U.S. Navy Analysis of Submarine Maintenance Data and the Development of Age and Reliability Profiles

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ABSTRACT

In 1961a U.S. Government sponsored task force reported its findings on the effect of scheduled maintenance and aircraft reliability. They stated "In the past, a great deal of emphasis has been placed on the control of overhaul periods to provide a satisfactory level of reliability. After careful study, the Committee is convinced that reliability and overhaul time control are not necessarily directly associated topics." Further studies that also supported this precept led to a new discipline known as "Reliability Centered Maintenance". This RCM discussion focuses on one of the principles of RCM - *Hardware may wear out or have random failure - Random is more common* – and the U.S. Navy's findings in regard to this principle. In 1998 Naval Sea Systems Command activity SUBMEPP (Submarine Maintenance Engineering, Planning and Procurement) developed the capability to generate Age and Reliability curves utilizing maintenance feedback data. This provided the organization a new means to objectively measure the effects of planned maintenance to engineer optimal maintenance plans. After three years of generating Age and Reliability curves, SUBMEPP is ready to report that the 1961 finding still holds true. In the majority of cases, there is no relationship between overhaul time and reliability.

INTRODUCTION

In 1961 a joint task force consisting of FAA (Federal Aviation Administration) and US airline company representatives reported its findings on the effect of scheduled maintenance and aircraft reliability. They stated "In the past, a great deal of emphasis has been placed on the control of overhaul periods to provide a satisfactory level of reliability. After careful study, the Committee is convinced that reliability and overhaul time control are not necessarily directly associated topics." Further studies that also supported this precept and efforts to determine just what does maintain reliability, led to a new discipline which eventually became known as "Reliability Centered Maintenance" – a set of principles and methodology to objectively determine the appropriate type and level of maintenance to maintain required asset functionality.

Reliability Centered Maintenance has been the subject matter of many papers and its success at both saving maintenance and operational dollars, while at the same time increasing reliability of equipment and systems, is worthy of many more. Criticality analysis, root cause failure analysis, condition monitoring and other tenants under the RCM umbrella have been responsible for this success. For this discussion, however, the subject shall be limited to just one of the principles of RCM - *Hardware may wear out or have random failure - Random is more common* – and the U.S. Navy's findings in regard to this principle. Specifically, this paper shall present the findings of SUBMEPP (Submarine Maintenance Engineering, Planning and Procurement), a field activity of Naval Sea Systems Command (NAVSEA). SUBMEPP, as NAVSEA's technical agent for submarine non-nuclear life cycle maintenance planning, provides maintenance products and engineering services to the fleet.

Inherent to most RCM seminars is the presentation of the Age and Reliability curves displayed in figure 1.

