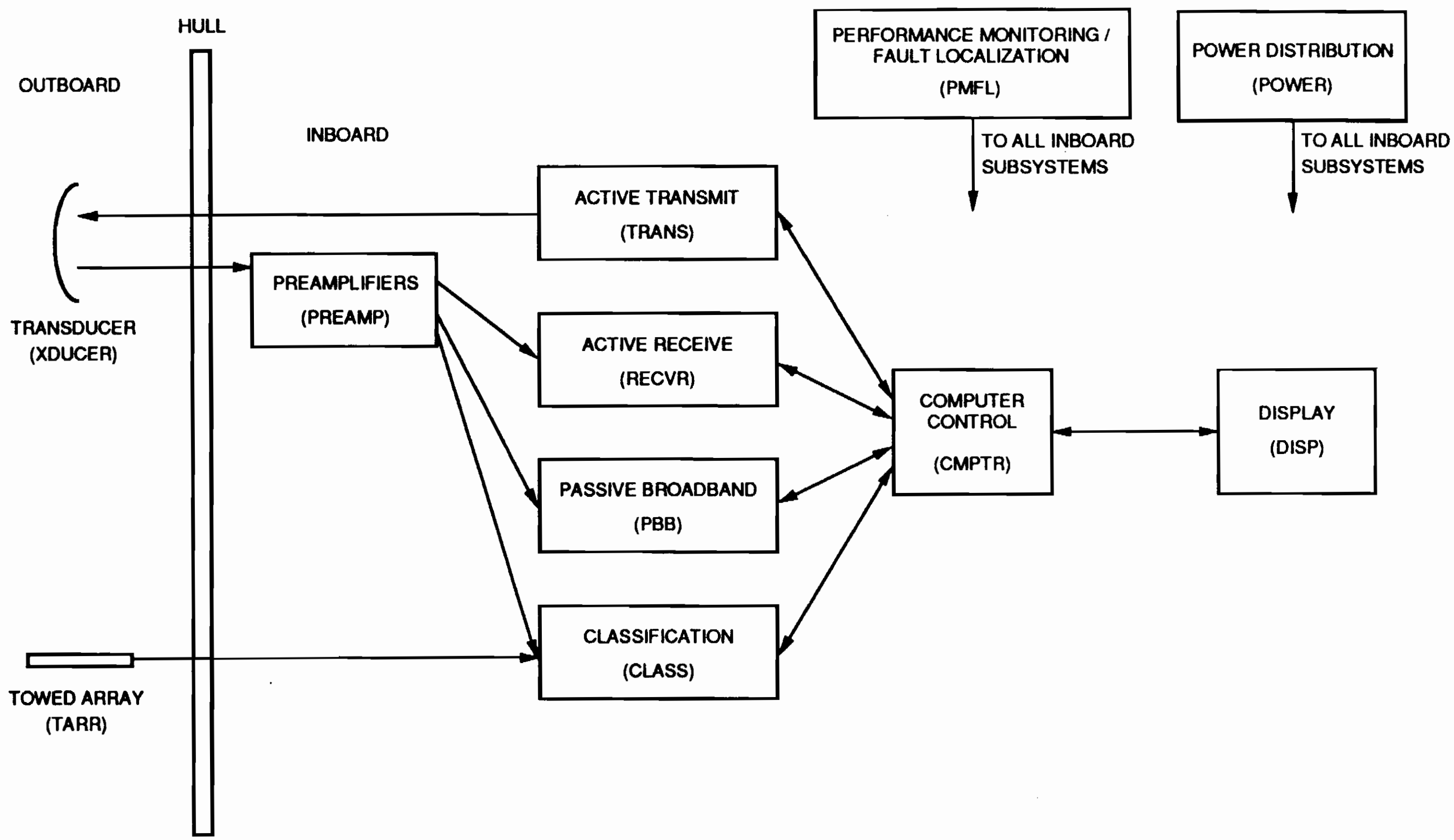


FIGURE 4. SYSTEM BLOCK DIAGRAM

Subsystem.

The passive functions are similar to the active functions except that the source of the signal is the target itself. Passive functions just listen for noise that the targets generate. The Transducer Subsystem and Towed Array Subsystems are used to listen for possible targets. Noise picked up from the Transducer Subsystem is amplified by the Preamplifier Subsystem and sent to the Passive Broadband and Classification Subsystems for processing. Noise picked up by the Towed Array Subsystem is processed through the Classification Subsystem. The operator selects passive functions and observes the potential targets from the Display Subsystem. The Computer Subsystem controls the entire process.

The system also has a Performance Monitoring/Fault Localization Subsystem that is used to monitor various points in all subsystems to identify faults and failures. The Power Distribution Subsystem is used to distribute and control the ship's power to all of the subsystems.

CHAPTER 2

DATA ANALYSIS

Data Source

This study is based on maintenance and supply data obtained from the U.S. Navy Submarine Fleet. For every maintenance action performed on a system, the maintenance technician is supposed to fill out form OPNAV 4790/2K which provides the details of the maintenance action. A sample of an OPNAV 4790/2K is provided in Appendix A. This form is then submitted to the Navy Ships Parts Control Center which enters the information into two separate data bases. One data base contains the coded information from Blocks 1 through 34 of OPNAV 4790/2K while the other is the narrative submitted by the maintenance technician in Block 35 of OPNAV 4790/2K. The Navy Ships Parts Control Center also maintains a separate data base that provides information on all requisitions for parts received from the fleet. All of these data bases are maintained as part of the Navy Maintenance and Material Management (3-M) system. The Naval Sea Systems Command periodically requests that the data for specific hulls during specified periods of time be transferred to a computer at the National

Institute of Health. The data is then down loaded for analysis on an IBM Personal Computer. The data in this study covers maintenance actions from seventeen submarines covering the period from January 1983 through June 1988 excluding all of 1984.

Since an understanding of the fields in the data bases and how they relate to each other is critical to the analysis, the fields in the three data bases were examined for applicability to this study. Examination of the coded data base yielded the following fields of interest:

> Ships Unit Identification Code (SUIC): This field contains a code that identifies the submarine the maintenance action occurred on [3].
>
> Job Sequence Number (JSN): This field assigns a number to each maintenance action. This number is assigned sequentially from a log maintained by the submarine crew [4].
>
> When Discovered Date (WDD): This is the Julian date of when the need for corrective maintenance action was discovered [5].

Corrective Action Date (CAD): This is the Julian date of when the maintenance action was completed [6].

When Discovered Status (WDS): This field contains a code that describes the effect of the failure or malfunction on the performance capability of the system. A code of 1 indicates the system remains operational, a code of 2 indicates the system is nonoperational, a code of 3 indicates the system has degraded performance and a code of 0 indicates other actions such as ordering documentation, reporting configuration changes, etc. [7].

Deferral Reason (DFR): If a maintenance action has to be deferred, a code is entered for the reason. The code of interest for this study is a 2 which indicates a lack of material available for the correction of the deficiency [8].

Action Taken (ACT): This field contains a code that best describes the action taken to correct the deficiency. A code of 1 or 2 indicates that parts were obtained to correct the deficiency, a code of 3 indicates that no parts were required, a code of 4 indicates the action was cancelled and a code of 5 indicates a configuration change [9].

Man Hours Expended (MHRE): This field contains the total man hours expended by maintenance personnel in completing the maintenance action. For example, if it took two men working for three hours to correct a problem, six hours would be entered [10].

Active Maintenance Time (AMT): This is the total clock hours to the nearest whole hour during which maintenance was actually being performed on the equipment. This field does not include any delay times [11].

The narrative data base contains the SUIC, JSN and the narrative submitted by the maintenance technician that describes the maintenance action.

The fields of interest that the supply data base contains are the SUIC, JSN, and the Source Replacement Code (SRC). The SRC field contains a code that indicates where the part was obtained from. For the purpose of this study, the only information needed is if the part was obtained from ship spares (coded as A, B, or C) or if the part was obtained from outside the ship (any other code) [12]. Table 1 summarizes the fields of interest and any associated codes for each of the three data bases.

Using the three data bases, a master data base was created that contained the fields of interest. The information described above was extracted from each data base by using the SUIC and JSN fields as the relational fields. This was done to create a central data base that is easier to maintain than three individual data bases. It is also much quicker to analyze data in a single data base rather than having the computer search three data bases for the required information. The entire flow of the data from the fleet to the establishment of the master data base is shown in Figure 5.

Data Reduction

The use of fleet data represents a unique data analysis since the source data is not validated and corrected at the time of the maintenance event. This study relies solely on the maintenance technician properly and completely filling out the maintenance action form. As a result, some of the data is incomplete. The data base was

TABLE 1

DATA BASE FIELDS OF INTEREST SUMMARY

DATA BASE	FIELD	CODE	CODE MEANING
Coded	SUIC		Ship Identifier
	JSN		Job Identifier
	WDD		Julian Date
	CAD		Julian Date
	WDS	1 2 3 0	System Operational System Nonoperational Degraded Performance Not Hardware Related
	DFR	2	Lack of Material
	ACT	1,2 3 4 5	Parts Obtained No Parts Required Action Cancelled Configuration Change
	MHRE		Man Hours Expended
	AMT		Active Maintenance Time
Narrative	SUIC		Ship Identifier
	JSN		Job Identifier
	NARR		Narrative
Supply	SUIC		Ship Identifier
	JSN		Job Identifier
	SRC	A,B,C D,E,F G,H,I J,K	Part Available Onboard Part Not Available on Ship

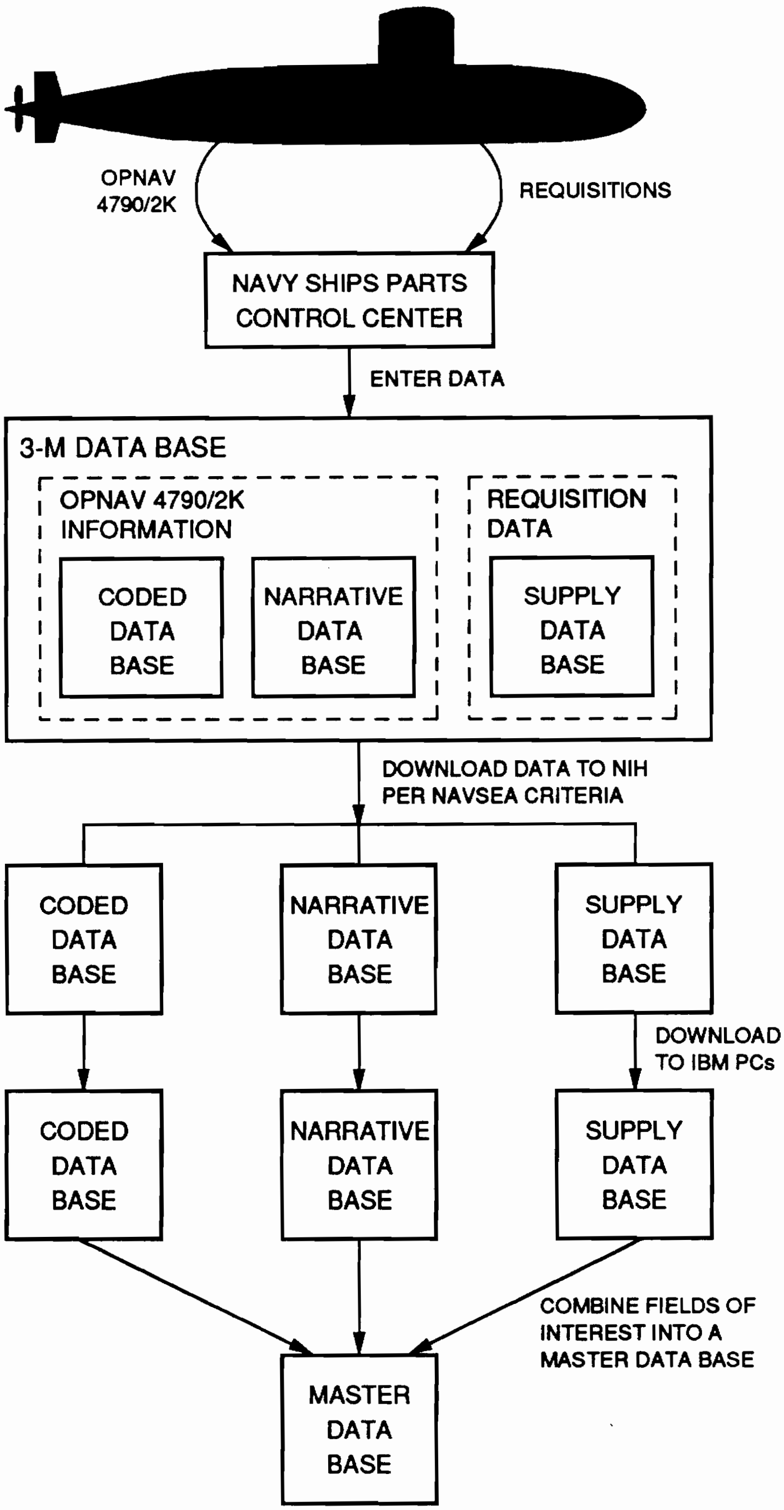


FIGURE 5. DATA FLOW

reviewed and records were eliminated which were missing the When Discovered Date or the Corrective Action Date. Without the When Discovered Date, it would be impossible to assign the maintenance action to a specific time period. With the Corrective Action Date missing, determining delay times would not be possible.

The next step in the data reduction process was to eliminate records that were not attributed to a hardware maintenance action. Records for which the Action Taken Code was 4, indicating the action was cancelled, or 5, which indicates a configuration change, were eliminated. The next step was to eliminate records for which the When Discovered Status code was 0 which is used to report documentation changes or deficiencies. These steps narrowed the data base down to only those records for which hardware maintenance was required because of a hardware malfunction. The total records in the data base was reduced from 824 to 680 as a result of the data reduction process. A flow diagram depicting this process is shown in Figure 6.

Data Review

The remaining records in the data base were then reviewed to try and identify information for fields that

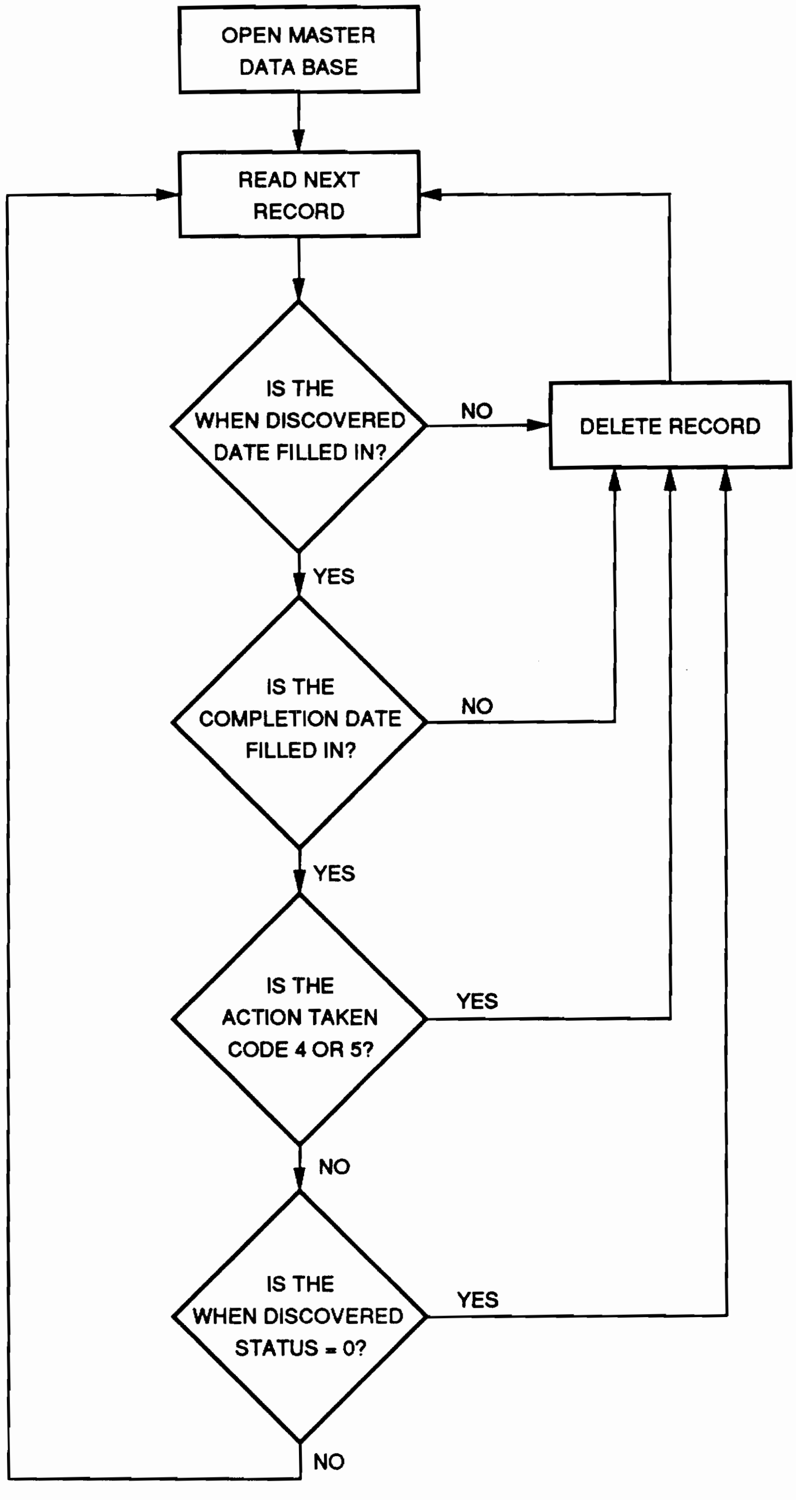


FIGURE 6. DATA REDUCTION PROCESS

were incomplete. In many instances, the narratives provided information for fields that were left blank in the coded report. Every narrative was reviewed to try and fill in as many incomplete fields as possible. It should be noted that the descriptions provided in the narrative varied greatly. Many of the narratives provided great detail of what was accomplished while others use terms like "Fixed problem". The narratives are a valuable source of information and if the maintenance technicians were aware that what they report could have an impact on future system changes, the narratives would most likely improve.

Since the analysis will be allocating the system level statistics to the subsystem level, the narratives were reviewed to identify the subsystem that each maintenance action was associated with. Fields were added to the master data base for the subsystem and filled in manually based on the narrative. If the subsystem could not be identified, the subsystem field in the data base was left blank.

After checking for the subsystem, each narrative was then reviewed to see if any other fields in the data base could be filled in. The narratives assisted in identifying information for two of the fields in the master base.

The first field was the Action Taken field. If the narrative indicated that parts were obtained to correct the deficiency and the Action Taken field was not filled in, a code of 1 was entered. The other field was the Source Replacement Code. The narratives were checked for those records in which the Source Replacement Code was blank. If the narrative indicated that the parts were drawn from shipboard spares, a code of "A" was entered. If the narrative indicated the part was placed on order, a code of "K" was entered to indicate that action was deferred until the parts were received. If no determination could be made, the field was left blank. A flow chart of this process is shown in Figure 7.

The data base has now been reduced to only hardware maintenance actions with the fields filled in as best as could be determined from the information provided. Not every field is filled in and assumptions will have to made in determining the system level and subsystem level statistics. These assumptions will be discussed during the discussions of the calculations. A sample of the data contained in the master data base is contained in Appendix B.

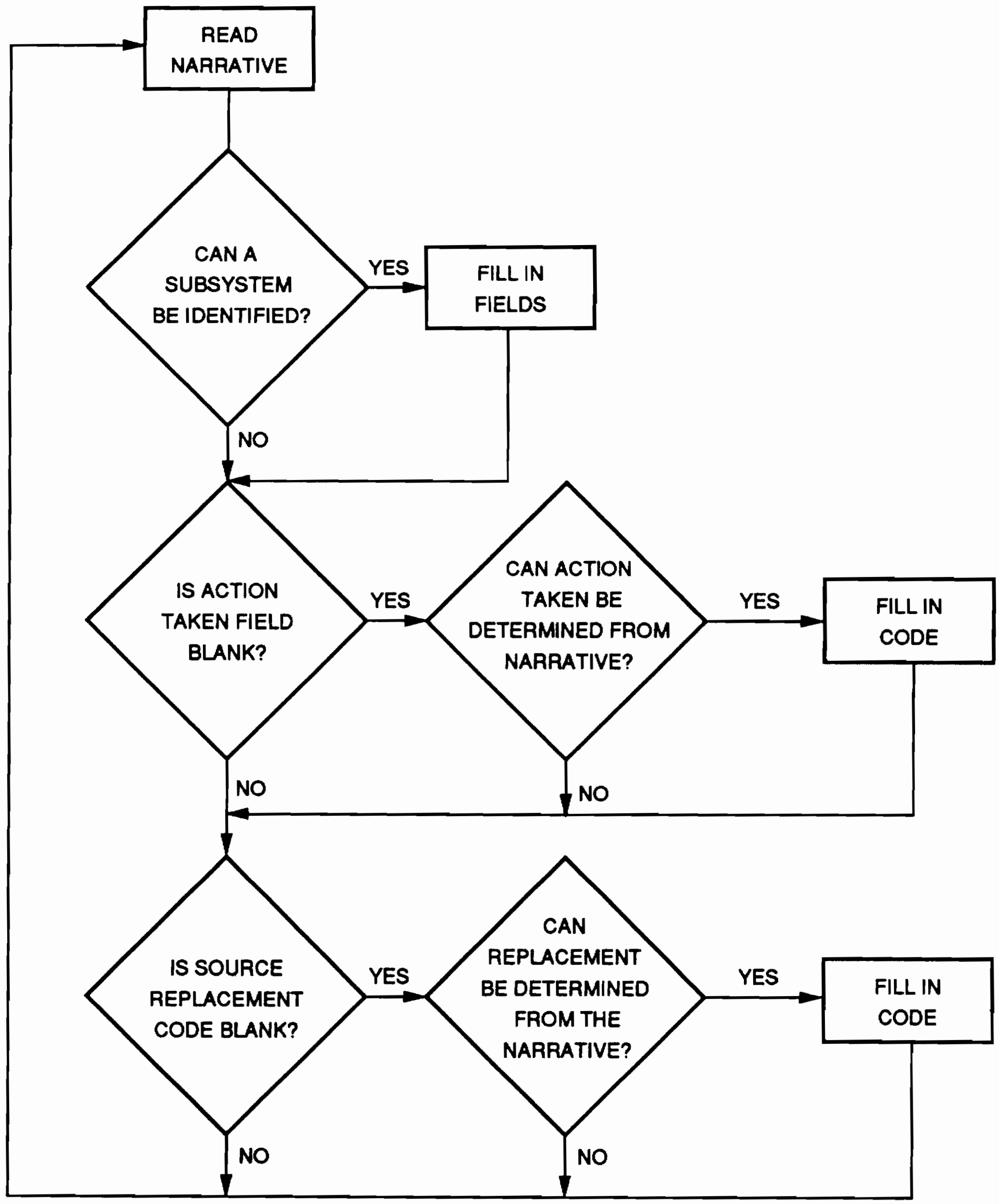


FIGURE 7. DATA REVIEW PROCESS

CHAPTER 3

RELIABILITY ANALYSIS

Introduction

This chapter describes the procedures used to calculate the Mean Time Between Corrective Maintenance and the Mean Time Between Failures system level statistics, the trend analysis and the allocation of the system statistics to the subsystems.

Mean Time Between Corrective Maintenance Analysis

A corrective maintenance event is any unscheduled action which occurs as the result of a hardware malfunction or failure [13]. For the Mean Time Between Corrective Maintenance (MTBCM) statistic, the concern is the total number of operating hours between corrective maintenance actions. The MTBCM statistic does not discriminate between faults and failures.

System Level Statistic

For every submarine hull in the data base, the number of maintenance actions for each six month increment was counted. If there were no maintenance actions reported during a six month period, it was assumed that the data was missing or not reported and no operating time was assigned to the interval.

The total operating hours of each submarine for each reporting period had to be determined. This was accomplished by reviewing the availability schedule of each submarine and subtracting the number of days in each reporting period that the submarine was not operationally available. The total hours for each operating period was calculated as follows:

(3.1) Total Hours = Days Available * 24 hours/day * 0.8

The 0.8 factor is used to estimate the total time that the system is engaged during the mission profile and also considers the typical time between missions. The MTBCM calculation for each time period was calculated as follows:

$$(3.2)\quad MTBCM_{period} = \frac{\text{Total Operating Hours}}{\text{Total Faults + Total Failures}}$$

The resultant matrix depicting each hull, the associated maintenance actions and total operating time for each time period for which maintenance actions were reported is contained in Appendix C.

Each of the MTBCM statistics for each operating period were then examined to determine if any of the statistics were markedly different from the other statistics in the set. The MTBCM statistics for each period were plotted versus time and any points that appeared unusual were analyzed further. The scatter plot is shown in Figure 8. To determine if any points are extreme, a box plot was utilized. The box plot is a graphical display that describes the behavior of the measurements in the middle of the distribution and also the behavior at the tails of the distribution [14]. Values that lie very far from the middle of the distribution are considered outliers. Other outlier tests which do not aggregate the data are available which may yield different results. The outliers can be caused by abnormal reporting conditions, inaccurate reporting, transcription errors, etc. These outliers can cause distortion in the analysis of the data. If a point or points are found to be outliers, a check with the source of the data is appropriate to see if there was a recording error or if it just an unusual point. This check was not possible for this analysis due to the age of the data and it is not possible to easily locate the maintenance technicians that performed the tasks. For this analysis,

Figure 8. Mean Time Between Corrective Maintenance Scatter Plot.

any points found to be outliers were eliminated. The outlier tests described above were performed using the statistical software package MINITAB [15]. The analysis is shown in Appendix D. The data point for the first six months of 1985 was found to be an outlier and was eliminated. The remaining data is considered valid for analysis.

The system MTBCM statistic was then calculated using the valid data points as follows:

$$(3.3) \quad MTBCM_{system} = \frac{\text{Sum of } MTBCM_{period}}{\text{Total Number of Periods}}$$

The MTBCM system was calculated along with 90% confidence interval based on the Student-t distribution using MINITAB. The 90% confidence interval was used to assist in determining how good the point estimate is and to also determine if the specified system statistic falls within the confidence interval. The system MTBCM was calculated to be 378 hours with a 90% confidence interval of (348, 408) hours. The MINITAB output is contained in Appendix E. The 90% confidence interval is fairly narrow which indicates the point estimate is fairly close to the true MTBCM. The system does not have a specified MTBCM that it is required to meet.

Trend Analysis

The valid data points were then plotted versus time and a least squares estimated (linear) regression analysis was performed. The linear regression analysis will result in a best fit of the data points to a trend line. From this line, the general trend of how the statistics are changing over time can be observed. I chose to aggregate the data for each time period and then perform the linear regression analysis. There are other techniques available that do not aggregate the data, such as the Cross Section Time Series Model, that may yield different results.

One of the assumptions in regression models is that the error terms are uncorrelated with each other [16]. When analyzing a time series, this assumption is not always valid. When analyzing the data over time, an error in the current time period might be similar or related to the error in the previous time period which would suggest there could be some correlation. A Durbin-Watson test, which is based on the residuals from the least squares estimated regression, can be performed to determine if the errors between time periods are related [17]. In general, if the Durbin-Watson test statistic is close to 2.00, there is no correlation between the errors and the linear regression model assumptions are valid [18].

The equation for the regression line and the Durbin-Watson test result was calculated using MINITAB. The time period was the independent variable and the MTBCM statistic was the dependent variable. Instead of using the year as the time period, the year 1983 was set at 0 months and every period thereafter was incremented by 6 months. This was done to normalize the time scale. Appendix E contains the output from the MINITAB analysis. The Durbin-Watson statistic was shown to be 2.54. For a large sample size, a hypothesis test can be conducted to determine if corellation exists based on the Durbin-Watson statistic. Since the sample size is small, the test can not be conducted so a judgement is made. This is assumed to be close to 2.00. Further analysis is required to verify that this assumption is valid.

To ensure that the calculated regression line is truly indicating the trend over time, a test of the hypothesis that the slope, designated as B, is 0 versus the alternate hypothesis that the slope is not 0 was performed. This will determine if there is strong evidence that the data is truly indicating a trend or not. The test is set up a follows:

(3.4) Null Hypothesis H_0: $B = 0$

(3.5) Alternative H_1: $B \neq 0$

(3.6) Decision Rule Reject H_0 if $B/s_b > t_{n-2,\alpha/2}$ [19]

or

$B/s_b < -t_{n-2,\alpha/2}$

Where s_b is the standard deviation of the least square estimator of the slope of the regression line. A 95% confidence interval is used. Since the sample size is small and the population variance is unknown, the Student-t distribution is used to test the hypothesis [20]. The test statistic is calculated as part of the regression analysis output provided by MINITAB in Appendix F. The statistic for the decision rule, which is shown as the t-ratio in Appendix F, is -0.87. The critical value of $t_{6,.025}$ is -2.447 [21]. Since the test statistic is less than the critical value of $t_{6,.025}$, the null hypothesis can not be rejected. There is not overwhelming evidence that there is a negative trend for the MTBCM statistic. Based on this, it is assumed that the MTBCM is constant over time. A plot of the valid data points and the constant trend line is shown in Figure 9.

The linear regression analysis shows that the system MTBCM is remaining fairly constant over time. This is not

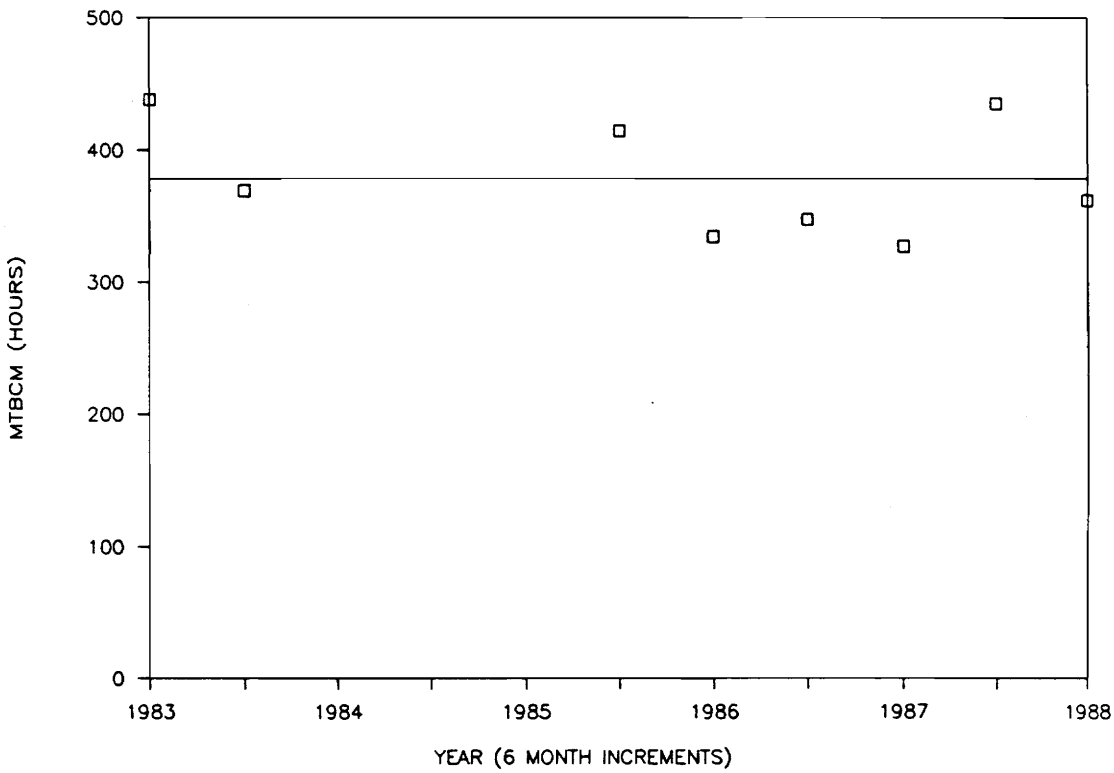


Figure 9. Mean Time Between Corrective Maintenance Trend.

what is expected since there have been reliability improvements incorporated into the system over the time period analyzed.

Allocations

The allocation of the system level MTBCM statistic to the subsystem level will help in identifying subsystems that have a large influence on the MTBCM statistic. The data base was reviewed and the total number of maintenance actions associated with each subsystem was calculated. Since not every maintenance event in the data base could be associated with a subsystem because of poor narratives, the system level statistic had to be allocated by using the percentages associated with the maintenance events that could be identified to the subsystem level. The percentages were calculated as follows:

$$(3.7)\quad \text{Subsystem \%} = \frac{\text{Total Actions Per Subsystem}}{\text{Total Actions for All Subsystems}}$$

To perform the allocation, the system MTBCM statistic must be converted to failures per hour, called $LAMDA_{system}$, as follows:

$$(3.8)\quad \text{MTBCM-LAMDA}_{system} = \frac{1}{\text{MTBCM}_{system}}$$

The MTBCM-LAMDA value for each subsystem, called $\text{MTBCM-LAMDA}_{subsystem}$, is calculated as follows:

$$(3.9)\ \text{MTBCM-LAMDA}_{subsystem} = \text{MTBCM-LAMDA}_{system} * \text{Subsystem } \%$$

Table 2 contains the subsystem calculations. A plot of the $\text{MTBCM-LAMDA}_{subsystem}$ values for each subsystem is shown in Figure 10. This plot clearly shows that the Display Subsystem is the major contributor to the system MTBCM.

Mean Time Between Failures Analysis

Introduction

A failure is defined as a hardware malfunction that is detrimental to the system performance. A failure could result in the entire system being nonoperational or could result in operating in a degraded mode. The Mean Time Between Failures (MTBF) statistic is based on those maintenance events that have an affect on system performance.

TABLE 2

MEAN TIME BETWEEN CORRECTIVE MAINTENANCE ALLOCATIONS

SUBSYSTEM	TOTAL ACTIONS	(A) SUBSYSTEM PERCENTAGE (%)	(B) SYSTEM LAMDA (failures/hour) ($x10^{-3}$)	(A*B) SUBSYSTEM LAMDA (failures/hour) ($x10^{-3}$)
PREAMP	24	4.2	2.64550	0.11111
POWER	16	2.8	2.64550	0.07407
TRANS	37	6.5	2.64550	0.17196
RECVR	57	10.0	2.64550	0.26455
PBB	69	12.1	2.64550	0.32011
CLASS	68	12.0	2.64550	0.31746
CMPTR	13	2.3	2.64550	0.06085
PMFL	30	5.3	2.64550	0.14021
DISP	230	40.5	2.64550	1.07143
XDUCER	10	1.8	2.64550	0.04762
TARR	14	2.5	2.64550	0.06613
TOTAL	**568**	**100.0**		**2.64550**

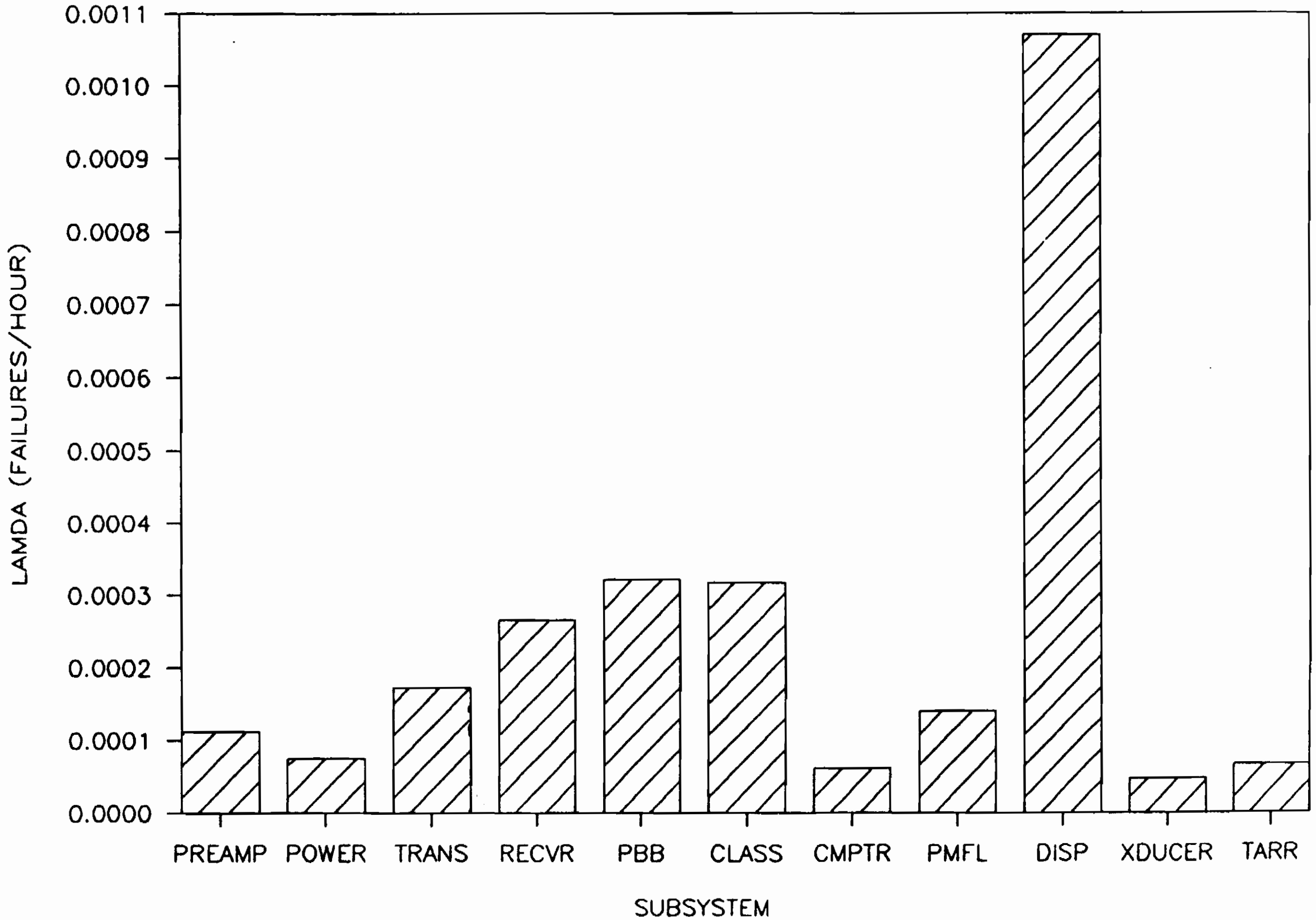


Figure 10. Mean Time Between Corrective Maintenance Allocation.

System Level Statistic

The maintenance actions in the master data base were reviewed and only those items for which the When Discovered Status was 2, indicating the system was nonoperational, or 3, which indicates degraded operation, were examined. The number of actions that met this criteria for each hull during each period were counted. The total operating hours for each period remained the same as it was in the Mean Time Between Corrective Maintenance calculations. If there were no failures reported in a period but there were maintenance actions (When Discovered Status = 1) in that period, the operating hours remained. The total operating hours in the MTBCM and MTBF calculations are identical.

The MTBF calculation for each time period was calculated as follows:

$$(3.10)\quad MTBF_{period} = \frac{\text{Total Operating Hours}}{\text{Total Failures}}$$

The matrix containing the total failures and operating times for each hull is contained in Appendix G.

The statistics for each time period were then plotted versus time as shown in Figure 11. From the plot in Figure 11, it appears that the data point associated with the first six months of 1985 is significantly different from

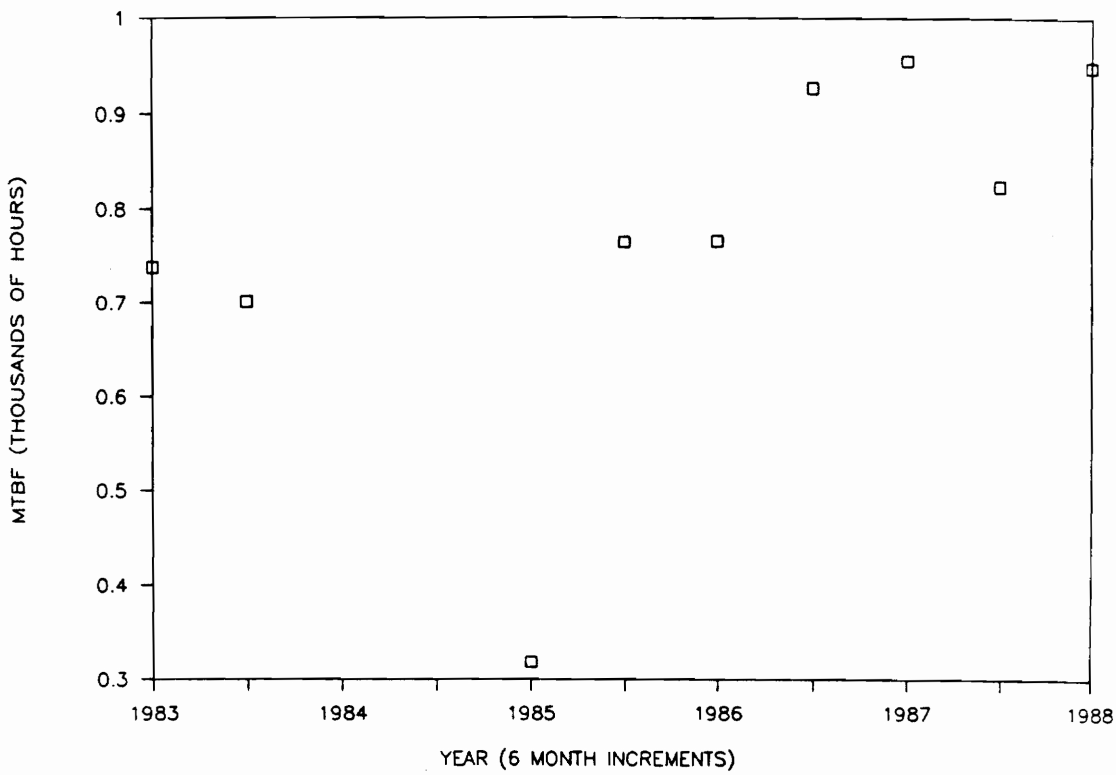


Figure 11. Mean Time Between Failures Scatter Plot.

the other data points and is a potential outlier. The outlier tests were conducted using the box plot feature in MINITAB and the results are contained in Appendix G. The suspect point was found to be an outlier and was eliminated.

The system MTBF statistic was then calculated using the valid data points as follows:

$$(3.11)\quad MTBF_{system} = \frac{\text{Sum of all } MTBF_{period}}{\text{Total Number of Periods}}$$

The calculation of the $MTBF_{system}$ statistic yielded 828 hours with a 90% confidence interval of (759, 896) hours. The calculations were performed using MINITAB and the results are contained in Appendix H. The specified MTBF of the system is 1500 hours. It appears that the system is not currently meeting the specified MTBF.

To verify this, a hypothesis test was conducted to test the null hypothesis that the $MTBF_{system}$ statistic is equal to the specified value verses the alternative hypothesis that the $MTBF_{system}$ statistic is less than the specified value. The test is based on the Student-t distribution since the sample size is small and the population variance is unknown [22]. A 99% confidence interval was chosen. The test was set up as follows:

(3.12) Null Hypothesis H_o: $MTBF_{system} = 1500$

(3.13) Alternative H_1: $MTBF_{system} < 1500$

(3.14) Decision Rule:

$$\text{Reject } H_o \text{ if } \frac{MTBF_{system} - 1500}{s_x/\sqrt{n}} < t_{n-1,.010}$$

Where s_x is the standard deviation of the sample and n is the sample size which in this case is 8. The test statistic, which is the left side of the inequality in equation 3.14, was calculated using MINITAB and the result is shown as T in Appendix H. The test statistic is -18.68. The critical value of $t_{7,.010}$ is -2.998 [23]. Since the test statistic is less than the critical value of $t_{7,.010}$, the null hypothesis is rejected. This indicates there is overwhelming evidence that the MTBF of the system is less than the specification.

Trend Analysis

A linear regression analysis was performed on the valid data points versus time. Again, the Durbin-Watson test had to be performed to ensure the errors terms were not correlated which would violate the regression analysis assumptions.

The equation for the regression line and the

Durbin-Watson statistic were calculated using MINITAB. The time period was the independent variable and the MTBF statistic was the dependent variable. The time periods were assigned the same way as the time periods in the MTBCM regression analysis. Appendix H contains the output from the MINITAB Analysis. The Durbin-Watson statistic was shown to be 2.21 which is close to 2.00 which indicates the errors are not correlated and the assumptions are valid. The slope of the line is positive which would seem to indicate that the MTBF statistic is improving over time.

To test that the calculated regression line is truly indicating a positive trend over time, the hypothesis test described by equations 3.4, 3.5 and 3.6 was conducted assuming a 95% confidence interval and a Student-t distribution. The test statistic, which is shown as the t-ratio in the MINITAB regression analysis output shown in Appendix I, is 3.26. The critical value of $t_{6,.025}$ is 2.477 [24]. Since 3.26 is greater than 2.477, the null hypothesis (that the slope is 0) is rejected. This indicates there is overwhelming evidence that the MTBF statistic is increasing over time. A plot of the valid MTBF data points and the regression equation is shown in Figure 12.

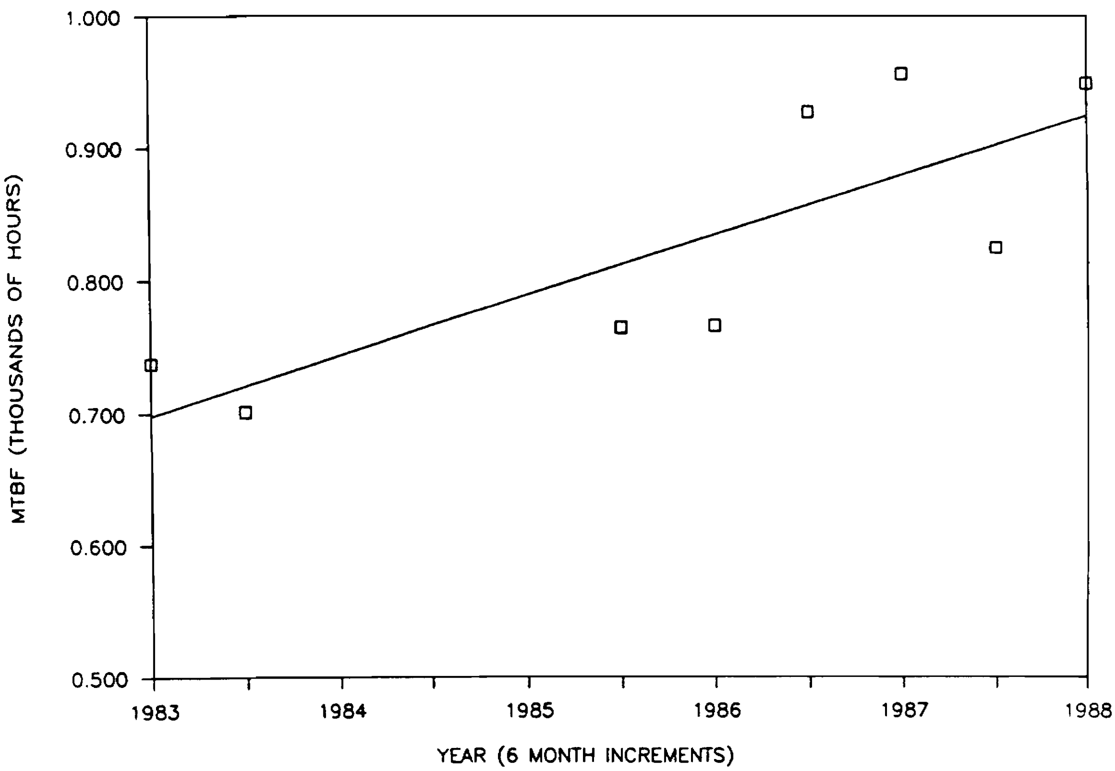


Figure 12. Mean Time Between Failures Trend.