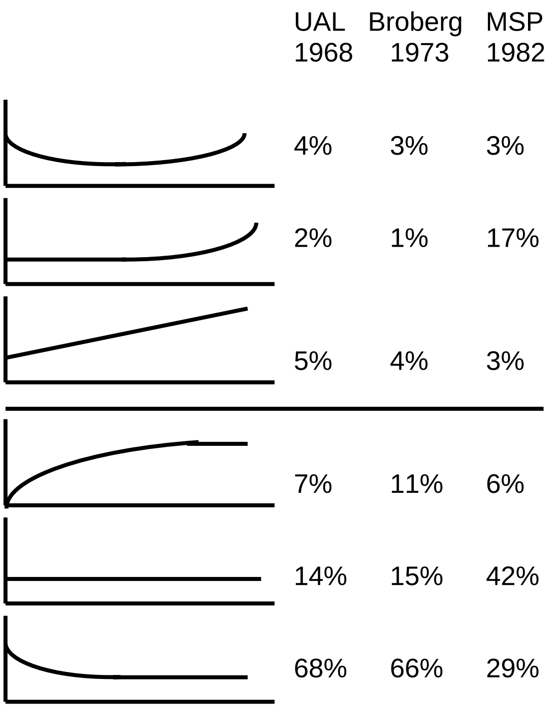


Figure 1. Age and Reliability Characteristic Categories

The graphs depict equipment failure rates (y-axis) vs. service time (x-axis). These curves and the associated population percentile applicabilities have helped dispel the long held notion that equipment reliability fits the so-called "bathtub curve". The bathtub curve theory, which postulates that equipment suffers higher than normal rates of failure early in its life (infant mortality), followed by lower and steady rates of failure for a time period, with an eventual wear out age at some defined time period, represents only 3-4% of sampled equipment populations according to three studies accomplished by United Airlines, Broberg (1973) and the U.S. Navy (1982 MSP). While the majority of sampled equipment populations did experience infant mortality, in general, 90% of the population did not experience an identifiable wear out period. The Navy results are an exception to this generalization. 20% of the Navy population did experience an identifiable wear out period. This has been attributed in part to the corrosive marine environment that affected many of the sample population. Also noteworthy was the finding that the population majority in the Navy study did not suffer infant mortality. This has been attributed to the fact that navy vessels, systems and components are thoroughly tested and "run in" prior to being put into service. Infant mortality certainly exists, but many instances of it are not on the "radar screen". While no one should accept these findings at face value without reviewing them in the context of each individual study, these curves have been used to demonstrate the precept voiced back in 1961 – that random failure predominates.

SUBMEPP began classical RCM analysis in 1995 for non-nuclear submarine systems. In 1998, SUBMEPP developed the capability to generate Age and Reliability curves utilizing maintenance data imported from the Navy's 3-M OARS (Maintenance and Material Management Open Architecture Retrieval System). This provided the organization a new means to objectively measure the effects of planned maintenance to engineer optimal maintenance plans. In turn, this progressive initiative significantly advanced SUBMEPP's ability to cost effectively maintain safe, reliable and mission capable submarines. After three years of generating Age and Reliability curves SUBMEPP is ready to report that the 1961 finding still holds true. In the majority of cases there is no relationship between overhaul time and reliability. Random failure predominates.

Past Ability to Profile Age and Reliability Relationships

SUBMEPP develops maintenance requirements following traditional RCM methodology and with the assistance of an RCM software application they developed in 1995. The application includes a Preventive Maintenance Task Evaluation module and within that module, the application questions the engineer whether certain task types would be applicable and effective in preventing those failure modes they have attributed to the equipment being analyzed. Specifically, the engineer must identify realistic root causes to failure and navigate through an Applicability and Effectiveness Logic Tree to prescribe maintenance tasks that work to prevent failure or reduce consequences of failure to an acceptable level. For non-safety related failures, those tasks must pay for themselves as well.

Among the optional task types, which include servicing, condition monitoring, condition directed, and failure finding, are *time directed* tasks. For a time directed task to be applicable (1) the failure mode must be wear or age related, (2) the probability of failure must increase at an identifiable age and (3) a large proportion of the items must survive to that age. To adequately determine the applicability of the task, therefore, a relationship between time and reliability must be demonstrated. This is most effectively accomplished by a regression and correlation analysis of failure rates and age.

Traditionally, the submarine technical community has specified engineered periodicities for all submarine components. An engineered periodicity is the maximum amount of time that a component can operate without being replaced or renewed through overhaul. These time periods are conservatively established to replace or renew well ahead of equipment wearout. In the past these time periods were typically established utilizing manufacturers recommendations and the collective input of the cognizant naval technical community. More often than not these periodicities were subjective and not derived through an objective and thorough analysis of lifecycle feedback data. This approach to maintenance was also the preferred means of ensuring equipment reliability.

As a result of the technical and cultural change undertaken by the submarine community toward condition based maintenance, it has now become necessary, as mentioned above, to demonstrate evidence of an age relationship to unreliability. In the not too distant past at SUBMEPP, this was a difficult task. It required an engineer to sift through reams of paper containing 3-M data, mailed by the folks at Naval Sea Logistics Center. The engineer would identify failures, tally them and determine if the older components suffered more failures than the younger components. Complicating matters was the fact that boat age usually didn't correlate to component age. And so the engineers struggled in their effort to determine if and when a time directed task would have the desired effect of improving reliability. Again, as before, that decision was more of a subjective one.

Current Ability to Profile Age and Reliability Relationships

SUBMEPP now has the capability to profile age and reliability relationships rather easily through computer automation. The journey to that point was a challenge however. Age and Reliability curves are difficult to construct. One of the more challenging aspects is the process of defining the population. All assets that experienced a failure, or had the opportunity to experience a failure, must be accounted for. All opportunity periods, not observable due to information system constraints, must be accounted for as well. The population for each age interval, for any entity studied, is typically not constant and may vary for each point along the x-axis. Asset populations for navy vessels are dynamic. Each year new vessels are brought on line and old vessels are retired. Asset lifecycles vary as well, depending on what maintenance was accomplished for each individual asset. Another complication is the requirement that all failures be identified to a known asset of a known age.