Allocations

The allocation of the MTBF statistic to the subsystem level will help to identify the subsystems that have a great affect on the MTBF statistic.

$$(3.15)\quad \text{Subsystem}_{\text{MTBF}}\ \% = \frac{\text{Total Failures per Subsystem}}{\text{Total Failures for All Subsystems}}$$

To perform the allocation, the system MTBF statistic must be converted to failures per hour, called $\text{MTBF-LAMDA}_{\text{system}}$, as follows:

$$(3.16)\quad \text{MTBF-LAMBDA}_{\text{system}} = \frac{1}{\text{MTBF}_{\text{system}}}$$

The LAMDA value for each subsystem, called $\text{MTBF-LAMDA}_{\text{subsystem}}$, is calculated as follows:

$$(3.17)\quad \text{MTBF-LAMBDA}_{\text{subsystem}} = \text{MTBF-LAMBDA}_{\text{system}} * \text{Subsystem}\ \%$$

Table 3 contains the subsystem calculations. A plot of the $\text{LAMDA}_{\text{subsystem}}$ values for each subsystem is shown in Figure 13. This plot clearly indicates that the Display Subsystem is the major contributor to the MTBF statistic.

TABLE 3

MEAN TIME BETWEEN FAILURES ALLOCATIONS

SUBSYSTEM	TOTAL ACTIONS	(A) SUBSYSTEM PERCENTAGE (%)	(B) SYSTEM LAMDA (failures/hour) ($x10^{-3}$)	(A * B) SUBSYSTEM LAMDA (failures/hour) ($x10^{-3}$)
PREAMP	12	4.0	1.20773	0.04831
POWER	5	1.6	1.20773	0.01932
TRANS	18	5.9	1.20773	0.07126
RECVR	31	10.2	1.20773	0.12319
PBB	37	12.2	1.20773	0.14734
CLASS	36	11.9	1.20773	0.14372
CMPTR	10	3.3	1.20773	0.03986
PMFL	10	3.3	1.20773	0.03986
DISP	135	44.6	1.20773	0.53865
XDUCER	3	1.0	1.20773	0.01207
TARR	6	2.0	1.20773	0.02415
TOTAL	**303**	**100.0**		**1.20773**

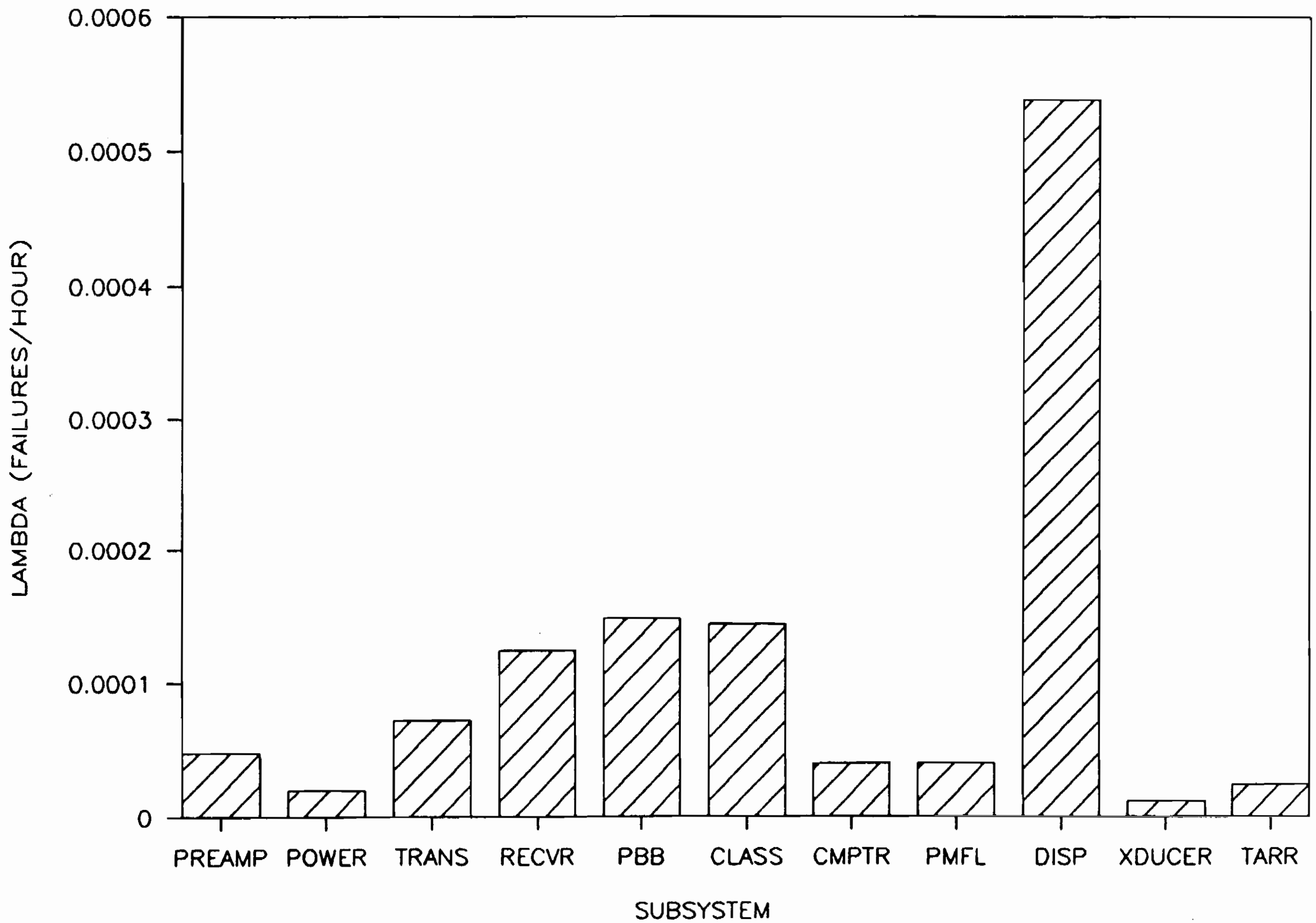


Figure 13. Mean Time Between Failures Allocation.

MTBF Results versus MTBCM Results

Trend Analysis Comparisons

It is interesting that the MTBCM statistic has remained constant over time while the MTBF statistic is showing considerable improvement over the same period. Reliability improvements made by adding redundancy will result in more parts in the system which could increase the total maintenance actions required but reduce the number of failures in the system. Reliability improvements made by using more reliable components should decrease the number of maintenance actions and also decrease the number of failures. The reliability improvements made to this system consist of both methods. The net result is that the increased actions as a result of redundancy are offset by the decreased actions as a result of using more reliable components. This results in the number of maintenance actions remaining constant while the system MTBF improves. This is a clear example of why it is extremely important to understand that not all corrective maintenance actions result from failures.

Allocation Comparisons

A comparison of Figure 8 and Figure 11 indicates that the subsystems follow the same relative patterns with regard to how they contribute to the MTBCM and MTBF. The Display Subsystem is the major contributor to both statistics followed by the Passive Broadband Subsystem, Classification Subsystem and Receiver Subsystem. The comparison was done to see if there were subsystems experiencing many maintenance actions and few failures or vice versa. The bar graphs indicate that the pattern between failures and all maintenance actions are consistent amongst the subsystems.

CHAPTER 4

MAINTAINABILITY ANALYSIS

Introduction

This chapter describes the procedures and analysis used to calculate the Mean Time To Repair (MTTR) for failure items. A trend analysis and allocation of the system level statistic to the subsystems is performed.

The Mean Time To Repair statistic includes only the actual repair time for which the work is in progress and does not include administrative or logistics delays [25]. The statistic is based on the Active Maintenance Time as reported in the OPNAV 4790/2K reports. The Active Maintenance Time does not distinguish between preventive and corrective maintenance actions. Any time a failed item is discovered it is reported. If no failure was found during a preventive maintenance action, the time is not reported nor included in this study.

Active Maintenance Time includes the time for the following tasks:

Localization - This is determining the location of a failure to the lowest possible level without using test equipment. For example, the Fault Localization software may identify a fault to a specific unit [26].

Isolation - This is the process of determining the exact location of the failure. This may require use of test equipment or maintenance assistance modules [27].

Disassembly - This step involves removing any parts or assemblies to gain access to the item that is to be replaced [28].

Interchange - This step involves removal of the defective item and installing the replacement. It is assumed the replacement has already been obtained and is available [29].

Reassembly - This step is the closing and reassembly of the equipment after the repair has been made [30].

Check Out - This is the performance of tests to verify that the system has been restored to satisfactory performance [31].

Mean Time To Repair for Failures

Introduction

The Mean Time To Repair was calculated for those maintenance actions for which the When Discovered Status was coded as 2 or 3. These are the same maintenance actions that are used to calculate the Mean Time Between Failures statistic. These items were specifically analyzed because they are the items that contribute to the overall down time of the system. Maintenance actions that had a When Discovered Status of 1, which indicates the system remains operational, are usually deferred until a period when the system is not required to be operational so these actions do not contribute to down time.

System Level Statistic

A review of the master data base revealed that the Active Maintenance Field for a majority of the records had not been filled in. However, all of the records had the Man Hours Expended field filled in. Each of the records that had both the Man Hours Expended, which is the total hours miltiplied by the number of people, and Active Maintenance Time filled in, of which there were 258, were extracted from the data base. A scatter plot of the Man Hours Expended versus the Active Maintenance Time, as shown in Figure 14, appeared to indicate that there was a correlation between the two statistics. Using MINITAB, a correlation calculation was performed on the data and the results are contained in Appendix I. The correlation coefficient calculated by MINITAB was 0.937 which indicates there is a very strong linear relationship between the two variables. A linear regression calculation between the two variables was performed using MINITAB to determine an equation that can be used to estimate the missing Active Maintenance Times. The MINITAB output containing the results is contained in Appendix I. The linear equation for the relationship between the two variables is as follows:

$$(4.1)\quad AMT = .502 + .460 * MHRE$$

The scatter plot with the straight line approximation is shown in Figure 15. Equation 4.1 was used to calculate the Active Maintenance Times in the data base that were missing.

The Active Maintenance Times for each action that contributed to down time were summed by hull and reporting period. The MTTR for each for each time period was

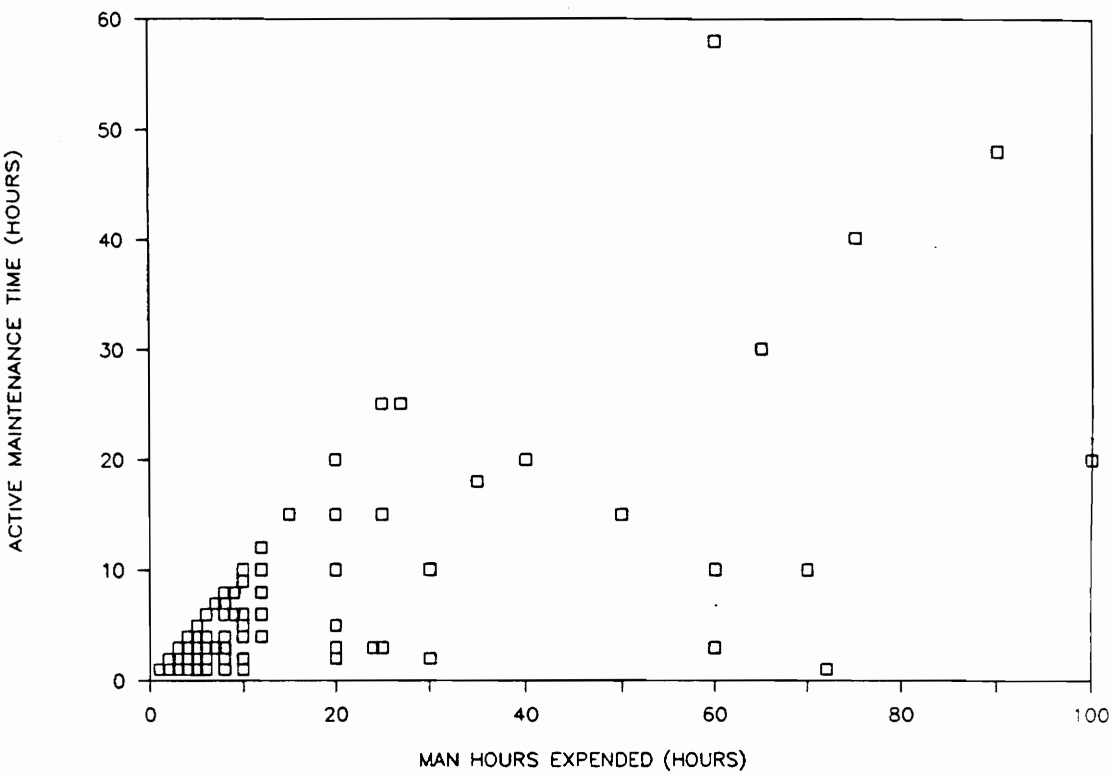


Figure 14. Man Hours Expended Versus Active Maintenance Time Scatter Plot.

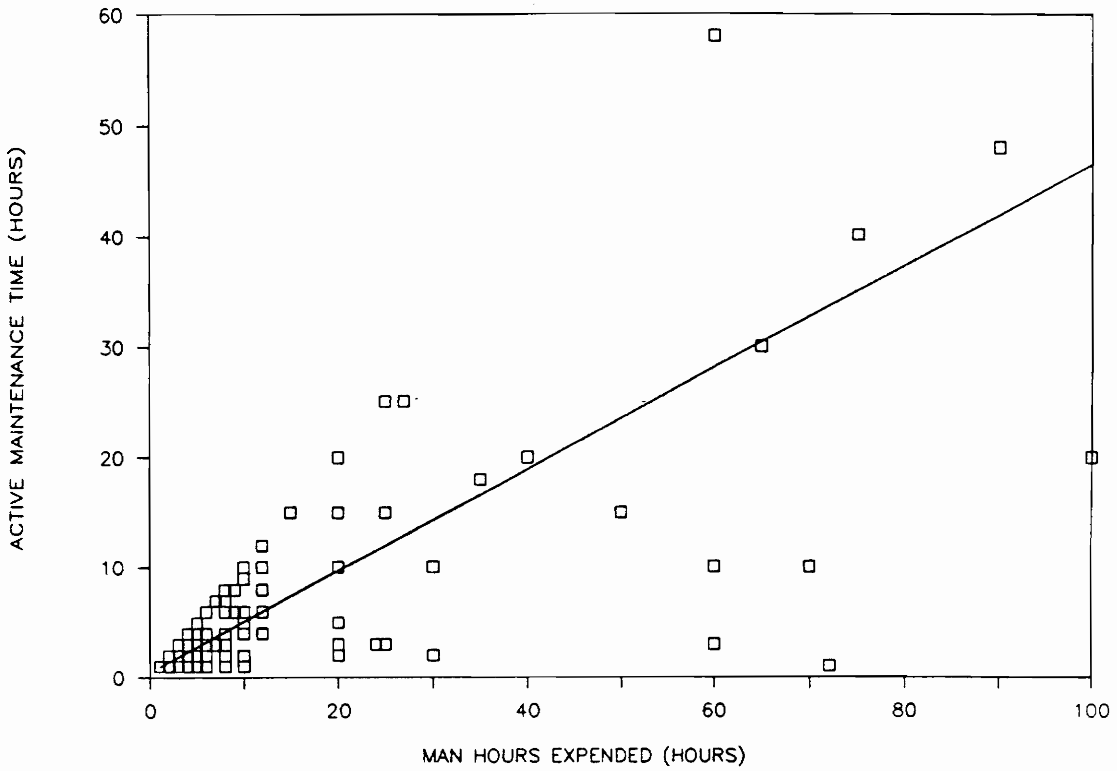


Figure 15. Man Hours Expended Versus Active Maintenance Time Linear Relationship.

calculated as follows:

$$(4.2)\quad MTTR_{period} = \frac{\text{Total Active Maintenance Time}}{\text{Total Maintenance Actions}}$$

The matrix containing the data by hull for each time period and the $MTTR_{period}$ statistic for each period is shown in Appendix J.

The statistics for each time period were then plotted versus time as shown in Figure 16. From the plot in Figure 16, it appears that the data is quite widespread with no points standing out as potential outliers. To verify this, the outlier tests were conducted using a box plot and the results are contained in Appendix K. As suspected, none of the points failed the outlier tests.

The system MTTR statistic was then calculated as follows:

$$(4.3)\quad MTTR_{system} = \frac{\text{Sum of all } MTTR_{period}}{\text{Total Number of Periods}}$$

The calculation of the $MTBF_{system}$ statistic yielded 4.46 hours with a 90% confidence interval of (2.94, 5.97) hours. The calculations were performed using MINITAB and

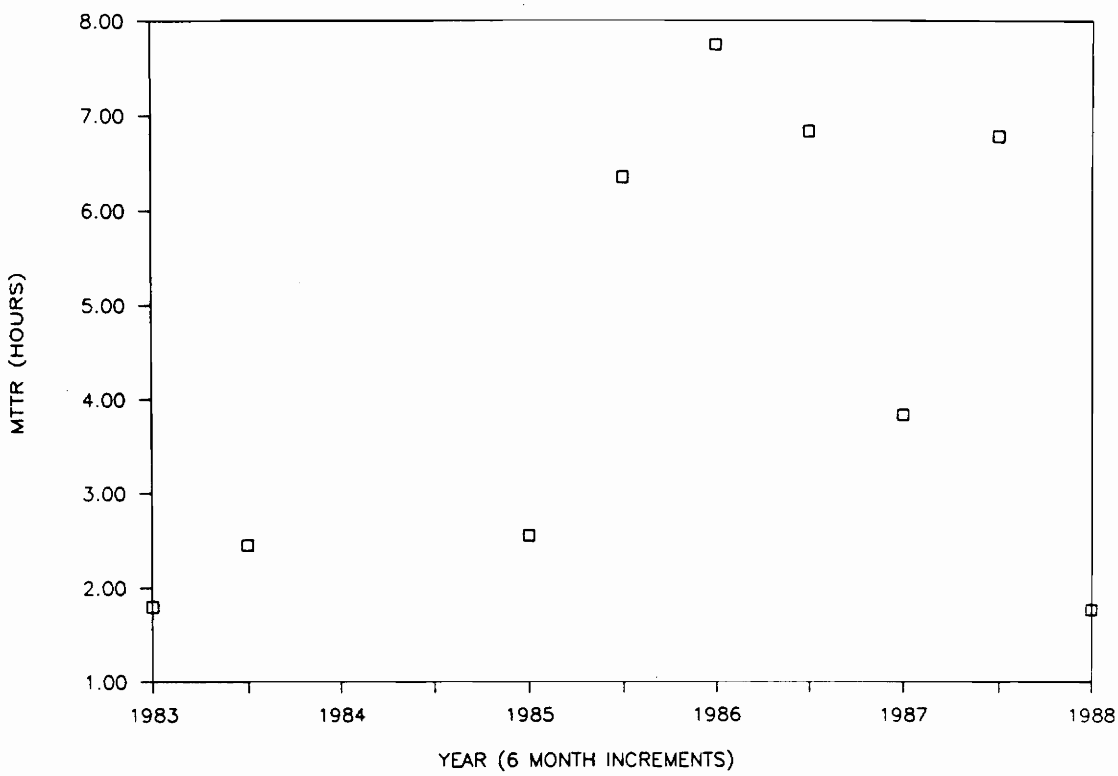


Figure 16. Mean Time to Repair Scatter Plot.

the results are contained in Appendix L. The specified MTBF of the system is 40 minutes or .67 hours. It appears that the system is not currently meeting the specified MTBF.

To verify this, a hypothesis test was conducted to test the null hypothesis that the $MTTR_{system}$ statistic is equal to the specified value verses the alternative hypothesis that the $MTTR_{system}$ statistic is greater than the specified value. The test is based on the Student-t distribution since the sample size is small and the population variance is unknown [32]. A 99% confidence interval was chosen. The test was set up as follows:

(4.4) Null Hypothesis H_o: $MTTR_{system} = .67$

(4.5) Alternative H_1: $MTTR_{system} > .67$

(4.6) Decision Rule:

$$\text{Reject } H_o \text{ if } \frac{MTTR_{system} - .67}{s_x/\sqrt{n}} > t_{n-1,.010}$$

Where s_x is the standard deviation of the sample and n is the sample size which in this case is 9. The test statistic, which is the left side of the inequality in equation 4.6, was calculated using MINITAB and the result is shown as T in Appendix M. The test statistic is 4.65. The critical value of $t_{8,.010}$ is 2.896 [33]. Since the test statistic is greater than the critical value of

$t_{8,.010}$, the null hypothesis is rejected. This indicates there is overwhelming evidence that the MTTR of the system is greater than the specification.

It should be noted that the fleet reporting requirements are always in terms of whole hours. For example, if an action takes 15 minutes to complete, it is reported as 1 hour. The fleet data will always show a slightly higher MTTR than what the true MTTR actually is. However, a MTTR of 4.46 hours is considered excessive even if there are rounding errors involved.

Trend Analysis

A linear regression analysis was performed on the data points versus time. Again, the Durbin-Watson test had to be performed to ensure the errors terms were not correlated which would violate the regression analysis assumptions.

The equation for the regression line and the Durbin-Watson statistic were calculated using MINITAB. The time period was the independent variable and the MTTR statistic was the dependent variable. The time periods were assigned the same way as the time periods in the Mean Time Between Corrective Maintenance regression analysis. Appendix L contains the output from the MINITAB Analysis. The Durbin-Watson statistic was shown to be 1.5 which is close to 2.00 which indicates the regression assumptions are valid. Further analysis must be performed to validate this assumption. The MINITAB output is contained in Appendix L.

To test that the calculated regression line is truly indicating an increasing trend over time, the hypothesis test described by equations 3.4, 3.5 and 3.6 was conducted assuming a 95% confidence interval and a Student-t distribution. The test statistic, which is shown as the t-ratio in the MINITAB regression analysis output shown in Appendix L, is 1.07. The critical value of $t_{6,.025}$ is 2.477 [34]. Since the t-ratio is less than the critical value of $t_{6,.025}$, the null hypothesis can not be rejected. This indicates there is not overwhelming evidence that the MTTR statistic is increasing over time.

A review of the scatter plot shown in Figure 14 seemed to indicate that there is an increasing trend from 1983 through 1987 with a sharp drop in 1988. The data point in 1988 was not an outlier but does not seem to follow the general trend of the previous years. The regression analysis was performed again not including the 1988 data point. The MINITAB output is contained in Appendix M. The Durbin-Watson statistic was shown to be 1.81 which is close to 2.00 which indicates there is no correlation between the errors terms over time.

The hypothesis test described by equations 3.4, 3.5 and 3.6 was again performed to see if there is evidence that the MTTR statistic is truly increasing over the time period from 1983 through 1987. The t-ratio shown in Appendix N is 2.57. The critical value of $t_{6,.025}$ is 2.477 [35]. Since the t-ratio is greater than the critical value of $t_{6,.025}$, the null hypothesis can be rejected which indicates there is truly an increasing trend to the MTTR statistic. The plot of the regression equation is shown in Figure 17.

The two trend analyses performed resulted in different conclusions. The analysis with the data point from 1988 deleted gives a more realistic presentation of what has actually been happening over the last seven years. This statistic should be monitored closely over the next few years to see if the 1988 statistic is indicative of what is actually occurring today. There is cause for concern if the MTTR trend for these items is truly increasing. There

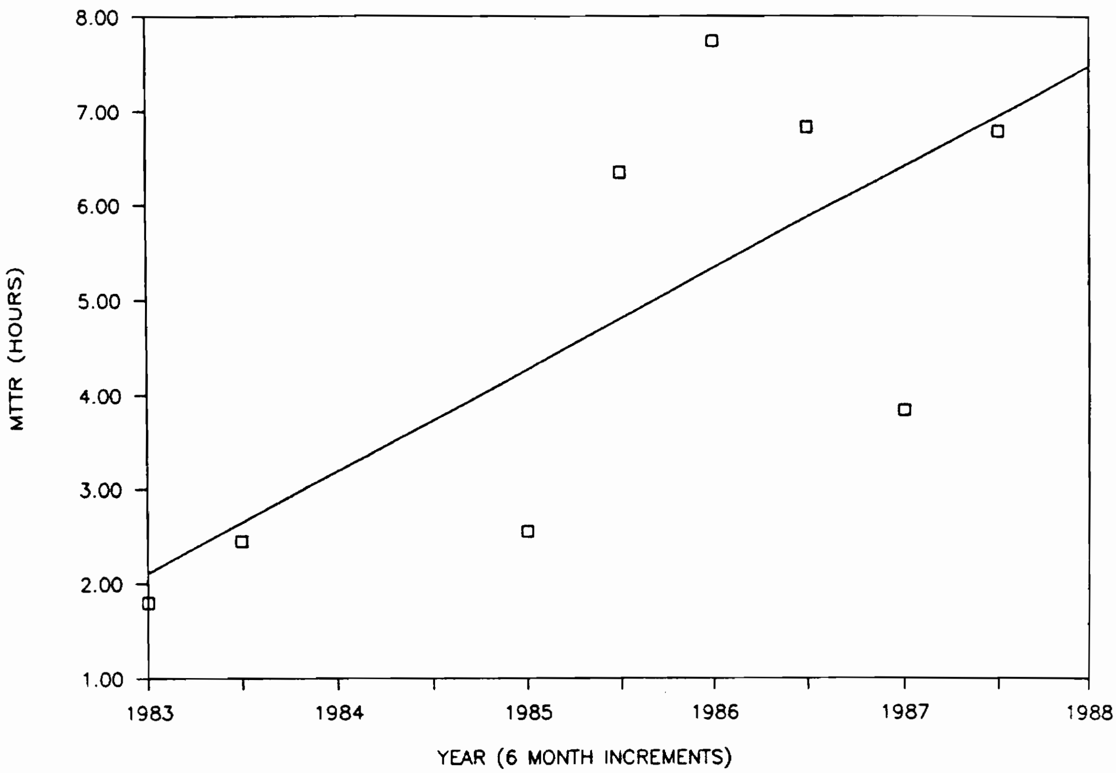


Figure 17. Mean Time to Repair Trend.

has been no significant repackaging of equipment or changes in the Fault Localization software that would constitute an increase in the MTTR. An area that could contribute to the increase in the MTTR is training. If the maintenance technicians have not received training or if the courses are not being properly taught, the system MTTR would be increasing.

MTTR Allocations

The system MTTR statistic was allocated to the subsystem level to identify the subsystems that are significant contributors to the MTTR. The master data base was reviewed and the total number of actions and total active maintenance time for each subsystem was calculated. The MTTR for each subsystem was calculated as follows:

$$(4.7) \quad MTTR_{subsystem} = \frac{\text{Total AMT for Failures}}{\text{Total Failure Actions}}$$

Since not every maintenance action could be identified to a subsystem, the subsystem calculations were normalized to the calculated system level statistic. To normalize the $MTTR_{subsystem}$ calculation, the mean of the $MTTR_{subsystem}$ values, called MEAN-MTTR, was calculated. This value was then used in conjunction with the system level MTTR to make the subsystem allocated MTTR equate to the system level MTTR. The adjusted MTTR is called MTTR-NORM. These steps are as follows:

$$\text{(4.8)} \quad \text{MEAN-MTTR} = \frac{\text{Sum of all MTTR}_{\text{subsystem}}}{\text{Number of Subsystem}}$$

$$\text{(4.9)} \quad \text{MTTR-NORM} = \frac{\text{MTTR}_{\text{system}}}{\text{MEAN-MTTR}} * \text{MTTR}_{\text{subsystem}}$$

Table 4 summarizes the results of the allocation process. Figure 18 is a bar graph of each of the subsystems MTTR-NORM values. The subsystems that exceed the calculated system MTTR are the Towed Array Subsystem and the Passive Broadband Subsystem. The Towed Array Subsystem is the major contributor to the system MTTR. The MTTR for this subsystem was expected to be much greater than that of the other subsystems. To perform repairs on this subsystem the array has to be extended, many times into the water, and then the work has to be performed. The array is extremely long and can take many hours just to extend and then bring back in. The large MTTR of this subsystem will be extremely difficult to decrease because of the physical characteristics required by the array.

TABLE 4

MEAN TIME TO REPAIR (MTTR) ALLOCATIONS

SUBSYSTEM	TOTAL FAILURES	TOTAL REPAIR TIME (hours)	MTTR SUBSYSTEM (hours)	MTTR-NORM (hours)
PREAMP	12	60.28	5.02	3.81
POWER	5	17.72	3.54	2.69
TRANS	18	100.16	5.56	4.22
RECVR	31	97.82	3.16	2.39
PBB	37	267.56	7.23	5.48
CLASS	36	185.74	5.16	3.91
CMPTR	10	41.10	4.11	3.12
PMFL	10	56.20	5.62	4.26
DISP	135	716.10	5.30	4.02
XDUCER	3	14.58	4.86	3.68
TARR	6	90.58	15.10	11.44
TOTAL	**303**	**1647.84**	**64.66**	**49.02**
MEAN			**5.88**	**4.46**

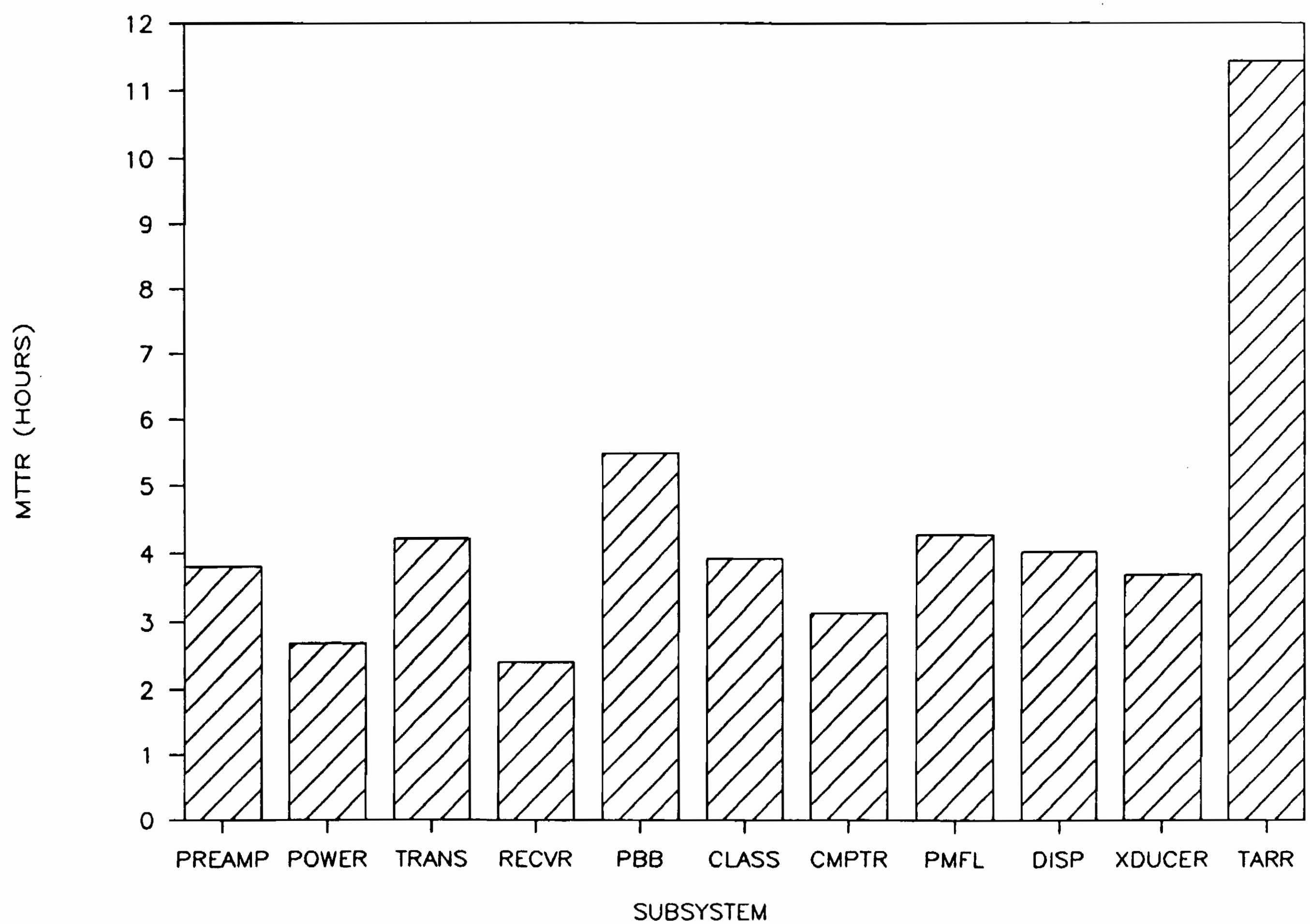


Figure 18. Mean Time to Repair Allocation.

CHAPTER 5

SUPPORTABILITY ANALYSIS

Introduction

This chapter describes the procedures and analyses used to calculate the Delay Times for Failures, Parts Available for Failures and Parts Available for Faults. A trend analysis and allocation of the system level statistics to the subsystems was performed.

Delay Times for Failure Items

System Level Statistic

The delay times associated with each maintenance action that contributes to the overall system down time was analyzed. The delay time used in this study includes logistic and administrative delays. The data is insufficient to break out the exact causes of the delay times associated with each maintenance action.

The key field used to determine what the delay time was for each maintenance action was the Source Replacement Code. This code indicates if the required parts were on board when demanded or not. If the part was available when demanded, a delay time of one hour was assigned. This is to allow for the technician to obtain the replacement part and any required test equipment. Former Navy personnel were consulted and they agreed that one hour was a reasonable estimate.

If a part was not on board when demanded, the delay time was assumed to be the difference between the When Discovered Date and the Corrective Action Date. The difference was then multiplied by 24 to convert to hours. Since the part was not immediately available, it had to either be ordered from the Navy supply system or obtained from other land based sources. The system had to remain in a nonoperational or degraded mode until a part was obtained. The only data available to estimate the delay time is the difference between the dates.

For the case where the part was available when demanded, the difference between the When Discovered Date and the Corrective Action Date was not considered. The instructions for filling in the Corrective Action Date state "Enter the Julian date the maintenance action was completed" [36]. Most of the maintenance actions for which parts were available when demanded had the same date for the When Discovered Date and Corrective Action Date. However, some of the records had large periods of time, some up to one year, between the When Discovered Date and the Corrective Action Date. Discussions with former Navy personnel indicate that the definition of when an action is complete differs. Some felt that the completion date is when the equipment becomes operational while others felt the action should not be closed until ship's spares were replenished. For the purposes of evaluating the system availability, it is assumed that the action is complete when the system becomes operational. As soon as the problem is corrected, the system becomes operational. Waiting for the part to arrive does not affect the availability of the system at that moment.

The data base was reviewed and the supply delay times were summed for all maintenance actions for each period that failures were reported. The average supply delay for each period was calculated as follows:

$$(5.1) \quad DELAY_{period} = \frac{\text{Total Delay Time}}{\text{Total Failures}}$$

The matrix containing the delay times and failures by period for each hull is contained in Appendix N.

The statistics for each time period were then plotted verses time as shown in Figure 19. The data points for this statistic are quite wide spread, with one third of the data above 300 hours and two thirds below 200.

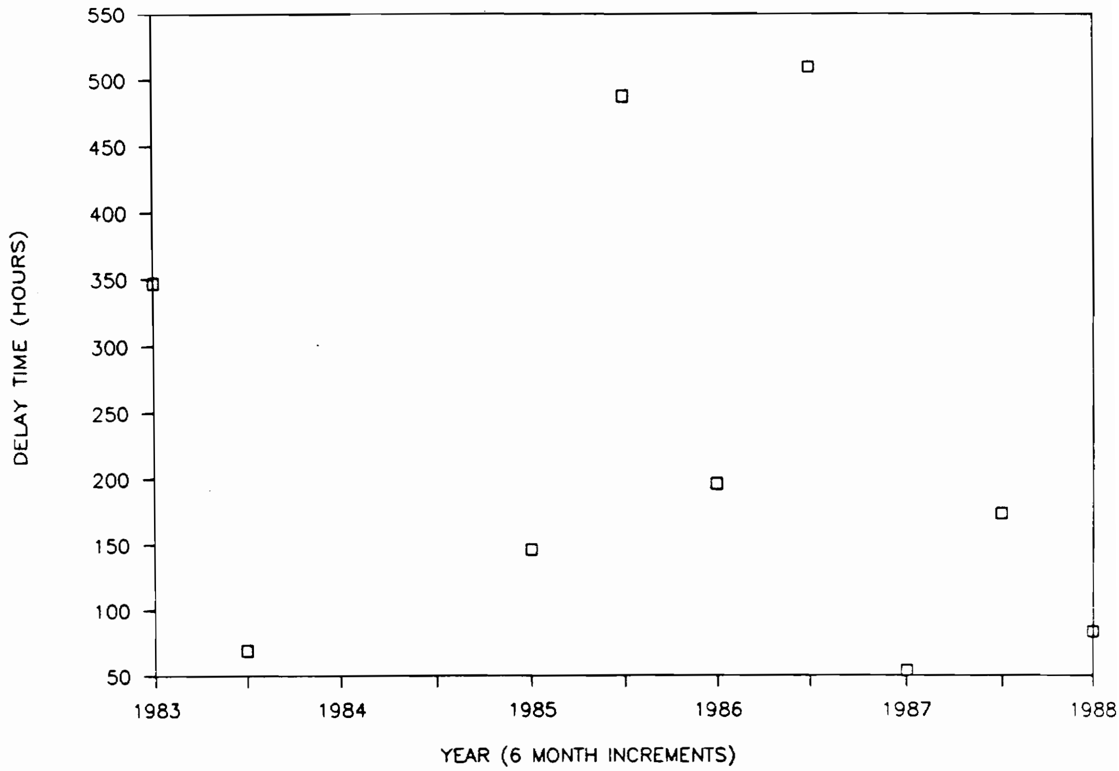


Figure 19. Delay Time Scatter Plot.

Outlier tests using the box plot were conducted and the results are contained in Appendix O. None of the points were considered to be outliers. Further analysis of the 3 points above 300 hours should be conducted to determine if the delays are in error or if they are actually that high.

The system delay time statistic was then calculated using the valid data points as follows:

$$(5.2) \quad DELAY_{system} = \frac{\text{Sum of all } DELAY_{period}}{\text{Total Number of Periods}}$$

The calculation of the Delay Time statistic yielded 230 hours with a 90% confidence interval of (120, 339) hours. The calculations were performed using MINITAB and the results are contained in Appendix P. The system does not have a specified delay time but uses a default value of 75 hours as a requirement. This default value was chosen so that the system Operational Availability calculation would achieve the specified value. It appears that the system is not currently meeting the specified delay time but since the data is so wide spread, a determination from the point statistic is difficult.

A hypothesis test was conducted to test the null hypothesis that the $DELAY_{system}$ statistic is equal to the specified value verses the alternative hypothesis that the $DELAY_{system}$ statistic is greater than the specified value. The test is based on the Student-t distribution since the sample size is small and the population variance is unknown [37]. A 99% confidence interval was chosen. The test was set up as follows:

(5.3) Null Hypothesis H_o: $DELAY_{system} = 75$

(5.4) Alternative H_1: $DELAY_{system} > 75$

(5.5) Decision Rule:

$$\text{Reject } H_o \text{ if } \frac{DELAY_{system} - 75}{s_x/\sqrt{n}} > t_{n-1,.010}$$

Where s_x is the standard deviation of the sample and n is the sample size which in this case is 9. The test statistic, which is the left side of the inequality in equation 5.5, was calculated using MINITAB and the result is shown as T in Appendix P. The test statistic is 2.63. The critical value of $t_{8,.010}$ is 2.896 [38]. Since the test statistic is less than the critical value of $t_{8,.010}$, the null hypothesis can not be rejected. This indicates there is not overwhelming evidence that the system delay time is greater than the specification. Therefore, it can not be determined that the delay time is out of specification. The point value determined will still be used in the remainder of the analysis since this is the value the available data provided.

Trend Analysis

A linear regression analysis was performed on the valid data points versus time. The Durbin-Watson test was performed to ensure there was not any correlation between the error terms for each time period.

The equation for the regression line and the Durbin-Watson statistic was calculated using MINITAB. The time period was selected as the independent variable and the Delay Time statistic was chosen as the dependent variable. The results are contained in Appendix P. The Durbin-Watson statistic is shown to be 2.54 which is close to 2.00 which indicates there is no correlation between the error terms. The slope of the regression line is negative which seems to indicate that the delay times are decreasing.

To determine if the data truly indicates a negative sloping line, the hypothesis test described by equations 3.4, 3.5, and 3.6 was conducted assuming a 95% confidence level and a Student-t distribution. The test statistic, which is shown as the t-ratio in Appendix P, is -0.46. The critical value of $-t_{7,.025}$ is -2.365 [39]. Since the test statistic is less than the critical value, the null hypothesis can not be rejected. This indicates that there is not sufficient evidence to indicate that the slope of the line is truly increasing. It is assumed the delay time remains constant over the time period analyzed. A plot of the valid data points and the constant trend line is shown in Figure 20.

Allocations

The allocation of the delay times to the subsystem level was done to identify specific subsystems that have delay problems. The delay time for each subsystem was calculated and then normalized to the system level statistic. The normalization had to be done because not all the maintenance actions could be identified to a subsystem.

The delay times associated with each subsystem was calculated as follows:

$$(5.6) \quad DELAY_{subsystem} = \frac{\text{Total Delay for Failures}}{\text{Total Failure Actions}}$$

To normalize the $DELAY_{subsystem}$ calculation, the mean of the $DELAY_{subsystem}$ values, called MEAN-DELAY, was calculated. This value was then used in conjunction with the system level delay time to make the subsystem allocated

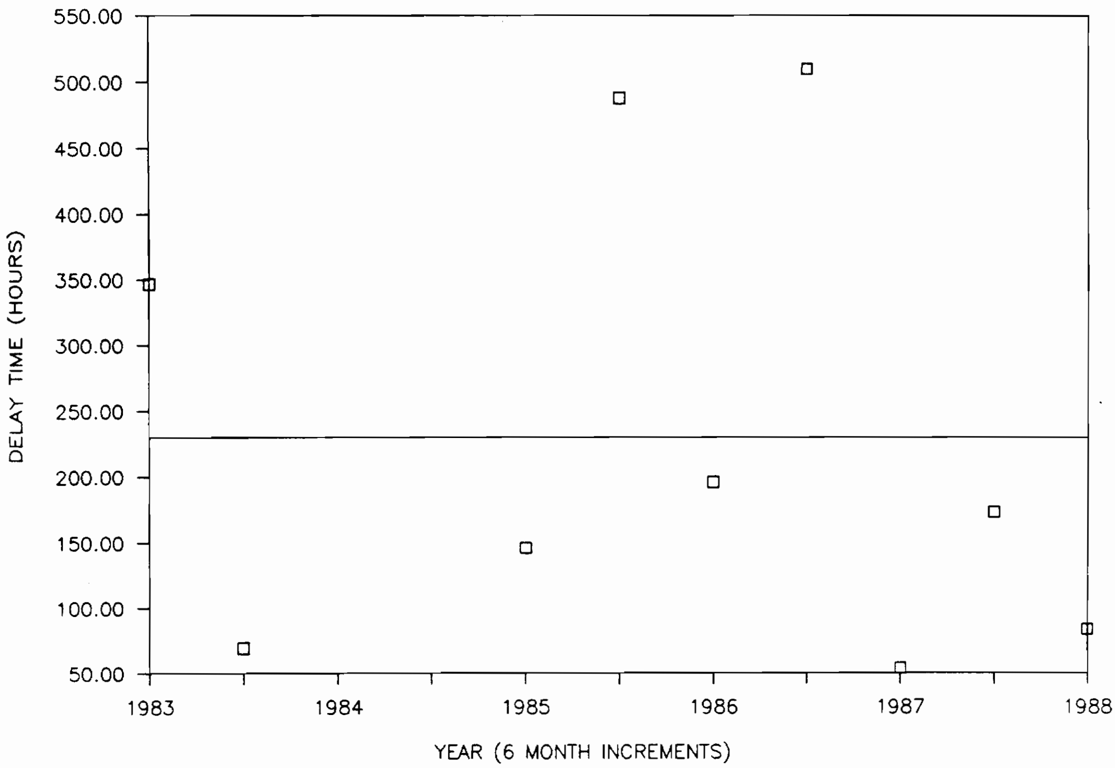


Figure 20. Delay Time Trend.

delay times equate to the system level delay times. The normalized delay times are called DELAY-NORM. These steps are as follows:

$$(5.7)\quad \text{MEAN DELAY} = \frac{\text{Sum of all DELAY}_{\text{subsystem}}}{\text{Number of Subsystems}}$$

$$(5.8)\quad \text{DELAY-NORM} = \frac{\text{DELAY}_{\text{system}}}{\text{MEAN-DELAY}} * \text{DELAY}_{\text{subsystem}}$$

Table 5 summarizes the results of the allocation process. Figure 21 is a bar graph of the delay times associated with each subsystem. The Towed Array, Passive Broadband, Classification and Preamplifier Subsystems all exceed the mean delay time of the system. The Towed Array subsystem has an extremely high delay time. This is expected since the towed array is external to the hull and can not be repaired by ships' force. Repairs have to be delayed until the ship returns to port or meets up with a tender. The other subsystems that exceed the system mean are all internal to the hull. The delays in these subsystems are most likely a result of delays associated with the Naval supply system. The ways to combat these delays are to either have the critical parts on board when demanded or increase the efficiency of the supply system.

TABLE 5

DELAY TIME ALLOCATIONS

SUBSYSTEM	TOTAL FAILURES	TOTAL DELAY TIME (hours)	SUBSYSTEM DELAY (hours)	DELAY-NORM (hours)
PREAMP	12	4470	373	284
POWER	5	892	178	135
TRANS	18	1358	75	57
RECVR	31	1846	60	46
PBB	37	16105	435	331
CLASS	36	14738	409	311
CMPTR	10	2719	272	207
PMFL	10	919	92	70
DISP	135	27008	200	152
XDUCER	3	482	167	127
TARR	6	6381	1064	810
TOTAL	**303**	**76918**	**3325**	**2530**
MEAN			**302**	**230**

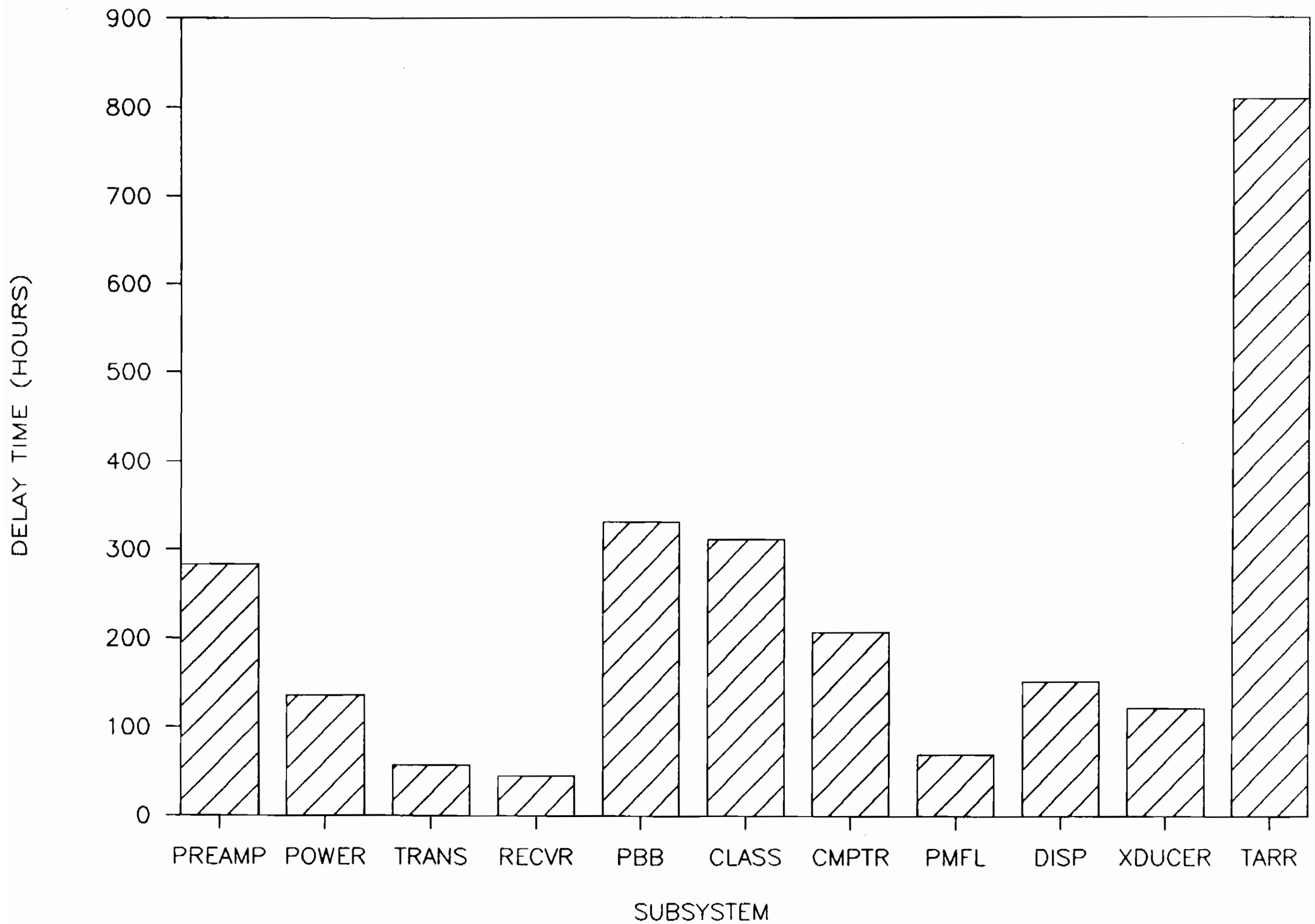


Figure 21. Delay Time Allocation.