SUBMEPP's Feedback Data Analysis System is a homegrown application developed after much time and effort with legal pad, pencil and PC. It is essentially a front-end application, with connectivity to 3-M OARS, utilizing common commercial-off-the-shelf database software operating in Windows. This type of analysis can also be accomplished with spreadsheet software, however this is generally not feasible without the support of a database. Some commercially available Computerized Maintenance Management Systems feature this capability as well.

In assessing a component's reliability as it ages, there are three types of data records to be assembled - corrective maintenance, scheduled maintenance and component “birth” records. Corrective maintenance records are the source materials in identifying and counting component failures. Scheduled maintenance and birth records provide essential dates to compute population ages and each component’s length of service time when failure occurs. These records are imported both externally and internally to populate a database file in SUBMEPP’s data analysis application (see figure 2). The majority of corrective maintenance records are retrieved through an open database connectivity (ODBC) interface with 3-M OARS at NAVSEA LOG Center. The specified criteria for these records are usually little more than the subject component’s Allowance Parts List (APL) number. Casualty Report (CASREP) data are retrieved from SUBMEPP’s Integrated Maintenance Analysis Profile (IMAP) database. Scheduled maintenance records are retrieved from IMAP as well. Once selection criteria are known, the retrieval process, for all records except birth records, takes only a minute to execute.

It is recognized that not all-component failures are reported to these information systems, although the lion’s shares of them probably are. The captured failures provide a representative sample of all age groups however. While the failure rate magnitude is affected by any unaccounted failures, the comparison between age groups should not be. In other words, those unaccounted failures should be scattered randomly and proportionally across all age intervals.

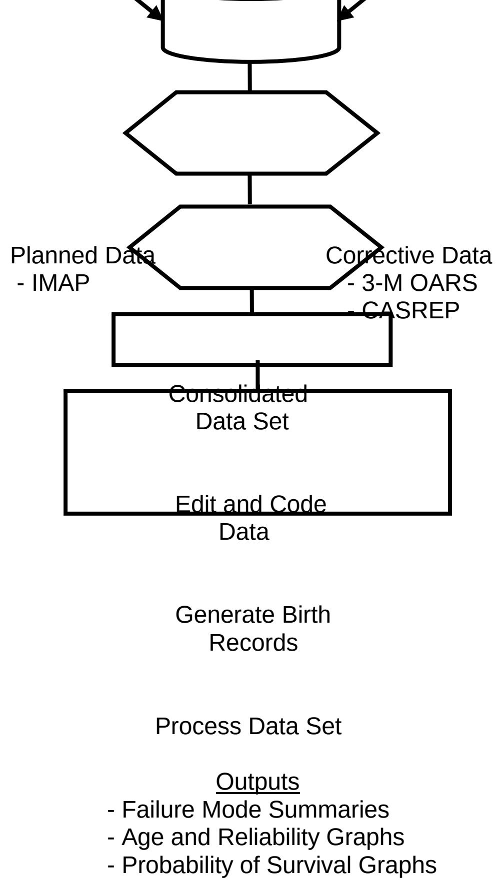


Figure 2. Feedback Data Analysis Process

Finally, to complete the assembly of necessary data records, the engineer must define the population of study to originate component birth records. The population must be born in order to study the effects of aging. This is accomplished by identifying through a selection menu those boats that are within the field of study. Typically this is an entire submarine class or a subset of that class. The final element in defining the overall population is to quantify the set of subject components onboard each boat by uniquely identifying each component, i.e. Trim Pump #1, Trim Pump #2, etc. Once the population is defined, the application automatically generates birth records utilizing submarine Post Shakedown Availability (PSA) dates that are contained in a resident table. PSA, the end of a trial period following commissioning, denotes delivery to the fleet and the commencement of 3-M OARS surveillance.