Parts Available for Failures

Introduction

The Parts Available for Failures statistic is analyzed to determine if there is adequate sparing of critical parts. Of particular interest is the relationship between the Parts Available for Failures and the supply delays associated with each subsystem. A comparison of the two statistics may reveal particular problem areas in terms of sparing or supply system problems.

System Level Statistic

The Source Replacement Codes in the master data base were reviewed for the maintenance actions associated with failures. For each hull and time period that failures were reported, the number of maintenance actions for which the Source Replacement Code identified that a part was available (a code of A, B, or C) were counted. The total number of failures and parts available were summed for each time period. The Parts Available for Failures for each time period was calculated as follows:

$$(5.9)\quad AVAIL_{period} = \frac{\text{Total Parts Available for Failures}}{\text{Total Failures}}$$

The matrix containing the total failures and parts available for each hull during each reporting period along with the Part Available for Failures statistic for each time period is contained in Appendix Q.

The statistics for each time period were then plotted versus time as shown in Figure 22. From the plot in Figure 22, there does not appear to be any outliers. Outlier tests were performed using a box plot and the results are contained in Appendix R. As expected, none of the data points were found to be outliers.

The system statistic for the Parts Available for Failures was calculated as follows:

$$(5.10)\quad AVAIL_{system} = \frac{\text{Sum of all } AVAIL_{period}}{\text{Total Number of Periods}}$$

The system statistic for the Parts Available for Failures was calculated to be 0.76 with a 90% confidence interval of (.71, .81). This indicates that 76% of all maintenance actions related to failures had parts on board to correct the failures. The 90% confidence interval is small so the point estimate is assumed to be reasonable. The MINITAB output of the calculations is shown in Appendix S. There

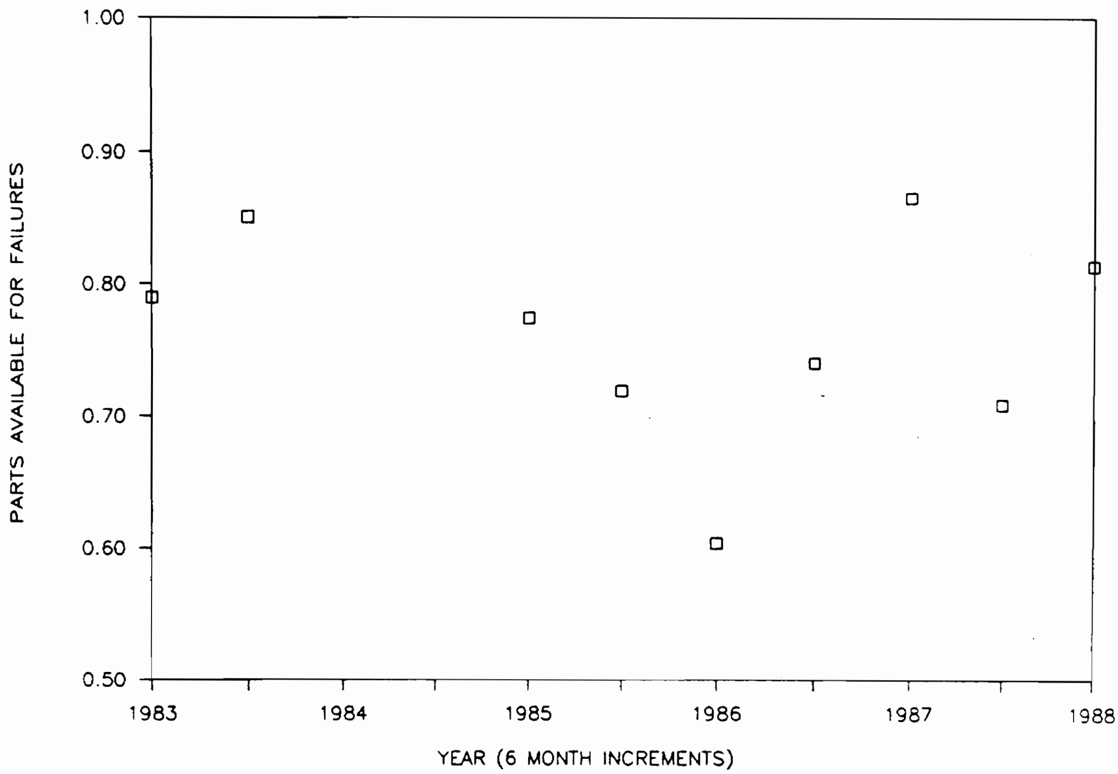


Figure 22. Parts Available for Failures Scatter Plot.

is no specified value for this statistic.

Trend Analysis

A linear regression analysis was performed on the data versus time using MINITAB. The Durbin-Watson test was performed to ensure there was no correlation amongst the error terms. The time period was selected as the independent variable and the Parts Available for Failures was chosen as the dependent variable. The output from MINITAB is contained in Appendix S. The Durbin-Watson statistic was 1.84 which is close to 2.00 which indicates there is no correlation amongst the errors over time. The regression equation in Appendix S indicates a slightly decreasing trend over time.

A test of the null hypothesis that the slope is 0 against the alternate hypothesis that the slope is not 0 was conducted in accordance with equations 3.4, 3.5 and 3.6. A 95% confidence interval and the Student-t distribution was assumed. The test statistic, shown as the t-ratio in Appendix T, was -0.46. The critical value for $t_{7,.025}$ is -2.365 [40]. Since the test statistic is greater than the critical value for $t_{7,.025}$, the null hypothesis can not be rejected. There is not overwhelming evidence that the slope of regression line is negative.

Based on this analysis, it is assumed the Parts Available for Failures is constant over time. A plot of the valid data points and the constant trend is shown in Figure 23.

Allocations

The system level statistic for Parts Available for Failures was allocated to the subsystems. The master data base was reviewed and the total parts available and total maintenance actions for failures for each subsystem were counted. The percentage of parts available for each subsystem was calculated as follows:

$$(5.11)\quad AVAIL_{subsys} = \frac{\text{Total Parts Available for Failures}}{\text{Total Failure Actions per Subsystem}}$$

Since not every maintenance event could be identified to the subsystem level, the statistic for each subsystem was normalized to the system level statistic. The normalization process followed the same procedure as used for the allocation of the delay times. The equations used are as follows:

$$(5.12)\quad \text{MEAN AVAIL} = \frac{\text{Sum of all } AVAIL_{subsys}}{\text{Number of Subsystems}}$$

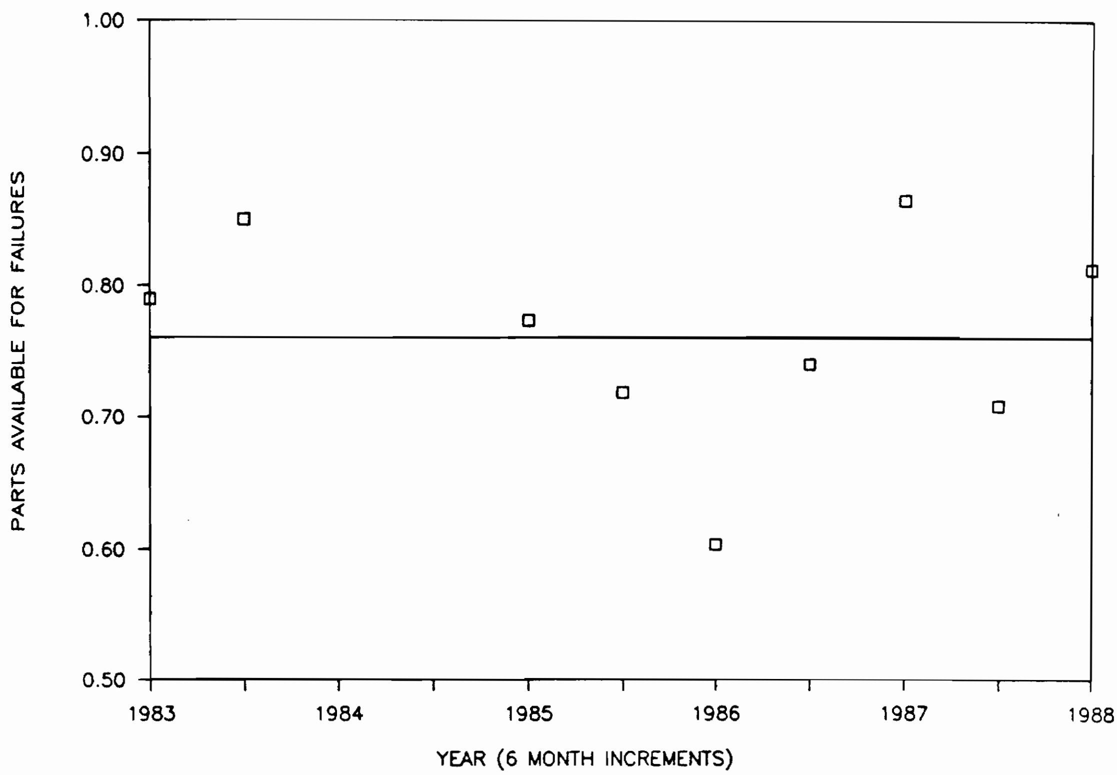


Figure 23. Parts Available for Failures Trend.

$$(5.13)\quad \text{AVAIL-NORM} = \frac{\text{AVAIL}_{system} * \text{AVAIL}_{subsys}}{\text{MEAN AVAIL}}$$

Table 6 summarizes the results of the allocation process. A bar chart of the normalized subsystem percentage of parts available for failures is shown in Figure 24. The Transducer Subsystem had no parts available on demand which is expected since the transducers are located outside the hull and are only replaced by a shore based facility. The Preamplifier Subsystem had a much lower percentage of parts available on demand for failures than the other subsystems. The rest of the subsystems had at least 80% of the parts available required to repair items that cause failures. Before looking at the relationship between the Parts Available for Failures and Delay Times, the statistic for the Parts Available for Faults was analyzed.

Parts Available for Faults

Introduction

The Parts Available for Faults statistic was analyzed to determine if there was excessive sparing of items that are not required for the system to remain in an operational status. The results of the allocation of this statistic

TABLE 6

PARTS AVAILABLE FOR FAILURES ALLOCATIONS

SUBSYSTEM	TOTAL FAILURES	PARTS AVAILABLE	PERCENT AVAILABLE SUBSYSTEM (%)	PERCENT AVAIL-NORM (%)
PREAMP	12	6	50	59
POWER	5	4	80	95
TRANS	18	14	78	92
RECVR	31	22	71	84
PBB	37	25	68	80
CLASS	36	27	75	89
CMPTR	10	7	70	83
PMFL	10	7	70	83
DISP	135	104	77	91
XDUCER	3	0	0	0
TARR	6	4	67	79
TOTAL	**303**	**220**	**706**	**835**
MEAN			**64**	**76**

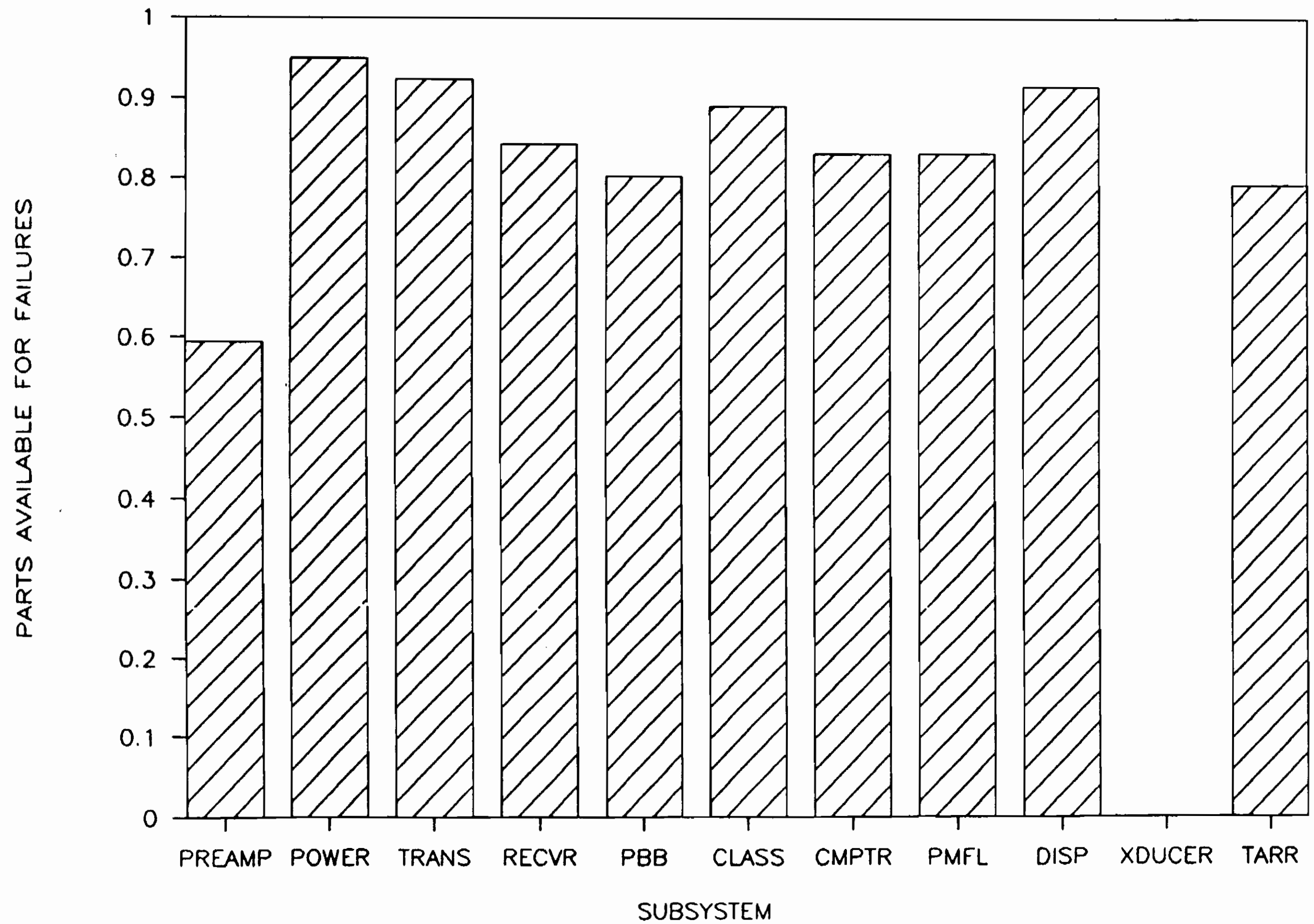


Figure 24. Parts Available for Failures Allocation.

will be compared with the results of the allocation of the Parts Available for Failures statistic to determine if there are problem areas in the sparing of subsystems.

System Level Statistic

The Source Replacement Codes in the master data base were reviewed for the maintenance actions associated with faults only. The statistic for each period was calculated as follows:

$$\text{(5.14)} \quad \text{FLT-AVAIL}_{\text{period}} = \frac{\text{Total Parts Available for Faults}}{\text{Total Faults}}$$

The matrix containing the total faults and parts available for each hull during each reporting period along with the percentage available statistic for each time period is contained in Appendix T.

The statistics for each time period were then plotted versus time as shown in Figure 25. From the plot in Figure 25, there does not appear to be any outliers. Outlier tests were performed using a box plot the results are contained in Appendix U. As expected, none of the data points were found to be outliers.

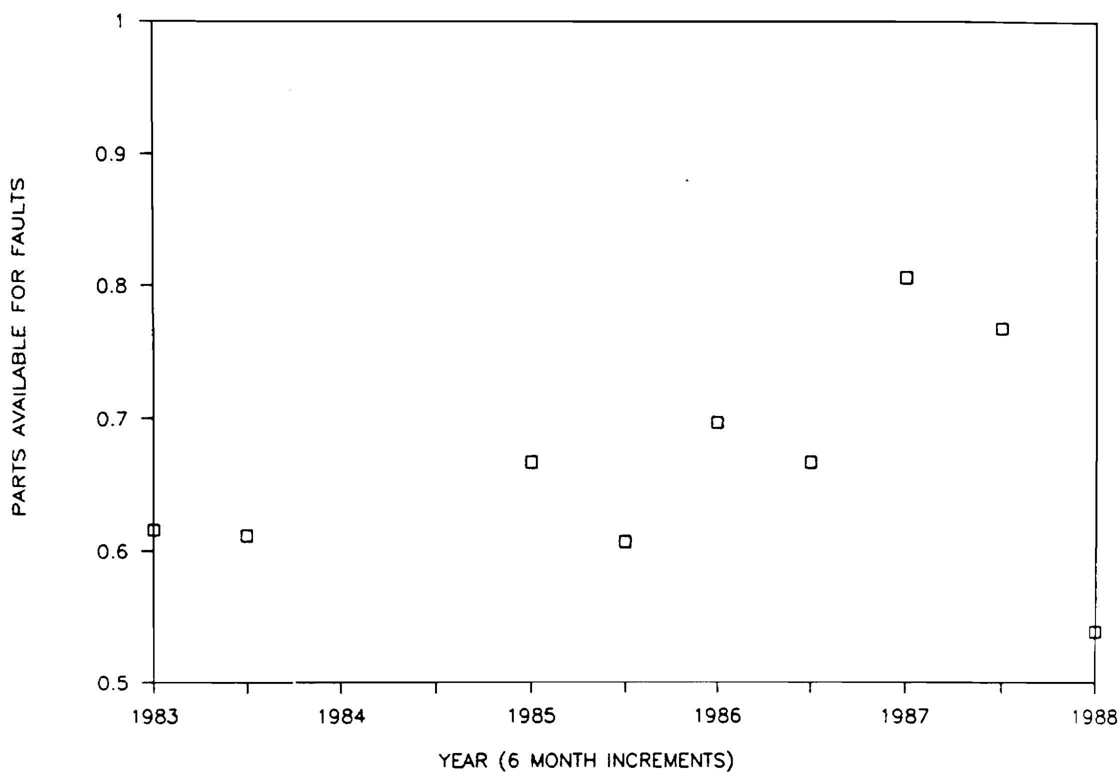


Figure 25. Parts Available for Faults Scatter Plot.

The system level statistic was calculated as follows:

$$(5.15) \quad \text{FLT-AVAIL}_{\text{system}} = \frac{\text{Sum of all FLT-AVAIL}_{\text{period}}}{\text{Total Number of Periods}}$$

The mean system level statistic for the percentage of parts available when demanded for faults is 0.67 with a 90% confidence interval of (.60, .73). This is shown as part of the MINITAB analysis in Appendix V. This indicates that 67% of all faults have replacements available on the submarine. The confidence interval is narrow which indicates the point estimate reasonable. There is no specified value for this statistic.

Trend Analysis

A linear regression analysis was performed on the data points versus time. The regression line and Durbin-Watson statistic were calculated using MINITAB. The time period was the independent variable and the Parts Available for Faults statistic was the dependent variable. The time periods were assigned in the same manner as the previous trend analyses. The Durbin-Watson statistic is shown to be 1.75 which is close to 2.00 which indicates there is no correlation between the error terms and time. The MINITAB output is contained in Appendix V.

The MINITAB output contained in Appendix V indicates that there is one point that has a large standard residual. This point has a strong influence on the calculation of the linear regression line. The point in question is the statistic for 1988. As can be seen from the scatter plot in Figure 25, this point does not seem to follow the general trend of the previous years. Since it is the last point in the time series, it is difficult to determine if there has been a drastic change in the sparing or if the point is just low as a result of the reporting. In order to properly evaluate the general trend over the last seven years, this data point was deleted and the regression analysis was performed again. The results are contained in Appendix W.

The Durbin-Watson statistic in this case was 2.33 which indicates there is no correlation amongst the errors. The regression equation indicates that there is an increasing trend in the Parts Available for Faults statistic. A test of the null hypothesis that the slope is 0 against the alternate hypothesis that the slope is not 0 was conducted in accordance with equations 3.4, 3.5 and 3.6. A 95% confidence interval and the Student-t distribution was assumed. The test statistic, shown as the t-ratio in Appendix W, was 3.27. The critical value for

$t_{6,.025}$ is 2.447 [41]. Since the test statistic is greater than the critical value for $t_{6,.025}$, the null hypothesis can be rejected. There is overwhelming evidence that the slope of regression line is positive. Based on this analysis, it is assumed the percentage of parts available on demand for faults is increasing over time. A plot of the data points used and the regression equation is shown in Figure 26.

Allocations

The allocation of the system level statistic to the subsystems for the parts available for faults statistic was accomplished using the same methodology as for the Parts Available for Failures statistic. The percentage of parts available for each subsystem was calculated as follows:

$$\text{(5.16)} \quad \text{FLT-AVAIL}_{subsys} = \frac{\text{Total Parts Available for Faults}}{\text{Total Fault Actions per Subsystem}}$$

This statistic was normalized as follows:

$$\text{(5.17)} \quad \text{MEAN FLT-AVAIL} = \frac{\text{Sum of all FLT-AVAIL}_{subsys}}{\text{Number of Subsystems}}$$

$$\text{(5.18)} \quad \text{FLT-AVAIL-NORM} = \frac{\text{FLT-AVAIL}_{system} * \text{FLT-AVAIL}_{subsys}}{\text{MEAN FLT-AVAIL}}$$

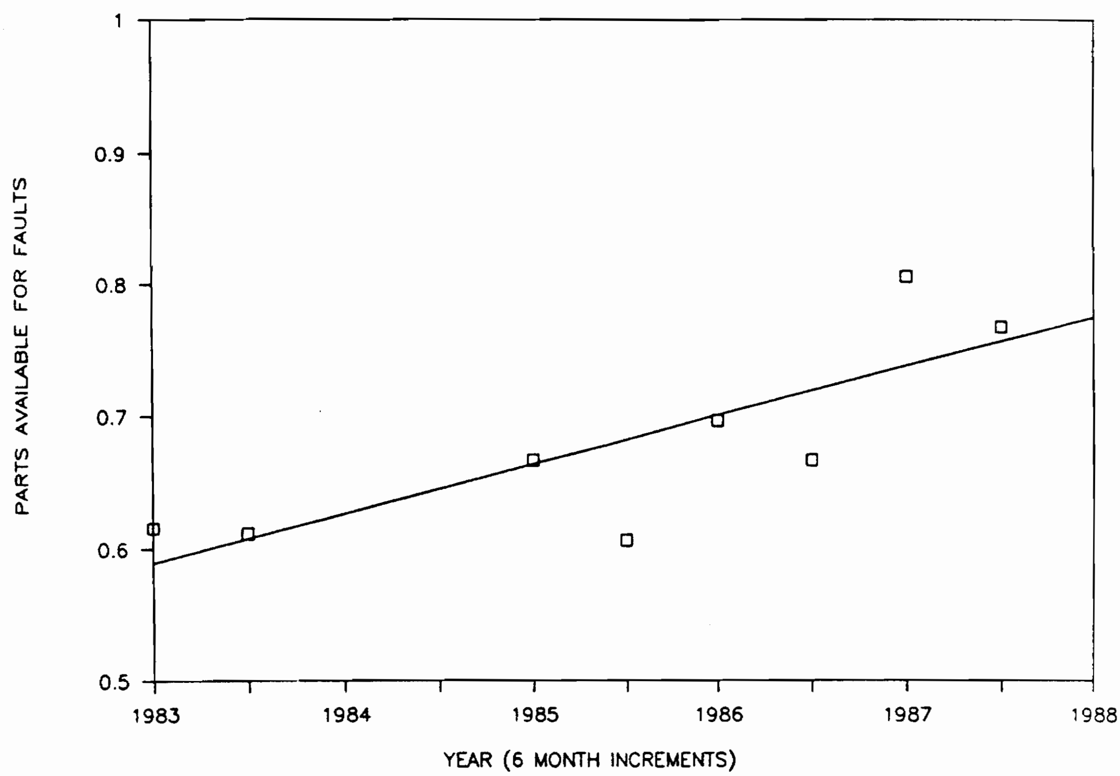


Figure 26. Parts Available for Faults Trend.