Corrective Maintenance records must be edited and coded by an engineer or analyst to enable processing of the data set. Some records provide too little information to discern whether a failure occurred or not and those records are invalidated. The application automatically consolidates multiple records having the same job control number. Coding of corrective maintenance records is accomplished to align the data with the ongoing RCM analysis. Each record is assigned a pre-defined failure mode, which corresponds to those failure modes identified by the engineer in the Failure Modes and Effects Analysis (FMEA) module of the RCM application. Additionally, because some corrective maintenance records are discrepancies that do not impair component functionality, the engineer identifies whether the failure mode was a functional failure or not. To gain efficiencies, the application is designed to facilitate batch coding in tandem with key word searches.

The objective is to graph component failure rates based on units of service time. The failure rate is defined as the percent of the population that failed during the observed time period. At a minimum, each valid corrective maintenance record must indicate the boat it is attributed to and the date of the failure. For each valid failure, the "time of service to failure" (age) is calculated during a processing cycle of the application. The age of the component at failure, expressed in months, is determined by subtracting from the date of component failure, the lifecycle origination date. If a component has not been renewed during its lifetime, that date is the PSA date.

$$\text{Age} = \text{Failure Date} - \text{Lifecycle Origination Date} \qquad \text{Equation (1)}$$

Lifecycle Origination Date = PSA Date **or** Last Component Renewal Date

Unit of service time is a parameter established by the engineer and it determines the number of plotted points along the age time line (x-axis). The engineer prescribes the age group duration for which a probability of failure is calculated, and generally that duration is twelve months. Lengthening the age duration serves to dampen fluctuations in the scatter graph. Once an age is computed for each failure and the time span per age interval is prescribed, the application counts the number of failures experienced for each successive interval. Table 1 exhibits a failure count for three age intervals that was derived during an analysis of SSN 688 Class Salvage Air Valves.

Table 1. Failure Counts per Age Interval

Age Interval	Total Failures
1-12 months	6
13-24 months	10
25-36 months	14

What constitutes a component renewal? Should unplanned renewals that were not credited by maintenance schedulers be counted? The answers are dependent on the objectives of the analyst. It should be noted that it is a reality that some corrective maintenance actions, which may renew the life of a component as well as a planned restoration or replacement, are not always appropriately reported to maintenance schedulers. Also, equating a repair with a planned overhaul is a subjective decision and if repairs fall short in comparison to a planned overhaul, both in scope and quality, error is induced. With that in mind, two approaches in studying the effects of aging are possible.

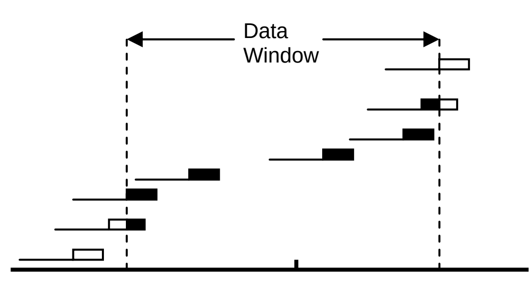
The first approach is to study *physical component health*, where the analyst will attempt through all means possible to account for any action that reverses the effects of component aging. Sometimes the analyst may find that a corrective maintenance record, which renewed the life of the component, was not credited as such in the maintenance management system. So, in addition to accounting for planned and unplanned renewals that were credited by maintenance schedulers, the analyst would ensure that unaccredited renewals were accounted for as well. At SUBMEPP, the engineer would reset the "lifecycle clock" to zero by denoting "Renewal Yes" within the appropriate record of the application. If the unaccredited renewal only renewed a specific component part, the renewal would be credited only when studying the component part in isolation. Anyone studying the component to improve design would utilize the physical component health approach.

The second approach is to study the effect of the component's time directed maintenance plan action on *system health*. This approach measures the effectiveness of the maintenance plan. Only those renewal records, both scheduled and unscheduled, which are credited by planned maintenance schedulers, are used to reset the component lifecycle clock. The analyst would accept that there might be unplanned events during the lifecycle, which reverse the effects of component aging, improving system reliability. Those events were not caused by the existence of an engineered component periodicity, nor did they influence the execution of the time based maintenance plan. Therefore, they are treated as outside environmental influences, which may or may not affect system health. In fact, if non-credited renewals occurred at some relevant frequency and maintained system reliability within a random failure pattern, even though a physical component age and reliability relationship actually existed, a time directed task would not be worth accomplishing. Although, if it were known that improvements were being made to report and credit unscheduled renewals and controls were established to lessen the subjectivity of crediting unscheduled maintenance, the first approach to study physical component health would be appropriate. Bottom line is, don't measure with a micrometer if the cut will be made with a saw.