The results are shown in Table 7. A bar chart of the normalized Parts Available for Faults statistic for each subsystem is shown in Figure 27. The area of concern in this particular analysis are those subsystem that have a Parts Available for Faults statistic that exceeds the system level statistic. The only subsystems that are under the system level statistic are the Preamplifier, Computer, Transducer and Towed Array Subsystems. This statistic indicates that most of the subsystems have excessive sparing of parts that are not required to maintain the system in an operational condition.

Trend Analysis Comparison

The trend analysis of the statistics for the Parts Available for Failures and Parts Available for Faults provided unexpected results. The Parts Available for Failures trend was constant over time while the Parts Available for Faults trend was improving over time. One would hope that just the opposite was true. Since it is the failures that affect the availability of the system, the emphasis should be on providing as many parts as possible on the submarine to correct failures so that the delay times can be reduced. The system manager has made a conscious effort to increase the sparing of this system to reduce logistics delay times

TABLE 7

PARTS AVAILABLE FOR FAULTS ALLOCATIONS

SUBSYSTEM	TOTAL FAILURES	PARTS AVAILABLE	PERCENT AVAILABLE SUBSYSTEM (%)	PERCENT AVAIL-NORM (%)
PREAMP	12	4	33	37
POWER	11	9	82	92
TRANS	19	16	84	94
RECVR	26	20	77	86
PBB	32	25	78	87
CLASS	32	20	63	70
CMPTR	3	1	33	37
PMFL	20	16	80	89
DISP	95	73	77	86
XDUCER	7	0	0	0
TARR	8	4	50	56
TOTAL	**265**	**188**	**657**	**734**
MEAN			**60**	**67**

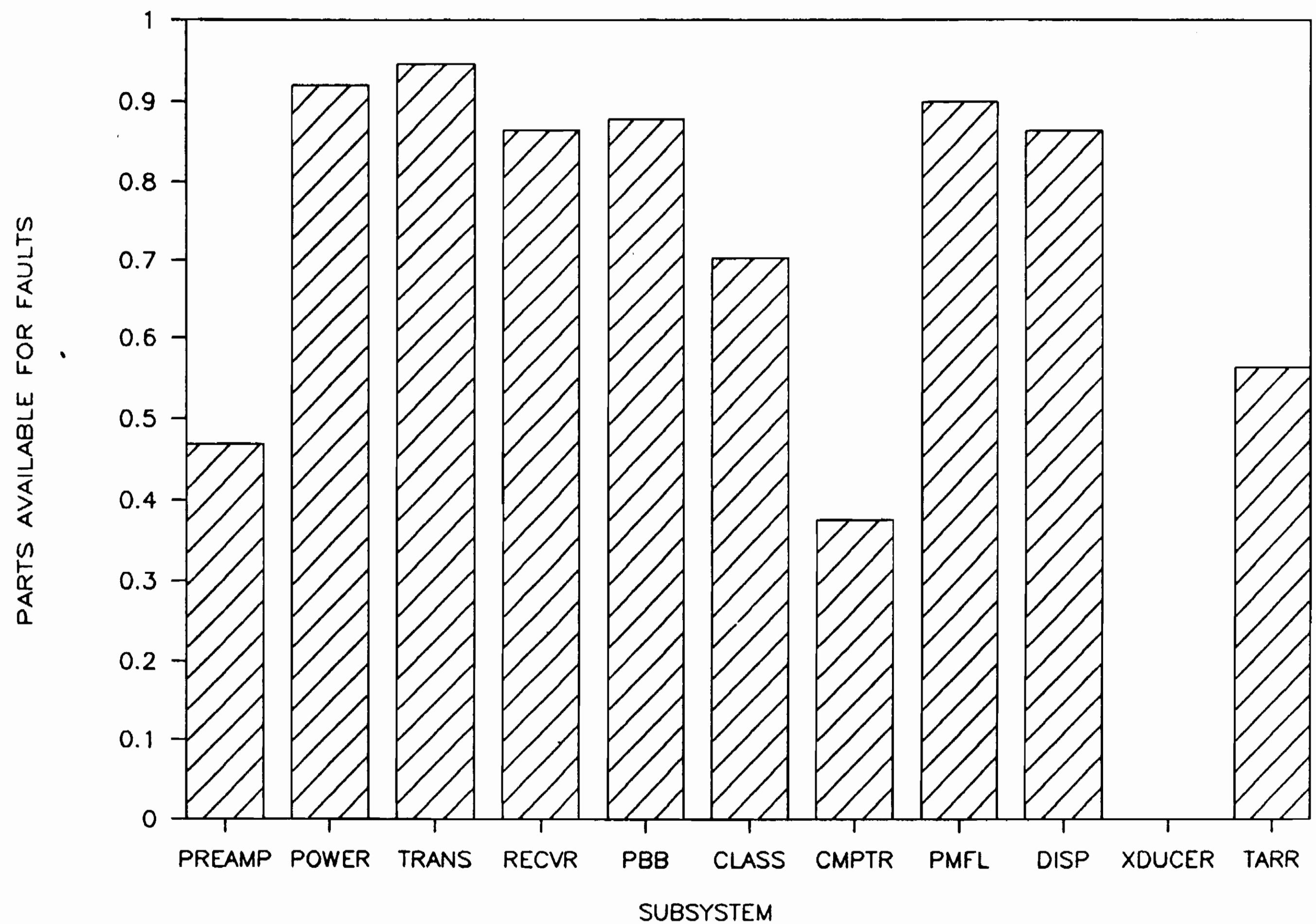


Figure 27. Parts Available for Faults Allocation.

associated with the Navy supply system. However, the data indicates that the increase in sparing has had little or no affect on the Parts Available for Failures statistic. This explains why the delay times did not decrease as was expected when the quantity of spare parts was increased on the submarine.

CHAPTER 6

OPERATIONAL AVAILABILITY ANALYSIS

Introduction

The chapter will determine the system Operational Availability based on equation 1.1 and using the results obtained in Chapters 3 through 5. A system level statistic will be developed and a trend analysis will be performed using data based on the linear regression models developed in the previous chapters.

System Level Statistic

It is very important to understand that when a fault has occurred in the system, it is still operating satisfactorily. The system has not lost any capability. Failures result in a loss of capability which results in an unsatisfactory operating condition. For this reason, only statistics related to failures are used in the Operational Availability analysis.

Table 8 contains a summary of the mean, best case and worst case values for each of the statistics used for the A_o calculation. The best case and worse case values are

TABLE 8

OPERATIONAL AVAILABILITY SUMMARY

	MTBF (hours)	MTTR (hours)	DELAY (hours)	A_o
MEAN	828	4.46	230	0.78
WORST CASE	759	5.97	339	0.68
BEST CASE	896	2.94	120	0.88

based on the 90% confidence intervals for the MTBF, MTTR and DELAY statistics calculated in the previous chapters. This results in a mean A_o of .78 with a worst case value of .68 and a best case value of .88. It is assumed the true A_o falls within this range. The specified A_o is .95. The data indicates that the system is not currently achieving its specified A_o.

Trend Analysis

The Operational Availability trend analysis was performed by using the results of the regression analyses from the statistics that make up equation 1.1. Table 16 in Appendix X contains the statistics for each time period as determined by the regression analysis performed for each statistic. The resultant plot of the Operational Availability verses time is shown in Figure 28. This plot shows the Operational Availability is improving slowly over time but is far below the specified Operational Availability. The trend is what was expected since the MTBF statistic was improving over time while the MTTR was increasing the and Delay Times was constant. The slow improvement is a result of the significant improvements in the MTBF statistic being offset by the increasing MTTR statistic.

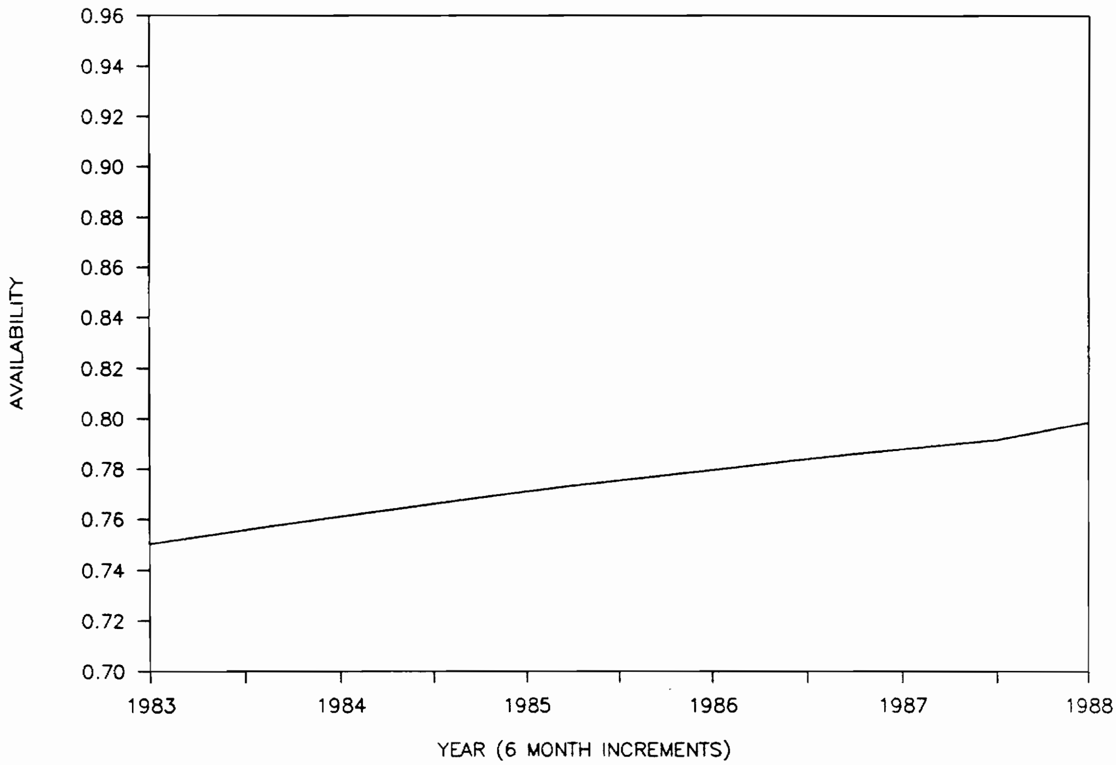


Figure 28. Operational Availability Trend.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

Availability Comments

To increase the overall Operational Availability of the system to the specified level, there must be a coordinated effort to improve the Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR) and Delay Time. Since all three statistics combine to calculate the Operational Availability, they need to be looked at together and not individually. The Operational Availability can be met without meeting all of the specified values of the parameters that make up the statistic.

One of the problems the Navy has in trying to reach a specified Operational Availability is that when the systems are designed, very little attention is paid to the actual logistics and administrative delay times associated with the Naval Supply System. The Navy always specifies a MTBF and MTTR that contractors must adhere to. However, when an Operational Availability is required for Navy testing of the system, they logistics delay times are specified to make the calculation equate to the specified value. More thought should be given to what the actual delays are before determining what MTBF and MTTR a contractor is required to meet.

Specific Recommendations

Design Changes

Despite the fact that the MTBF is improving over the study period, the analysis has shown that the Display Subsystem is experiencing a majority of the system failures. This subsystem is not exhibiting any major problems in the MTTR and Delay Time statistics. Therefore, a redesign of the Display Subsystem, with considerations of the sparing and maintainability parameters, should be accomplished. This redesign should have a significant impact on the system MTBF which will in turn improve the system Operational Availability.

The Towed Array Subsystem was found to have an extremely high MTTR when compared with the other subsystems. This subsystem is currently serviced by intermediate shore maintenance activities. The repair is accomplished by replacing the entire towed array with a refurbished towed array. The time consuming portion of the repair cycle is that the array has to be carefully unwound and then the replacement array has to be wound up. To reduce this time, a feasibility study on a possible redesign of the towed array handling system should be considered. The redesign would be from a maintainability standpoint and should focus on ways to remove and install the towed array without having to unwind the entire array to replace it. Problems to be overcome include the location of the handling system and the weight of the array. The location of the handling system is in the ballast tanks which limits space available to work and may preclude removal of handling systems. Also, the towed array and handling systems weigh in excess on one ton which may cause difficulties in removal. This redesign could significantly reduce the MTTR of the system but may not feasible or cost affective to accomplish, especially since the MTTR statistic has a lower impact on the Operational Availability calculation when compared with the MTBF and Delay Times.

Supportability Improvements

The Delay Time associated with the Towed Array Subsystem is also high when compared with the other subsystems. This is because of the fact that the array can only be serviced by an intermediate facility and the ships' mission dictates when the system can be serviced. The only way to reduce the delay associated with this problem is to have the towed array be serviceable by ships' force which is not feasible due to the location of the array and handling system.

An area of concern in the supportability area is subsystems that have a high delay time and also a high percentage of Parts Available for Failures statistic. This indicates that for the few parts required that are not on the submarine, the Navy Supply System is extremely slow in responding to the requisition. The subsystems that exhibit this problem are the Passive Broadband and Classification Subsystems. Both of these subsystems have Delay Times in excess of 300 hours combined with a Parts Available for Failures statistic in excess of 80%. What is also interesting is that these subsystems also have a high percentage of Parts Available for Faults statistic. A short term solution would be to reevaluate the sparing associated with these subsystems to determine if adjustments can be made to increase the number of parts to repair failures and decrease the number of parts to repair faults. The total sparing level would remain unchanged but by having more parts available for failures, the delays related to the Navy Supply System would be decreased.

The Preamplifier Subsystem exhibits a delay time of approximately 300 hours and has a low percentage (60%) of Parts Available for Failures. In this case, the delay time is due to the fact the sparing in this subsystem is inadequate. The sparing levels for failure items should be increased. The sparing level for Parts Available for Faults is already low so sparing trade-offs with other subsystems should be conducted so the total system sparing level does not increase. The increase in sparing for failure items in this subsystem will reduce the delays associated with the Navy Supply System.

It is also recommended that the sparing level of the whole system be examined. The percentage of Parts Available for Faults was shown to be increasing over time while the percentage of Parts Available for Failures remained constant. This indicates that the increased sparing levels had no affect on the system performance. This increase in the sparing of parts to correct faults also manifests itself in the allocation of the parts to the subsystem levels. The percentage of parts available for faults for most of the subsystems is in excess of 80%. This is another indication of excessive sparing of parts that do not affect system performance. In addition to having little affect on the overall system performance, excessive sparing is expensive and takes up valuable space on the submarine. The entire sparing of the system should be reevaluated. Proper sparing of cards that contribute to the down time of the system will help reduce delays related to the Naval Supply System. The total number of spares can be reduced and still increase the Operational Availability of the system.

Repair Time Improvements

As mentioned in Chapter 4, there have been no apparent changes in the system that would impact the Mean Time To Repair of the system. The increasing trend of this statistic is of concern. It is recommended that the Navy reevaluate the training curriculums and instructors to ensure that the maintenance courses are being properly taught. The Navy should also make sure that all of the maintenance technicians assigned to the system have had proper training. Since there is no system changes that would affect this statistic, training must be evaluated to determine if it is the cause of the problem.

Future Studies

Since the Navy Supply System is a major contributor to the Operational Availability statistic in terms of logistics delays, it is recommended that the current system be evaluated and improvements recommended. This will require a coordinated effort by the system manager and the

Ships Parts Control Center (SPCC). A complete understanding of the roles of the system manager and SPCC and the problems each of the organizations face (budget constraints, competition, lead time, etc.) is required by both parties for any changes to be successful.

It is also recommended that an attempt be made to allocate the statistics down to the unit level to determine if there are specific units that are driving the statistics. The problem encountered with doing this is that the current reporting requirements do not require that a unit or a subsystem be identified for each maintenance action. Only through the reading of the narratives is the information identified. The Navy should look at adding additional reporting requirements to the OPNAV 4790/2K form. The form could remain as is and the instructions could be changed to require the unit be reported in the narrative. This change, along with informing the sailors that the reports they generate are analyzed, will help to better locate specific problem areas.

It is recommended that this report be updated semiannually to include the latest reporting period. The older data could be dropped as new data is added. This would be especially useful in assessing the impact of any recommendations that are implemented.

This study used the aggregation of large amounts of data for analysis. It is recommended that a follow-on study be conducted that does not aggregate the data. Utilization of different techniques may confirm or contradict the findings in this report.

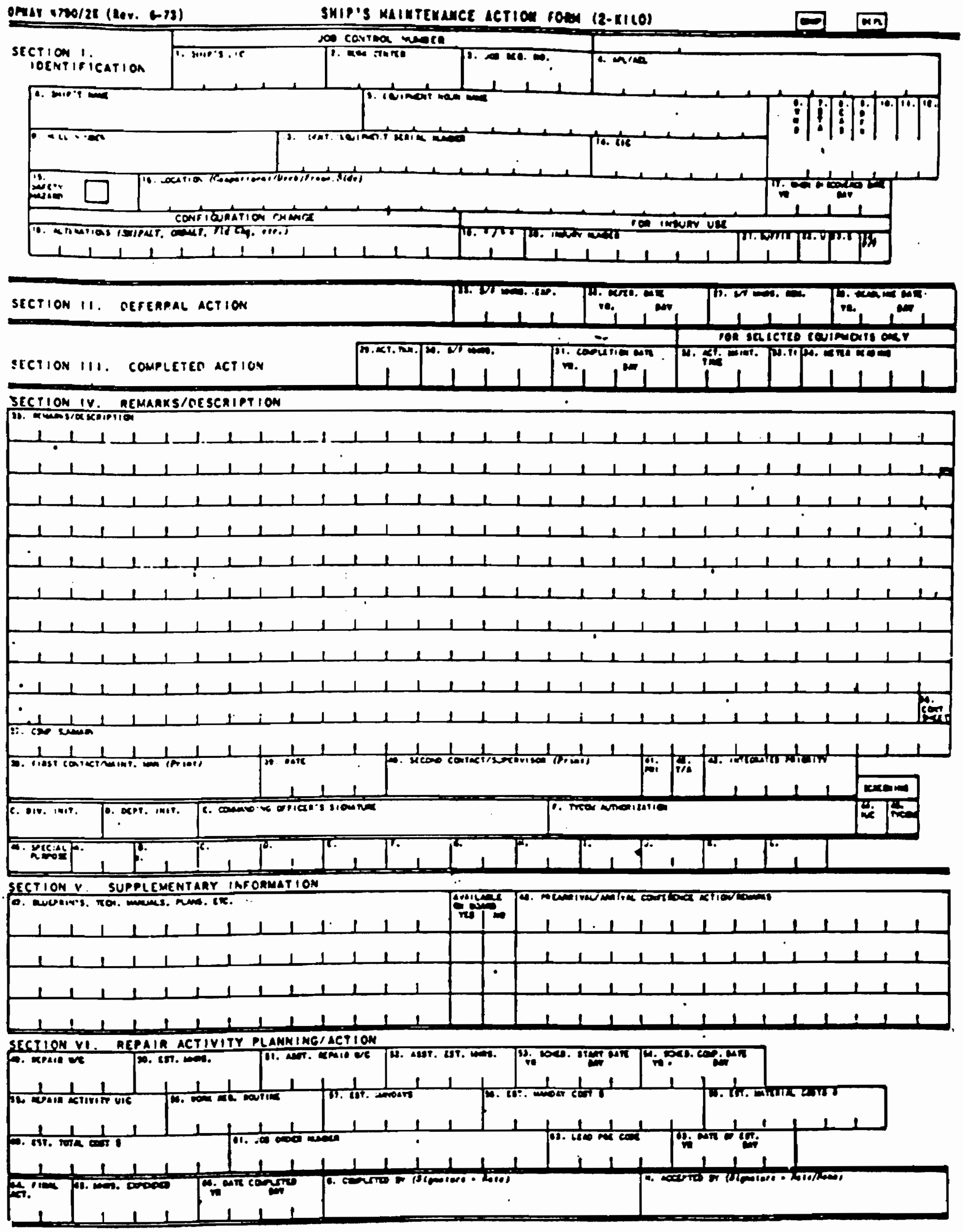
Summary

This analysis showed that based on data obtained form the fleet, the system is not currently meeting its' specified Operational Availability. The study did point out specific areas that are having a negative impact on the system Operational Availability and recommended possible avenues to pursue to correct the problems. The recommendations provided do not guarantee the system will the meet the specified Operational Availability. These recommendations provide a starting point for improvement and only through continued monitoring and analysis will the system meet and maintain the specified Operational Availability.

APPENDIX A

SAMPLE OPNAV 4790/2K FORM

This appendix contains a sample of the form that the maintenance technicians fill out and submit to the Navy Ships Parts Control Center for every maintenance action performed.


OPNAV 4790/2K (Rev. 6-73)

SHIP'S MAINTENANCE ACTION FORM (2-KILO)

SECTION I. IDENTIFICATION

JOB CONTROL NUMBER

CONFIGURATION CHANGE

FOR INSURV USE

SECTION II. DEFERRAL ACTION

FOR SELECTED EQUIPMENTS ONLY

SECTION III. COMPLETED ACTION

SECTION IV. REMARKS/DESCRIPTION

SECTION V. SUPPLEMENTARY INFORMATION

SECTION VI. REPAIR ACTIVITY PLANNING/ACTION

Figure 29. Sample OPNAV 4790/2K, Ships Maintenance Action Form.

APPENDIX B

MASTER DATA BASE SAMPLE

This appendix contains a sample of the data in the master data base. The entire data base is too large to include in this report and would not provide any pertinent information required for the reader to understand this analysis.