Next, the population for each age interval must be calculated to compute the failure rate. Given a particular age interval, what is the number of components that could have had an observed failure? For instance, there are many *Los Angeles* class submarine components that have operated at least a year, but there are far fewer with twenty years of service life. A factor complicating this determination is the often times limited duration of the corrective maintenance data "window". While sixty *Los Angeles* class boats have had components serve through at least one year of service time, many of those components served their first twelve month age interval prior to 1989, and 3-M OARS data can not be retrieved for dates earlier than that. The SSN 700 boat had components serve during their first year of service in 1982, but it is not known what failed during that time period.

Because the time span of 3-M OARS data has limits, and because an analyst in any industry may choose to study only a targeted calendar time frame, the beginning and end dates of the data window must be accounted for to enable accurate processing. The maintenance plan strategy for a particular component is often changed at a particular date, so for comparison, the analyst may wish to independently study age and reliability relationships both prior to and after the date of that change. By accounting for the data window span, the system will ignore those component service times outside of the window. An analyst should be careful not to confuse the time span of the data window with the overall age span of the population. There is no relationship.

For example, the data window for a particular analysis may commence January 1, 1990 and end on January 1, 2000. If the specified age interval duration was 12 months and the application was calculating the third age interval (25-36 months), then the population of components that experienced the age of 25 to 36 months, anytime between Jan 1 1990, and January 1, 2000, must be counted. All components whose lifecycles commenced between January 1, 1988 and January 1, 1997 would satisfy the requirement of having fully served the third age interval during that ten year data window, if they indeed lasted that long (see figure 3). If an existing component was placed in service on January 1, 1980, it would experience an age span of 121 to 252 months during the data window. That would represent age intervals 11 through 25. Of course, component lifecycles usually don't start and end at the same time of year as the data window boundaries, so SUBMEPP's application accounts for this by calculating fractional populations. The population for a specific age interval is not always a whole number.



Jan 1990 Jan 1995 Jan 2000

= Third age interval (24-36 months). Shaded region represents interval portion observable within data window.

Figure 3. Third Age Interval Population

Constrained data windows can induce error if not accounted for properly. If the analyst is studying physical component health, component ages, for those put into service prior to the start of the data window, can not be verified. In that case, those component lifecycles must be omitted from the study until the first known life renewal occurs within the data window. This is one of the reasons why most SUBMEPP analyses are conducted utilizing the system health approach.

Some people do not readily accept the premise that the entire life of some components in the study need not be observed. The process should be thought of as an age comparison. A good analogy of SUBMEPP's process would be the studying of a newspaper's obituary section. On any given day there are usually more eighty-year-olds listed than thirty-year-olds. If subsequent daily readings yielded the same result, the analyst may generally conclude that death at eighty is more likely than death at thirty. If the analyst then reviewed census data to estimate the regional population counts for those age groups, and normalized the results for the two age groups, the analyst's conclusions would be even more relevant. The analyst would not have to study eighty years worth of newspaper obituaries to accurately conclude that the probability of death at eighty is higher than the probability of death at thirty.

Finally, when all variables are accounted for properly, the failure rate is computed by dividing the total number of failures per age interval, by the population for that age interval.

Utilizing the Salvage Air Valve failure counts exhibited in table 1, the failure rates are calculated and displayed in table 2 based on actual age interval populations. Now the effects of age on reliability can be observed (figure 4). This is done through regression analysis where probability of failure is the dependent variable and age is the independent variable. SUBMEPP's application creates a scatterchart of plotted points, and fits both a line and 2nd order polynomial. The mathematical equation for these curves is generated as well. While a mathematical function can most always be created from scattered data, its relevance will be based on the results of a correlation analysis. The application conducts a correlation analysis as well for both curves to explain how well the plotted points fit about the generated curves. Coefficients of determination are calculated to indicate what portion of data variance is explained by the independent variable (age).

Table 2. Failure Rate Computations

Age Interval (months)	Total Failures	Population	Failure Rate (%)
1-12	6	292	2.1
13-24	10	312	3.2
25-36	14	337	4.2

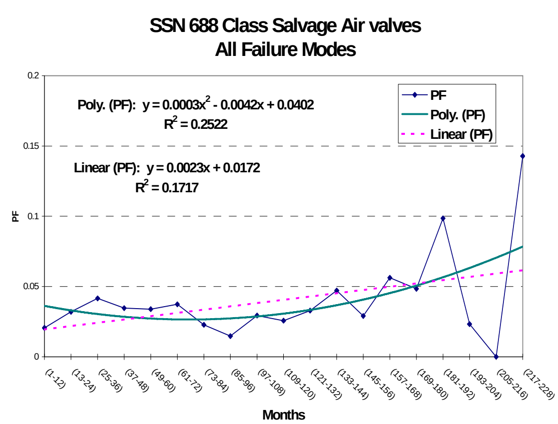


Figure 4. Age and Reliability Graph for SSN 688 Class Salvage Air Valves

Results

SUBMEPP's Reliability Centered Maintenance group supports the organization's Engineering division and Maintenance and Availability Planning Programs division. In the capacity of process owners, the group works collaboratively with submarine system maintenance engineers, in a team environment, to conduct RCM analysis on specific system components. Another aspect of the group's mission is to train engineers in all areas of RCM. The data analysis application was created to be utilized by either professional data analysts or by maintenance engineers. Both approaches have worked well and each has its own advantages. To date, Age and Reliability graphs have been generated for fifty-two submarine component types. These components are as complex as communications equipment, refrigeration plants, turbine generators and towed array handling equipment. Simple, but vital components have been analyzed as well such as hull and backup valves, gas regulating valves, steam isolation valves and ship's whistle. Air dehydrators, switchboards, circuit breakers, hatches, compressors, pumps, condensers, motor generators, torpedo tubes, atmosphere control equipment, and propulsion shaft bearings are all examples of the type of equipment comprising this paper's fifty-two component sample.

71% of the components profiled by SUBMEPP experienced a steady state of random failure after their early years of operation. Some of the components in this group did experience infant mortality or short-lived increases in their rates of failure. This compares generally well with the UAL (89%), Broberg (92%) and MSP (77%) studies. As mentioned previously, UAL and Broberg are based on aircraft. MSP and SUBMEPP are based on navy vessel components and so it is logical that SUBMEPP's results parallel MSP much closer than UAL and Broberg. The concept of industry norms is reinforced here.

SUBMEPP's age and reliability characteristic findings are categorized in figure 5 based on sample population proportions. Only 12% of the sample supported the traditional belief that equipment operates at a steady state of reliability and then wears out at an identifiable time period. The remaining 17% that demonstrated age related wear out did so at an increasing but steady rate over their life span.

The differences between characteristics B and C may possibly be explained by the complexity of the component. The simpler the component and the fewer failure modes attributed to it, the more likely that sudden wear out occurs, if indeed there is an age and reliability relationship. Interestingly enough, all of the components in the sample that exhibited characteristic B were either valves or valve like in function. There was one component that matched characteristic A and, being an electro-mechanical device with numerous valves, it suffered predominately electrical type failures in its early years and predominately valve related failures in its later years.

Characteristic C components tended to be more complex then characteristic B. Complex components have multiple modes of failure and those individual modes may fit characteristic B when viewed in isolation. However wear out

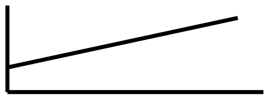
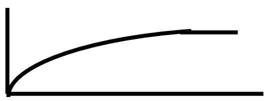
Characteristic Category		UAL 1968	Broberg 1973	MSP 1982	SUBMEPP 2001
A		4%	3%	3%	2%
B		2%	1%	17%	10%
C		5%	4%	3%	17%
D		7%	11%	6%	9%
E		14%	15%	42%	56%
F		68%	66%	29%	6%