TABLE 9

SAMPLE FROM MASTER DATA BASE

SUIC	JSN	WDD	CAD	WDS	DFR	ACT	MHRE	AMT	SRC	SUBSYS	NARR
05115	0794	85312	85312	1	0	1	12	8	A	DISP	ZJS CARD IN LOCATION 168C2D39 FOUND BAD
05115	0861	86002	86008	1	0	1	2	2	A	TRANS	MOD DRIVER 17A28 FOUND FIRING INTERMITTENTLY. REPLACED WITH PART DRAWN FROM SUPPLY
05115	0862	85364	86005	1	0	1	4	2	A	PREAMP	UNIT 4 DISPLAY WENT BAD. CIRCUIT CARD 4A1A21 FOUND BAD. REPLACE WITH PART FROM SUPPLY.
05115	0865	86010	86010	1	0	1	2	2	A		BRUSH FOUND BAD. REPLACED WITH PART FROM SUPPLY.
05115	0867	86015	86016	3	0	1	2	2	A	TRANS	MOD DRIVER 15A26 NOT FIRING. REPLACED WITH PART FROM SUPPLY.
05115	0886	86118	86118	1	0	1	20	2	A	DISP	DURING OPERATION OF UNIT 123, NUMEROUS LOCKOUTS OCCURRED.
05115	0897	86098	86098	2	0	1	4	2	A	DSIP	POWER SUPPLY 123D/P53 FOUND BAD. REPLACED WITH PARTS FROM SUPPLY.
05115	0898	86099	86115	3	0	1	6	2	K		TRANSDUCER LOCATIONS T-39 AND T-40 FOUND DEFECTIVE.
05115	1007	87076	87077	1	0	1	10	10	A	TRANS	INVERSE COMP BRUSHES IN B12-37, B12-38, B12-4, B12-5, B12-2, B11-5, B11-2 WERE FOUND BAD
05115	1065	87244	87244	3	0	1	2	2	A	PBB	UNIT 113 POWER SUPPLY FOUND BAD DURING NORMAL OPERATION. REPLACED WITH PART FROM SUPPLY.
05115	1073	87253	87253	1	0	1	2	2	A	TRANS	WHILE RUNNING FC4024 MOD DRIVERS 12A3, 13A17, 15A28 WERE FOUND BAD.
05121	0159	86034	86039	1	0	1	20	20	J	DISP	UNABLE TO ADJUST 700 VOLT POWER SUPPLY ON 123A1A1. REPLACED 123A1A1.
05121	0190	86147	86149	3	0	1	4	4	A	DISP	UNABLE TO CALIBRATE CURSOR. REPLACED ASSEMBLY 169B1Z22 WITH PART FROM SUPPLY.
05121	0214	86239	86240	1	0	1	5	3	A	PBB	FOUND BAD POWER SUPPLY IN UNIT 113. REPLACED ASSEMBLY 113A1PS5.
05121	0249	87058	87058	3	0	1	3	3	A	DISP	FOUND BAD 123A1A2A2 CARD. REPLACED WITH PART FROM SUPPLY.
05121	0253	87072	87072	1	0	1	2	2	A	PBB	FOUND BAD SMV CARD 111A1B23. REPLACED WITH PART FROM SUPPLY.
05121	0255	87075	87075	3	0	1	1	1	A	CLASS	UNIT 119 POWER SUPPLY FAILED DURING NORMAL OPERATION. REPLACED WITH PART FROM SUPPLY.
05121	0257	87082	87082	1	0	1	3	3	A	DISP	FOUND BAD CURSOR POT 169B1Z2. REPLACED WITH PART FROM SUPPLY.
05121	0265	87112	87112	3	0	1	2	2	A	DISP	FOUND UNIT 169 LOWER GRAPHICS BAD. FOUND 169AA2A2A7 FAULTY.
05121	0266	87112	87112	3	0	1	4	2	A	PBB	DURING NORMAL OPERATION LOST DATA. FOUND 115PS1 FAULTY. REPLACED PART FROM SUPPLY.
05136	1893	85341	85341	1	0	1	3	2	A	DISP	FOUND POWER SUPPLY 169DPS3 BAD. REPLACED WITH PART FROM ON BOARD SUPPLY.
05136	1895	85342	85342	1	0	1	8	6	A	PMFL	FOUND CIRCUIT CARD 124A1A14 FAULTY. REPLACED WITH ON BOARD SUPPLY PART.
05136	1900	85342	85343	1	0	1	6	3	K	DISP	169C2D11 ZJS CARD FOUND BAD.
05136	1901	85342	85343	1	0	1	6	1	K	RECVR	CIRCUIT CARD 116B4A20 FOUND BAD. REPLACE WITH PART FROM SUPPLY.
05146	0373	83037	83132	3	2	0	3	3	J	CLASS	UNIT 129 SWITCHES 129A6A4 AND 129A6A5 FAULTY. REQUISITION NUMBER 33164/4195.
05146	0445	83144	83144	3	0	1	1	1	A	DISP	FAULT GROUP 23028 IN FL-5310. REPLACED 927 PAGE IN UNIT 123 LOWER.
05146	0454	83163	83177	3	0	1	1	1	K	DISP	PHOSPHER BURNED 168168A1 CAUSING DEGRADATION. REPLACE WITH PART FROM SUPPLY REQUISITION NO 3164/4195.

APPENDIX C

MEAN TIME BETWEEN CORRECTIVE MAINTENANCE MATRIX

This appendix contains a matrix of the number of maintenance actions and operating hours for each submarine for each time interval that actions were reported.

TABLE 10
MEAN TIME BETWEEN CORRECTIVE MAINTENANCE MATRIX

HULL NO		DATES FOR WHICH ACTIONS REPORTED										
		JAN-JUN 1983	JUL-DEC 1983	JAN-JUN 1984	JUL-DEC 1984	JAN-JUN 1985	JUL-DEC 1985	JAN-JUN 1986	JUL-DEC 1986	JAN-JUN 1987	JUL-DEC 1987	JAN-JUN 1988
607	ACTIONS						11	22	17	21	10	
	OPERATING HOURS						3504	3504	3504	3504	3504	
613	ACTIONS							6	1	8		
	OPERATING HOURS							3504	1752	3504		
649	ACTIONS						16	27	10	24	12	
	OPERATING HOURS						3504	3504	3504	3504	3504	
660	ACTIONS						5	3	8	0	7	
	OPERATING HOURS						3504	1752	3504	3504	3504	
671	ACTIONS	9	6			3	2	15	21			
	OPERATING HOURS	3504	3504			1752	3504	3504	3504			
679	ACTIONS								4	4	5	2
	OPERATING HOURS								2920	3504	4504	1168
681	ACTIONS						6	11	1			
	OPERATING HOURS						3504	3504	3504			
688	ACTIONS						3	2	3	1	2	
	OPERATING HOURS						1168	1752	3504	3504	3504	
689	ACTIONS	9	11					6	10	8	6	3
	OPERATING HOURS	3504	3504					1752	3504	3504	3504	1752
690	ACTIONS	11	11					10			6	9
	OPERATING HOURS	3504	3504					3504			3504	3504

TABLE 10 (CONTINUED)

HULL NO		DATES FOR WHICH ACTIONS REPORTED										
		JAN-JUN 1983	JUL-DEC 1983	JAN-JUN 1984	JUL-DEC 1984	JAN-JUN 1985	JUL-DEC 1985	JAN-JUN 1986	JUL-DEC 1986	JAN-JUN 1987	JUL-DEC 1987	JAN-JUN 1988
685	ACTIONS						4	3		1		
	OPERATING HOURS						1752	2336		3504		
704	ACTIONS	3	10			25	11	4	2	12	2	19
	OPERATING HOURS	3504	3504			3504	3504	1752	1752	3504	1752	3504
698	ACTIONS						1	6	16	17	12	
	OPERATING HOURS						584	3504	3504	3504	3504	
707	ACTIONS						2	5	7			
	OPERATING HOURS						1752	3504	1752			
708	ACTIONS								6	12	17	2
	OPERATING HOURS								2920	1752	3504	1752
715	ACTIONS							11	17	9	9	7
	OPERATING HOURS							3504	3504	3504	3504	3504
716	ACTIONS						11	2		1	3	
	OPERATING HOURS						3504	3504		1752	1752	
TOTALS	ACTIONS	32	38	0	0	28	72	133	123	118	91	42
	OPERATING HOURS	14016	14016	0	0	5256	29784	44384	42632	38544	39544	15184
MTBCM	OPERATING HOURS / ACTIONS	438.00	368.84			187.71	413.67	333.71	346.60	326.64	434.55	361.52

APPENDIX D

MEAN TIME BETWEEN CORRECTIVE MAINTENANCE OUTLIER TEST

This appendix contains the MINITAB output for the outlier tests. This printout shows the initial data (C1), a histogram to show the data is mound shaped, and its associated box plot. In this case, one point is identified as an outlier as shown by the *. This point was deleted and another boxplot was constructed which showed no outliers.

```
MTB > print c1

C1
  438.00   368.84   187.71   413.67   333.71   346.60   326.64   434.55
  361.52

MTB > histogram c1

Histogram of C1   N = 9

Midpoint   Count
     200       1  *
     240       0
     280       0
     320       2  **
     360       3  ***
     400       1  *
     440       2  **

MTB > boxplot c1


                                              -----------------
             *                              --I      +         I-----
                                              -----------------
          ------+---------+---------+---------+---------+---------+C1
              200       250       300       350       400       450

MTB > delete row 3 c1
MTB > boxplot c1


                    ----------------------------------
               -----I         +                      I-----
                    ----------------------------------
          ------+---------+---------+---------+---------+---------+C1
              325       350       375       400       425       450

MTB > stop
*** Minitab Release 6.1.1 *** Minitab, Inc. ***
Storage available 16179
```

APPENDIX E

MINITAB OUTPUT FOR THE MEAN TIME BETWEEN CORRECTIVE MAINTENANCE ANALYSIS

This appendix contains the MINITAB output for the statistical analysis accomplished on the data for the Mean Time Between Corrective Maintenance. In the output, the term C1 is the Mean Time Between Corrective Maintenance statistic for each time period and C2 is the assigned time period. Important MINITAB terms that are used to calculate critical parameters are as follows:

TINTERVAL: This provides the mean of the sample and the range of the 90% confidence interval for a Student-t distribution.

REGRESS: This performs the linear regression calculation between two variables.

DW: This requests that the Durbin-Watson statistic be calculated as part of the regression analysis.

```
MTB > PRINT C1 C2

 ROW        C1      C2

   1    438.00       0
   2    368.84       6
   3    413.67      30
   4    333.71      36
   5    346.60      42
   6    326.64      48
   7    434.55      54
   8    361.52      60

MTB > TINTERVAL 90 C1

               N       MEAN     STDEV  SE MEAN     90.0 PERCENT C.I.
C1             8      377.9      44.7     15.8   (   348.0,    407.9)

MTB > REGRESS C1 1 C2;
SUBC> DW.

The regression equation is
C1 = 402 - 0.693 C2

Predictor        Coef         Stdev    t-ratio         p
Constant       401.84         31.74      12.66     0.000
C2            -0.6929        0.7930      -0.87     0.416

s = 45.52        R-sq = 11.3%      R-sq(adj) = 0.0%

Analysis of Variance

SOURCE        DF          SS          MS          F        p
Regression     1        1581        1581       0.76    0.416
Error          6       12430        2072
Total          7       14011


Durbin-Watson statistic = 2.54

MTB > STOP
*** Minitab Release 6.1.1 *** Minitab, Inc. ***
Storage available 16179
```

APPENDIX F

MEAN TIME BETWEEN FAILURES MATRIX

This appendix contains a matrix of the number of maintenance actions attributed to failures and operating hours for each submarine for each time interval that actions were reported.

TABLE 11
MEAN TIME BETWEEN FAILURES MATRIX

HULL NO		DATES FOR WHICH ACTIONS REPORTED										
		JAN-JUN 1983	JUL-DEC 1983	JAN-JUN 1984	JUL-DEC 1984	JAN-JUN 1985	JUL-DEC 1985	JAN-JUN 1986	JUL-DEC 1986	JAN-JUN 1987	JUL-DEC 1987	JAN-JUN 1988
607	FAILURES						1	5	2	5	6	
	OPERATING HOURS						3504	3504	3504	3504	3504	
613	FAILURES							3	0	5		
	OPERATING HOURS							3504	1752	3504		
649	FAILURES						6	5	6	11	8	
	OPERATING HOURS						3504	3504	3504	3504	3504	
660	FAILURES						4	3	3	0	3	
	OPERATING HOURS						3504	1752	3504	3504	3504	
671	FAILURES	7	3			2	1	7	5			
	OPERATING HOURS	3504	3504			1752	3504	3504	3504			
679	FAILURES								2	1	3	0
	OPERATING HOURS								2920	3504	4504	1168
681	FAILURES						0	1	0			
	OPERATING HOURS						3504	3504	3504			
688	FAILURES						1	2	1	0	1	
	OPERATING HOURS						1168	1752	3504	3504	3504	
689	FAILURES	0	2					6	7	6	0	3
	OPERATING HOURS	3504	3504					1752	3504	3504	3504	1752
690	FAILURES	10	11					8			2	3
	OPERATING HOURS	3504	3504					3504			3504	3504

TABLE 11 (CONTINUED)

HULL NO		DATES FOR WHICH ACTIONS REPORTED										
		JAN-JUN 1983	JUL-DEC 1983	JAN-JUN 1984	JUL-DEC 1984	JAN-JUN 1985	JUL-DEC 1985	JAN-JUN 1986	JUL-DEC 1986	JAN-JUN 1987	JUL-DEC 1987	JAN-JUN 1988
685	FAILURES						4	2		0		
	OPERATING HOURS						1752	2336		3504		
704	FAILURES	2	4			20	11	4	0	2	1	8
	OPERATING HOURS	3504	3504			3504	3504	1752	1752	3504	1752	3504
698	FAILURES					0	1	5	13	10	9	
	OPERATING HOURS					1752	584	3504	3504	3504	3504	
707	FAILURES						2	0	0			
	OPERATING HOURS						1752	3504	1752			
708	FAILURES								1	3	9	2
	OPERATING HOURS								2920	1752	3504	1752
715	FAILURES							7	6	1	4	0
	OPERATING HOURS							3504	3504	3504	3504	3504
716	FAILURES						8	0		0	2	
	OPERATING HOURS						3504	3504		1752	1752	
TOTALS	FAILURES	19	20	0	0	22	39	58	46	44	48	16
	OPERATING HOURS	14016	14016	0	0	7008	29784	44384	42632	42048	39544	15184
MTBCM	OPERATING HOURS / FAILURES	737.68	700.80			318.55	763.69	765.24	926.78	955.64	823.83	949.00

APPENDIX G

MEAN TIME BETWEEN FAILURES OUTLIER TEST

This appendix contains the MINITAB output for the outlier tests. This printout shows the initial data (C1), a histogram to show the data is mound shaped, and its associated box plot. In this case, one point is identified as an outlier as shown by the *. This point was deleted and another boxplot was constructed which showed no outliers.

```
MTB > print c1

C1
  737.68   700.80   318.55   763.69   765.24   926.78   955.64   823.83
  949.00

MTB > histogram c1

Histogram of C1   N = 9

Midpoint   Count
     300       1  *
     400       0
     500       0
     600       0
     700       2  **
     800       3  ***
     900       2  **
    1000       1  *

MTB > boxplot c1

                                                   ----------------
            *                                   ---I  +            I---
                                                   ----------------
         ------+---------+---------+---------+---------+---------+C1
              360       480       600       720       840       960

MTB > delete row 3 c1
MTB > boxplot c1

                        ---------------------------------------
           ----------I        +                               I---
                        ---------------------------------------
         --+---------+---------+---------+---------+---------+----C1
          700       750       800       850       900       950

MTB > stop
*** Minitab Release 6.1.1 *** Minitab, Inc. ***
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```

APPENDIX H

MINITAB OUTPUT FOR THE MEAN TIME BETWEEN FAILURES ANALYSIS

This appendix contains the MINITAB output for the statistical analysis accomplished on the data for the Mean Time Between Failures. In the output, the term C1 is the Mean Time Between Failures statistic for each time period and C2 is the assigned time period. Important MINITAB terms that are used to calculate critical parameters are as follows:

TINTERVAL: This provides the mean of the sample and the range of the 90% confidence interval for a Student-t distribution.

REGRESS: This performs the linear regression calculation between two variables.

DW: This requests that the Durbin-Watson statistic be calculated as part of the regression analysis.

TTEST: This calculates the test statistic for a hypothesis test assuming a Student-t distribution.

```
MTB > PRINT C1 C2

 ROW        C1     C2

   1    737.68      0
   2    700.80      6
   3    763.69     30
   4    765.24     36
   5    926.78     42
   6    955.64     48
   7    823.83     54
   8    949.00     60

MTB > TINTERVAL 90 C1

                 N      MEAN     STDEV  SE MEAN    90.0 PERCENT C.I.
C1               8     827.8     102.2     36.1  (   759.4,    896.3)

MTB > TTEST 1500 C1

TEST OF MU = 1500.000 VS MU N.E. 1500.000

                 N      MEAN     STDEV   SE MEAN          T    P VALUE
C1               8   827.833   102.204    36.135     -18.60     0.0000

MTB > REGRESS C1 1 C2;
SUBC> DW.

The regression equation is
C1 = 698 + 3.77 C2

Predictor         Coef         Stdev    t-ratio         p
Constant        697.91         46.26      15.09     0.000
C2               3.766         1.156       3.26     0.017

s = 66.34        R-sq = 63.9%      R-sq(adj) = 57.9%

Analysis of Variance

SOURCE       DF          SS           MS         F         p
Regression    1       46714        46714     10.61     0.017
Error         6       26406         4401
Total         7       73120


Durbin-Watson statistic = 2.21
```

APPENDIX I

MINITAB OUTPUT FOR THE ACTIVE MAINTENANCE TIME ANALYSIS

This appendix contains the MINITAB output for the statistical analysis accomplished on the data for the Man Hours Expended and Active Maintenance Time. In the output, the term C12 is the Man Hours Expended and C13 is the Active Maintenance Time. Important MINITAB terms that are used to calculate critical parameters are as follows:

CORR: This performs a correlation analysis between two variables.

REGRESS: This performs the linear regression calculation between two variables.

```
MTB > CORR C12 C13

Correlation of SMHRE and SAMT = 0.936

MTB > REGRESS C13 1 C12

The regression equation is
SAMT = 0.502 + 0.460 SMHRE

Predictor        Coef        Stdev     t-ratio        p
Constant       0.5025       0.3224        1.56    0.120
SMHRE         0.45985      0.01082       42.49    0.000

s = 4.911        R-sq = 87.5%      R-sq(adj) = 87.5%

Analysis of Variance

SOURCE        DF          SS          MS          F         p
Regression     1       43540       43540    1805.63     0.000
Error        257        6197          24
Total        258       49737
```

APPENDIX J

MEAN TIME TO REPAIR MATRIX

This appendix contains a matrix of the number of maintenance actions attributed to failures and the total Active Maintenance Time for each submarine for each time interval that actions were reported.

TABLE 12
MEAN TIME TO REPAIR FOR FAILURES MATRIX

HULL NO		DATES FOR WHICH ACTIONS REPORTED										
		JAN-JUN 1983	JUL-DEC 1983	JAN-JUN 1984	JUL-DEC 1984	JAN-JUN 1985	JUL-DEC 1985	JAN-JUN 1986	JUL-DEC 1986	JAN-JUN 1987	JUL-DEC 1987	JAN-JUN 1988
607	FAILURES						1	5	2	5	6	
	HOURS OF MAINT.						3	11	2.42	8.18	65.68	
613	FAILURES							3	0	5		
	HOURS OF MAINT.							8.22	0	9.42		
649	FAILURES						6	5	6	11	8	
	HOURS OF MAINT.						31	19.34	37.86	77.72	56.34	
660	FAILURES						4	3	3	0	3	
	HOURS OF MAINT.						13.96	32.32	12.9	0	23.58	
671	FAILURES	7	3			2	1	7	5			
	HOURS OF MAINT.	19.38	2.92			1.96	5.1	10.4	7.1			
679	FAILURES								2	1	3	0
	HOURS OF MAINT.								104.96	1	7.42	0
681	FAILURES						0	1	0			
	HOURS OF MAINT.						0	14.3	0			
688	FAILURES						1	2	1	0	1	
	HOURS OF MAINT.						23.96	56.2	1.42	0	1.88	
689	FAILURES	0	2					6	7	6	0	3
	HOURS OF MAINT.	0	3.76					43.02	80.9	30.6	0	6.68
690	FAILURES	10	11					8			2	3
	HOURS OF MAINT.	11.96	26					161.78			10.66	8.4

TABLE 12 (CONTINUED)

HULL NO		DATES FOR WHICH ACTIONS REPORTED										
		JAN-JUN 1983	JUL-DEC 1983	JAN-JUN 1984	JUL-DEC 1984	JAN-JUN 1985	JUL-DEC 1985	JAN-JUN 1986	JUL-DEC 1986	JAN-JUN 1987	JUL-DEC 1987	JAN-JUN 1988
685	FAILURES						4	2		0		
	HOURS OF MAINT.						5	5		0		
704	FAILURES	2	4			20	11	4	0	2	1	8
	HOURS OF MAINT.	2.84	16.26			54.16	112.24	52.14	0	4.22	1.42	10.9
698	FAILURES					0	1	5	13	10	9	
	HOURS OF MAINT.					0	2.34	14.46	28.12	30	40.22	
707	FAILURES						2	0	0			
	HOURS OF MAINT.						4.68	0	0			
708	FAILURES								1	3	9	2
	HOURS OF MAINT.								25.34	6.1	48.18	2.38
715	FAILURES							7	6	1	4	0
	HOURS OF MAINT.							20.98	13.12	1.42	10.74	0
716	FAILURES						8	0		0	2	
	HOURS OF MAINT.						46.22	0		0	59.42	
TOTALS	FAILURES	**19**	**20**	**0**	**0**	**22**	**39**	**58**	**46**	**44**	**48**	**16**
	HOURS OF MAINT.	**34.18**	**48.94**	**0**	**0**	**56.12**	**247.5**	**449.16**	**314.14**	**168.66**	**325.54**	**28.36**
MTBCM	HOURS OF MAINT. / FAILURES	**1.80**	**2.45**			**2.55**	**6.35**	**7.74**	**6.83**	**3.83**	**6.78**	**1.77**

APPENDIX K

MEAN TIME TO REPAIR OUTLIER TEST

This appendix contains the MINITAB output for the outlier tests. This printout shows the initial data (C1), a histogram to show the data is mound shaped, and its associated box plot. In this case, all of the data passed the oulier test.

```
MTB > print c1

C1
  1.80   2.45   2.55   6.35   7.74   6.83   3.83   6.78   1.77

MTB > histogram c1;
SUBC> start 1;
SUBC> increment .5.

Histogram of C1   N = 9

Midpoint   Count
   1.000       0
   1.500       0
   2.000       2  **
   2.500       2  **
   3.000       0
   3.500       0
   4.000       1  *
   4.500       0
   5.000       0
   5.500       0
   6.000       0
   6.500       1  *
   7.000       2  **
   7.500       1  *

MTB > boxplot c1

                 ---------------------------------------
            -----I           +                         I-------
                 ---------------------------------------
         ---------+---------+---------+---------+---------+--------C1
                 2.4       3.6       4.8       6.0       7.2

MTB > stop
*** Minitab Release 6.1.1 *** Minitab, Inc. ***
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```

APPENDIX L

MINITAB OUTPUT FOR THE MEAN TIME TO REPAIR ANALYSIS

This appendix contains the MINITAB output for the statistical analysis accomplished on the data for the Mean Time to Repair. In the output, the term C1 is the Mean Time to Repair statistic for each time period and C2 is the assigned time period. The term C3 is the error terms or residuals that result from the regression analysis. Important MINITAB terms that are used to calculate critical parameters are as follows:

TINTERVAL: This provides the mean of the sample and the range of the 90% confidence interval for a Student-t distribution.

TTEST: This calculates the test statistic for a hypothesis test assuming a Student-t distribution.

REGRESS: This performs the linear regression calculation between two variables.