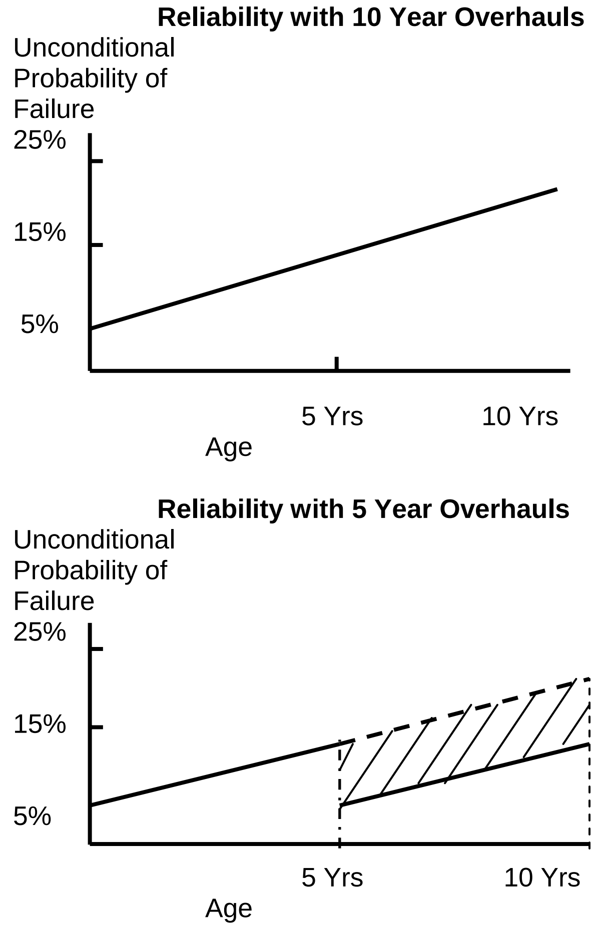
Figure 5. Age and Reliability Characteristic Categories

patterns among these individual modes tend to occur at different times and when viewed in the aggregate, the overall failure rate pattern matches characteristic C.

Characteristic C represented a larger portion of SUBMEPP's sample than it represented for MSP. Conversely, characteristic B represented a much smaller portion of SUBMEPP's sample than it represented for MSP. The analytical approach may bear some responsibility. Recall the two possible approaches - physical component health and system health. The majority of SUBMEPP analyses were conducted utilizing a system health approach where only planned overhauls were considered life renewals. This inevitably resulted in some dampening of failure rate increases. For instance, SUBMEPP analyzed a desurger and found that it experienced an increased failure rate as it aged. When the physical component health was analyzed, where some unscheduled repairs or part replacements were considered life renewals, the failure pattern matched characteristic B. This was caused by the desurger's rubber bladder. The bladder had a pronounced failure rate increase at 133 months. However, when system health was analyzed, where only scheduled component renewals were credited, the failure pattern matched characteristic C. Under the physical component health approach, not all components last to the latter age intervals. The failure rate is termed the "conditional" probability of failure. The condition being, the component must survive to that age interval. However, under the system health approach, many more components survive to the latter age intervals, even though some measure of life renewal occurred along the way. It is that unaccredited measure of life renewal that results in an improved reliability outlook and tends to create a linear incline, vice an exponential incline. It tends to blur any sharp swing in the pattern.

Ideally, life renewal tasks are prescribed when a characteristic B situation occurs - just prior to the upswing in the probability of failure. Life renewal tasks might still be applicable and effective in a characteristic C situation if system health was analyzed. If, for instance, it is demonstrated that a failure rate beyond a certain percentage is undesirable, a maintenance task at that point should return the failure rate to that found at the x-axis origin. What is the return on investment? Figure 6 displays an unconditional probability of failure graph for an asset where only planned renewals were credited. The asset has a planned renewal every ten years. The probability of failure is termed “unconditional” since the entire population shall survive to an age of ten years, unless the component or system is removed from operation. Now, suppose that a 15% failure rate is deemed unacceptable. What would be the effect of a planned renewal at five years? The action would prevent the annual failure rate from increasing beyond 15%, of course, and the increased repair costs beyond five years would be avoided. The reliability effect would be quantifiable by subtracting the area under the curve prior to five years, from the area under the curve beyond five years. If cost were the sole determining factor, the analyst would quantify the costs associated with failure and the costs associated with a planned renewal to determine if there are savings worthy of an investment.

8% of SUBMEPP’s sample population exhibited infant mortality characteristics. This differs significantly with the earlier findings of UAL and Broberg. As mentioned previously, navy vessels go through a lengthy test period prior to entering service. Infant mortality likely exists however those failures are not captured in 3-M OARS during those test periods. SUBMEPP’s infant mortality statistics differ from MSP as well. 32% of MSP’s sample suffered from infant mortality. Differences may be caused by the type of equipment analyzed. The majority of SUBMEPP’s components fitting characteristics A and F were more electrical in nature, than mechanical. Electrical devices are more prone to sudden failure early in their life. The majority of components in SUBMEPP’s sample were mechanical in nature, however, and that may differ from MSP and the other studies.