DW: This requests that the Durbin-Watson statistic be calculated as part of the regression analysis.

```
MTB > PRINT C1 C2

 ROW      C1     C2

   1    1.80      0
   2    2.45      6
   3    2.55     24
   4    6.35     30
   5    7.74     36
   6    6.83     42
   7    3.83     48
   8    6.78     54
   9    1.77     60

MTB > TINTERVAL 90 C1

             N      MEAN     STDEV  SE MEAN    90.0 PERCENT C.I.
C1           9     4.456     2.442    0.814  (    2.941,     5.970)

MTB > TTEST .67 C1

TEST OF MU = 0.670 VS MU N.E. 0.670

             N      MEAN     STDEV   SE MEAN          T    P VALUE
C1           9     4.456     2.442     0.814       4.65     0.0000

MTB > REGRESS C1 1 C2;
SUBC> DW;
SUBC> RESIDUAL C3.

The regression equation is
C1 = 2.97 + 0.0446 C2

Predictor       Coef        Stdev    t-ratio        p
Constant       2.968        1.602       1.85    0.106
C2           0.04463      0.04154       1.07    0.318

s = 2.419       R-sq = 14.2%     R-sq(adj) = 1.9%

Analysis of Variance

SOURCE       DF          SS          MS         F        p
Regression    1       6.757       6.757      1.15    0.318
Error         7      40.969       5.853
Total         8      47.726


Durbin-Watson statistic = 1.50
```

APPENDIX M

MINITAB OUTPUT FOR THE MEAN TIME TO REPAIR ANALYSIS LESS 1988

This appendix contains the MINITAB output for the statistical analysis accomplished on the data for the Mean Time to Repair not including the data from 1988. In the output, the term C1 is the Mean Time to Repair statistic for each time period and C2 is the assigned time period. Important MINITAB terms that are used to calculate critical parameters are as follows:

REGRESS: This performs the linear regression calculation between two variables.

DW: This requests that the Durbin-Watson statistic be calculated as part of the regression analysis.

RESIDUAL: This command calculates and stores the residual for each data point in the correlation analysis.

CORR: This performs a correlation analysis between two variables.

```
MTB > PRINT C1 C2

 ROW     C1     C2

   1   1.80      0
   2   2.45      6
   3   2.55     24
   4   6.35     30
   5   7.74     36
   6   6.83     42
   7   3.83     48
   8   6.78     54

MTB > REGRESS C1 1 C2;
SUBC> DW;
SUBC> RESIDUALS C3.

The regression equation is
C1 = 2.11 + 0.0895 C2

Predictor        Coef        Stdev    t-ratio        p
Constant        2.107        1.218       1.73    0.134
C2            0.08949      0.03482       2.57    0.042

s = 1.773        R-sq = 52.4%     R-sq(adj) = 44.5%

Analysis of Variance

SOURCE       DF         SS          MS         F        p
Regression    1     20.758      20.758      6.61    0.042
Error         6     18.854       3.142
Total         7     39.613


Durbin-Watson statistic = 1.81

MTB > PRINT C2 C3

 ROW    C2        C3

   1     0  -0.30653
   2     6  -0.19347
   3    24  -1.70431
   4    30   1.55875
   5    36   2.41181
   6    42   0.96486
   7    48  -2.57208
   8    54  -0.15903

MTB > CORR C2 C3

Correlation of C2 and C3 = -0.000
```

APPENDIX N

DELAY TIME MATRIX

This appendix contains a matrix of the number of maintenance actions attributed to failures and the total Delay Times associated with these actions for each submarine for each time interval that actions were reported.

TABLE 13
DELAY TIME FOR FAILURES MATRIX

HULL NO		DATES FOR WHICH ACTIONS REPORTED										
		JAN-JUN 1983	JUL-DEC 1983	JAN-JUN 1984	JUL-DEC 1984	JAN-JUN 1985	JUL-DEC 1985	JAN-JUN 1986	JUL-DEC 1986	JAN-JUN 1987	JUL-DEC 1987	JAN-JUN 1988
607	FAILURES						1	5	2	5	6	
	HOURS OF DELAY						1	388	2	484	749	
613	FAILURES							3	0	5		
	HOURS OF DELAY							121	0	5		
649	FAILURES						6	5	6	11	8	
	HOURS OF DELAY						291	1395	4683	1498	413	
660	FAILURES						4	3	3	0	3	
	HOURS OF DELAY						9147	26	4634	0	1633	
671	FAILURES	7	3			2	1	7	5			
	HOURS OF DELAY	6579	3			2	1	5	5			
679	FAILURES								2	1	3	0
	HOURS OF DELAY								8449	1	3	0
681	FAILURES						0	1	0			
	HOURS OF DELAY						0	1	0			
688	FAILURES						1	2	1	0	1	
	HOURS OF DELAY						4984	2	1	0	1	
689	FAILURES	0	2					6	7	6	0	3
	HOURS OF DELAY	0	25					4586	1229	195	0	3
690	FAILURES	10	11					8			2	3
	HOURS OF DELAY	10	11					3482			457	841

TABLE 13 (CONTINUED)

HULL NO		DATES FOR WHICH ACTIONS REPORTED										
		JAN-JUN 1983	JUL-DEC 1983	JAN-JUN 1984	JUL-DEC 1984	JAN-JUN 1985	JUL-DEC 1985	JAN-JUN 1986	JUL-DEC 1986	JAN-JUN 1987	JUL-DEC 1987	JAN-JUN 1988
685	FAILURES						4	2		0		
	HOURS OF DELAY						843	97		0		
704	FAILURES	2	4			20	11	4	0	2	1	8
	HOURS OF DELAY	2	1346			3207	1329	267	0	2	1	487
698	FAILURES					0	1	5	13	10	9	
	HOURS OF DELAY					0	1	984	371	10	9	
707	FAILURES						2	0	0			
	HOURS OF DELAY						1441	0	0			
708	FAILURES								1	3	9	2
	HOURS OF DELAY								1	3	1014	2
715	FAILURES							7	6	1	4	0
	HOURS OF DELAY							7	4059	168	2325	0
716	FAILURES						8	0		0	2	
	HOURS OF DELAY						990	0		0	1705	
TOTALS	FAILURES	**19**	**20**	**0**	**0**	**22**	**39**	**58**	**46**	**44**	**48**	**16**
	HOURS OF DELAY	**6591**	**1385**	**0**	**0**	**3209**	**19028**	**11361**	**23434**	**2366**	**8310**	**1333**
MTBCM	HOURS OF DELAY / FAILURES	**346.89**	**69.25**			**145.86**	**487.90**	**195.88**	**509.43**	**53.77**	**173.13**	**83.31**
		0	**6**	**12**	**18**	**24**	**30**	**36**	**42**	**48**	**54**	**60**

APPENDIX O

DELAY TIME OUTLIER TEST

This appendix contains the MINITAB output for the outlier tests. This printout shows the initial data (C1), a histogram to show the data is mound shaped, and its associated box plot. In this case, all of the data passed the oulier test.

```
MTB > print c1

C1
  346.89    69.25   145.86   487.90   195.88   509.43    53.77   173.13
   83.31

MTB > histo c1

Histogram of C1   N = 9

Midpoint   Count
      50       2  **
     100       1  *
     150       2  **
     200       1  *
     250       0
     300       0
     350       1  *
     400       0
     450       0
     500       2  **

MTB > boxplot c1

                  ----------------------------
               ---I        +                 I----------------
                  ----------------------------
          +---------+---------+---------+---------+---------+------C1
          0       100       200       300       400       500

MTB > stop
*** Minitab Release 6.1.1 *** Minitab, Inc. ***
Storage available 16179
```

APPENDIX P

MINITAB OUTPUT FOR THE DELAY TIME ANALYSIS

This appendix contains the MINITAB output for the statistical analysis accomplished on the data for the Delay Time. In the output, the term C1 is the Mean Time to Repair statistic for each time period and C2 is the assigned time period. Important MINITAB terms that are used to calculate critical parameters are as follows:

TINTERVAL: This provides the mean of the sample and the range of the 90% confidence interval for a Student-t distribution.

TTEST: This calculates the test statistic for a hypothesis test assuming a Student-t distribution.

REGRESS: This performs the linear regression calculation between two variables.

DW: This requests that the Durbin-Watson statistic be calculated as part of the regression analysis.

```
MTB > print c1 c2

 ROW        C1     C2

   1    346.89      0
   2     69.25      6
   3    145.86     24
   4    487.90     30
   5    195.88     36
   6    509.43     42
   7     53.77     48
   8    173.13     54
   9     83.31     60

MTB > TINTERVAL 90 C1

             N      MEAN     STDEV  SE MEAN   90.0 PERCENT C.I.
C1           9     229.5     176.1     58.7  (   120.3,    338.7)

MTB > TTEST 75 C1

TEST OF MU =  75.000 VS MU N.E.  75.000

             N      MEAN     STDEV   SE MEAN         T    P VALUE
C1           9   229.491   176.121    58.707      2.63      0.030

MTB > REGRESS C1 1 C2;
SUBC> DW.

The regression equation is
C1 = 278 - 1.45 C2

Predictor       Coef        Stdev    t-ratio         p
Constant       277.8        122.9       2.26     0.058
C2            -1.450        3.186      -0.46     0.663

s = 185.6       R-sq = 2.9%       R-sq(adj) = 0.0%

Analysis of Variance

SOURCE       DF          SS          MS         F        p
Regression    1        7130        7130      0.21    0.663
Error         7      241018       34431
Total         8      248148


Durbin-Watson statistic = 2.54
```

APPENDIX Q

PARTS AVAILABLE FOR FAILURES MATRIX

This appendix contains a matrix of the number of maintenance actions attributed to failures and the total parts available associated with these actions for each submarine for each time interval that actions were reported.

TABLE 14
PARTS AVAILABLE FOR FAILURES MATRIX

HULL NO		DATES FOR WHICH ACTIONS REPORTED										
		JAN-JUN 1983	JUL-DEC 1983	JAN-JUN 1984	JUL-DEC 1984	JAN-JUN 1985	JUL-DEC 1985	JAN-JUN 1986	JUL-DEC 1986	JAN-JUN 1987	JUL-DEC 1987	JAN-JUN 1988
607	FAILURES						1	5	2	5	6	
	PARTS AVAILABLE						1	4	2	4	5	
613	FAILURES							3	0	5		
	PARTS AVAILABLE							1	0	5		
649	FAILURES						6	5	6	11	8	
	PARTS AVAILABLE						3	3	3	10	5	
660	FAILURES						4	3	3	0	3	
	PARTS AVAILABLE						3	2	2	0	1	
671	FAILURES	7	3			2	1	7	5			
	PARTS AVAILABLE	3	3			2	1	5	5			
679	FAILURES								2	1	3	0
	PARTS AVAILABLE								1	1	3	0
681	FAILURES						0	1	0			
	PARTS AVAILABLE						0	1	0			
688	FAILURES						1	2	1	0	1	
	PARTS AVAILABLE						0	2	1	0	1	
689	FAILURES	0	2					6	7	6	0	3
	PARTS AVAILABLE	0	1					2	5	3	0	3
690	FAILURES	10	11					8			2	3
	PARTS AVAILABLE	10	11					2			1	1

TABLE 14 (CONTINUED)

HULL NO		DATES FOR WHICH ACTIONS REPORTED										
		JAN-JUN 1983	JUL-DEC 1983	JAN-JUN 1984	JUL-DEC 1984	JAN-JUN 1985	JUL-DEC 1985	JAN-JUN 1986	JUL-DEC 1986	JAN-JUN 1987	JUL-DEC 1987	JAN-JUN 1988
685	FAILURES						4	2		0		
	PARTS AVAILABLE						3	1		0		
704	FAILURES	2	4			20	11	4	0	2	1	8
	PARTS AVAILABLE	2	2			15	9	3	0	2	1	7
698	FAILURES					0	1	5	13	10	9	
	PARTS AVAILABLE					0	1	2	11	10	7	
707	FAILURES						2	0	0			
	PARTS AVAILABLE						1	0	0			
708	FAILURES								1	3	9	2
	PARTS AVAILABLE								1	3	6	2
715	FAILURES							7	6	1	4	0
	PARTS AVAILABLE							7	3	0	3	0
716	FAILURES						8	0		0	2	
	PARTS AVAILABLE						6	0		0	1	
TOTALS	FAILURES	19	20	0	0	22	39	58	46	44	48	16
	PARTS AVAILABLE	15	17	0	0	17	28	35	34	38	34	13
% PART AVAIL.	PARTS AVAILABLE / FAILURES	0.79	0.85			0.77	0.72	0.60	0.74	0.86	0.71	0.81

APPENDIX R

PARTS AVAIALBLE FOR FAILURES
OUTLIER TEST

This appendix contains the MINITAB output for the outlier tests. This printout shows the initial data (C1), a histogram to show the data is mound shaped, and its associated box plot. In this case, all of the data passed the oulier test.

```
MTB > print c1

C1
  0.79   0.85   0.77   0.72   0.60   0.74   0.86   0.71   0.81

MTB > histogram c1

Histogram of C1   N = 9

Midpoint   Count
    0.60       1  *
    0.64       0
    0.68       0
    0.72       2  **
    0.76       2  **
    0.80       2  **
    0.84       1  *
    0.88       1  *

MTB > boxplot c1

                                   ------------------
           ------------------------I         +       I----------
                                   ------------------
         --+---------+---------+---------+---------+---------+----C1
         0.600     0.650     0.700     0.750     0.800     0.850

MTB > stop
*** Minitab Release 6.1.1 *** Minitab, Inc. ***
Storage available 16179
```

APPENDIX S

MINITAB OUTPUT FOR THE PARTS AVAILABLE FOR FAILURES ANALYSIS

This appendix contains the MINITAB output for the statistical analysis accomplished on the data for the Parts Available for Failures. In the output, the term C1 is the Mean Time to Repair statistic for each time period and C2 is the assigned time period. The term C3 is the error terms or residuals that result from the regression analysis. Important MINITAB terms that are used to calculate critical parameters are as follows:

TINTERVAL: This provides the mean of the sample and the range of the 90% confidence interval for a Student-t distribution.

REGRESS: This performs the linear regression calculation between two variables.

DW: This requests that the Durbin-Watson statistic be calculated as part of the regression analysis.

```
MTB > PRINT C1 C2

 ROW      C1     C2

   1    0.79      0
   2    0.85      6
   3    0.77     24
   4    0.72     30
   5    0.60     36
   6    0.74     42
   7    0.86     48
   8    0.71     54
   9    0.81     60

MTB > TINTERVAL 90 C1

                N      MEAN     STDEV   SE MEAN    90.0 PERCENT C.I.
C1              9    0.7611    0.0804    0.0268   (  0.7113,   0.8109)

MTB > REGRESS C1 1 C2;
SUBC> DW;
SUBC> RESIDUALS C3.

The regression equation is
C1 = 0.783 - 0.00066 C2

Predictor         Coef        Stdev     t-ratio        p
Constant       0.78325      0.05608       13.97    0.000
C2           -0.000664     0.001454       -0.46    0.662

s = 0.08468      R-sq = 2.9%      R-sq(adj) = 0.0%

Analysis of Variance

SOURCE       DF          SS          MS         F        p
Regression    1    0.001497    0.001497      0.21    0.662
Error         7    0.050192    0.007170
Total         8    0.051689


Durbin-Watson statistic = 1.84
```

APPENDIX T

PARTS AVAILABLE FOR FAULTS MATRIX

This appendix contains a matrix of the number of maintenance actions attributed to faults and the total parts available associated with these actions for each submarine for each time interval that actions were reported.

TABLE 15
PARTS AVAILABLE FOR FAULTS MATRIX

HULL NO		DATES FOR WHICH ACTIONS REPORTED										
		JAN-JUN 1983	JUL-DEC 1983	JAN-JUN 1984	JUL-DEC 1984	JAN-JUN 1985	JUL-DEC 1985	JAN-JUN 1986	JUL-DEC 1986	JAN-JUN 1987	JUL-DEC 1987	JAN-JUN 1988
607	FAULTS						10	17	15	16	4	
	PARTS AVAILABLE						8	17	12	13	4	
613	FAULTS							3	1	3		
	PARTS AVAILABLE							1	1	3		
649	FAULTS						10	22	4	13	4	
	PARTS AVAILABLE						5	13	3	11	3	
660	FAULTS						0	0	5		4	
	PARTS AVAILABLE						0	0	4		3	
671	FAULTS	2	3			1	1	8	16			
	PARTS AVAILABLE	0	3			0	1	7	10			
679	FAULTS								3	3	2	2
	PARTS AVAILABLE								2	3	2	0
681	FAULTS						6	10	1			
	PARTS AVAILABLE						4	8	0			
688	FAULTS						2	0	2	1	1	
	PARTS AVAILABLE						0	0	1	0	1	
689	FAULTS	9	9					0	3	2	6	0
	PARTS AVAILABLE	8	5					0	2	2	5	0
690	FAULTS	1	0					2			4	6
	PARTS AVAILABLE	0	0					1			1	6

TABLE 15 (CONTINUED)

HULL NO		DATES FOR WHICH ACTIONS REPORTED										
		JAN-JUN 1983	JUL-DEC 1983	JAN-JUN 1984	JUL-DEC 1984	JAN-JUN 1985	JUL-DEC 1985	JAN-JUN 1986	JUL-DEC 1986	JAN-JUN 1987	JUL-DEC 1987	JAN-JUN 1988
685	FAULTS						0	1		1		
	PARTS AVAILABLE						0	0		1		
704	FAULTS	1	6			5	0	0	2	8	1	11
	PARTS AVAILABLE	0	3			4	0	0	1	5	1	2
698	FAULTS						1	5	3	7	3	
	PARTS AVAILABLE						1	2	2	6	3	
707	FAULTS						0	5	7			
	PARTS AVAILABLE						0	3	3			
708	FAULTS								5	9	8	0
	PARTS AVAILABLE								4	8	6	0
715	FAULTS							4	11	8	5	7
	PARTS AVAILABLE							1	7	5	4	6
716	FAULTS						3	2		1	1	
	PARTS AVAILABLE						1	2		1	0	
TOTALS	FAULTS	13	18	0	0	6	33	79	78	72	43	26
	PARTS AVAILABLE	8	11	0	0	4	20	55	52	58	33	14
% PART AVAIL.	PARTS AVAILABLE / FAULTS	0.62	0.61			0.67	0.61	0.70	0.67	0.81	0.77	0.54

APPENDIX U

PARTS AVAIALBLE FOR FAULTS
OUTLIER TEST

This appendix contains the MINITAB output for the outlier tests. This printout shows the initial data (C1), a histogram to show the data is mound shaped, and its associated box plot. In this case, all of the data passed the oulier test.

```
MTB > print c1

C1
   0.62    0.61    0.67    0.61    0.70    0.67    0.81    0.77    0.54

MTB > histogram c1

Histogram of C1   N = 9

Midpoint   Count
    0.56       1  *
    0.60       2  **
    0.64       1  *
    0.68       2  **
    0.72       1  *
    0.76       1  *
    0.80       1  *

MTB > boxplot c1


                      -------------------
        --------------I           +     I----------------------
                      -------------------
      ----+---------+---------+---------+---------+---------+--C1
        0.550     0.600     0.650     0.700     0.750     0.800

MTB > stop
*** Minitab Release 6.1.1 *** Minitab, Inc. ***
Storage available 16179
```

APPENDIX V

MINITAB OUTPUT FOR THE PART AVAILABLE FOR FAULTS ANALYSIS

This appendix contains the MINITAB output for the statistical analysis accomplished on the data for the Parts Available for Faults. In the output, the term C1 is the Parts Available for Faults statistic for each time period and C2 is the assigned time period. The term C3 is the error terms or residuals that result from the regression analysis. Important MINITAB terms that are used to calculate critical parameters are as follows:

TINTERVAL: This provides the mean of the sample and the range of the 90% confidence interval for a Student-t distribution.

REGRESS: This performs the linear regression calculation between two variables.

DW: This requests that the Durbin-Watson statistic be calculated as part of the regression analysis.

```
MTB > PRINT C1 C2

 ROW     C1     C2

   1   0.62      0
   2   0.61      6
   3   0.67     24
   4   0.61     30
   5   0.70     36
   6   0.67     42
   7   0.81     48
   8   0.77     54
   9   0.54     60

MTB > TINTERVAL 90 C1

             N      MEAN     STDEV  SE MEAN    90.0 PERCENT C.I.
C1           9    0.6667    0.0844   0.0281   (  0.6143,   0.7190)

MTB > REGRESS C1 1 C2;
SUBC> DW;
SUBC> RESIDUALS C3.

The regression equation is
C1 = 0.625 + 0.00125 C2

Predictor        Coef        Stdev    t-ratio        p
Constant      0.62500      0.05692      10.98    0.000
C2           0.001250     0.001476       0.85    0.425

s = 0.08594      R-sq = 9.3%       R-sq(adj) = 0.0%

Analysis of Variance

SOURCE       DF          SS          MS          F        p
Regression    1    0.005300    0.005300       0.72    0.425
Error         7    0.051700    0.007386
Total         8    0.057000

Unusual Observations
Obs.      C2        C1        Fit Stdev.Fit  Residual   St.Resid
  9     60.0    0.5400     0.7000    0.0487   -0.1600     -2.26R

R denotes an obs. with a large st. resid.
```

```
Durbin-Watson statistic = 1.75

MTB > PRINT C2 C3

 ROW     C2         C3

   1      0    -0.0050
   2      6    -0.0225
   3     24     0.0150
   4     30    -0.0525
   5     36     0.0300
   6     42    -0.0075
   7     48     0.1250
   8     54     0.0775
   9     60    -0.1600

MTB > CORR C2 C3

Correlation of C2 and C3 = -0.000

MTB > STOP
*** Minitab Release 6.1.1 *** Minitab, Inc. ***
Storage available 16179
```

APPENDIX W

MINITAB OUTPUT FOR THE PARTS AVAILABLE FOR FAULTS ANALYSIS LESS 1988

This appendix contains the MINITAB output for the statistical analysis accomplished on the data for the Parts Available for Faults not including the data from 1988. In the output, the term C1 is the Mean Time to Repair statistic for each time period and C2 is the assigned time period. Important MINITAB terms that are used to calculate critical parameters are as follows:

TINTERVAL: This provides the mean of the sample and the range of the 90% confidence interval for a Student-t distribution.

REGRESS: This performs the linear regression calculation between two variables.

DW: This requests that the Durbin-Watson statistic be calculated as part of the regression analysis.

```
MTB > PRINT C1 C2

 ROW      C1     C2

   1    0.62      0
   2    0.61      6
   3    0.67     24
   4    0.61     30
   5    0.70     36
   6    0.67     42
   7    0.81     48
   8    0.77     54

MTB > REGRESS C1 1 C2;
SUBC> DW.

The regression equation is
C1 = 0.589 + 0.00310 C2

Predictor        Coef        Stdev     t-ratio        p
Constant      0.58944      0.03321       17.75    0.000
C2          0.0031019    0.0009492        3.27    0.017

s = 0.04832      R-sq = 64.0%      R-sq(adj) = 58.0%

Analysis of Variance

SOURCE       DF          SS          MS         F        p
Regression    1    0.024939    0.024939     10.68    0.017
Error         6    0.014011    0.002335
Total         7    0.038950


Durbin-Watson statistic = 2.33

MTB > STOP
*** Minitab Release 6.1.1 *** Minitab, Inc. ***
Storage available 16179
```

APPENDIX X

OPERATIONAL AVAILABILITY REGRESSION TABLE

This appendix contains a table of the calculated outputs from the regression analysis of the Mean Time Between Failures, Mean Time to Repair, and Delay Time statistics. The Operational Availability is then calculated for each time period using equation 7.1.

TABLE 16
OPERATIONAL AVAILABILITY REGRESSION TABLE

	JAN-JUN 1983	JUL-DEC 1983	JAN-JUN 1984	JUL-DEC 1984	JAN-JUN 1985	JUL-DEC 1985	JAN-JUN 1986	JUL-DEC 1986	JAN-JUN 1987	JUL-DEC 1987	JAN-JUN 1988
MTBF	698.00	720.62	743.24	765.86	788.48	811.10	833.72	856.34	878.96	901.58	942.20
MTTR	2.11	2.65	3.18	3.72	4.26	4.80	5.33	5.87	6.41	6.94	7.48
DELAY	230	230	230	230	230	230	230	230	230	230	230
AVAILABILITY	**0.750**	**0.756**	**0.761**	**0.766**	**0.771**	**0.776**	**0.780**	**0.784**	**0.788**	**0.792**	**0.799**

APPENDIX Z

REFERENCES

This appendix contains the list of references used in this study.

REFERENCE LIST

Number	Reference
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2	OPNAVINST 3000.12, Chief of Naval Operations Instruction, Operational Availability of Equipments and Weapons Systems. Department of Defense, December 1987.
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37 Newbold, Paul, 1988. Statistics for Business and Economics. Englewood Cliffs, NJ: Prentice-Hall.

38 Ibid.

39 Ibid.

40 Ibid.

41 Ibid.