Shaded portion represents reliability gains.

Figure 6. Reliability Effect of Time Based Overhaul

Platform differences may contribute as well. SUBMEPP’s results are derived from a sample of submarine components and MSP’s results are derived from a sample of surface ship components. Corrective maintenance accomplished during a submarine overhaul is not captured by 3-M OARS. Not until the boat is delivered to the fleet is corrective maintenance reported to 3-M OARS.

For the purposes of this paper it should be stated in mathematical terms how SUBMEPP categorized components as characteristic E or C. None of the components within this group had a regression line with a perfect slope of zero. Some had a negative slope and some had a slight but positive slope. For a component to be deemed characteristic C, the slope had to exceed 0.003X, and it had to have a coefficient of determination of at least 0.1 (10% of the variation is explainable by age). The slope of 0.003X was judged to be too slight to qualify as a component experiencing wear out. It would take 33 years for the failure rate to increase from 10% per year to 20% per year.

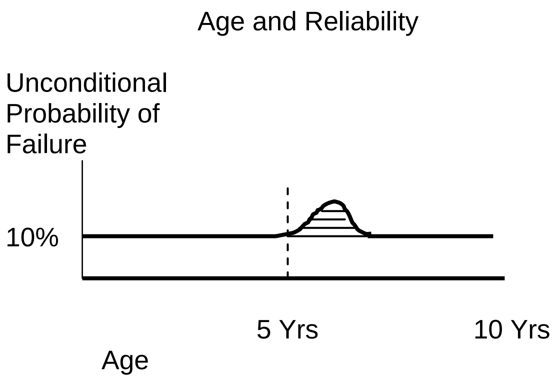
Maintenance Plan Changes

The majority of components analyzed by SUBMEPP did not demonstrate an age and reliability relationship and consequently, many existing time directed component overhauls have been deleted from class maintenance plans. These deletions have allowed the Navy a substantial cost avoidance for submarine depot availabilities. The term avoidance is used here because one can not project beyond the age span of study to predict future probabilities of failure. Components may or may not experience failure rate increases and that will be a future determination when maintenance strategies for these components are revisited. SUBMEPP's review of components does shed light on the effectiveness of many overhaul periodicity extensions made in the early 1980's however. The majority of components that fit non-wear out characteristics D, E and F once had overhaul periodicities half as long.

The RCM approach is to extend or eliminate overhaul periodicities in the absence of an age and reliability relationship. The decision whether to extend the periodicity or delete the action entirely often depends on the consequences of failure. Extensions are more appropriate for components with safety related failures for which no effective condition monitoring techniques have been devised. Deletions are more appropriate for non-safety related components. Maintenance plan strategies should not be based entirely on failure rates viewed at the equipment level. Individual failure modes should be viewed in isolation as well to determine if an age and reliability relationship exists. If so, a surgical maintenance approach may be appropriate where only a piece part or subassembly is replaced.

The portion of components analyzed by SUBMEPP, that did demonstrate an age and reliability relationship, was further analyzed to determine if a time directed maintenance task was appropriate. For non-severe failures, where there are no additional costs attributed to failure beyond material and labor to repair the component, a fix-when-fail strategy may still be more cost effective. Labor and overhead cost differences must be taken into account. And if there are mission or collateral damage costs associated with failure, condition monitoring can sometimes be substituted for a time directed task. Condition monitoring must detect potential failure conditions and allow a known and sufficient time period for adequate correction. A more surgical maintenance strategy may be appropriate as well. Pareto's rule that 80% of the problems are generally caused by 20% of the actors has been validated by RCM analyses. Maintenance professionals should concentrate on the few "bad actors" which degrade reliability. Also, if one took the physical component health approach, they must calculate the population that has survived to the age where a time directed task is desired. The action may be saving only a small portion of the population.

When pursuing the system health approach, one must recognize that steady increases in unreliability are generally non-sustainable. At some point, the majority of items that are going to fail have failed and the influence of corrective maintenance improves reliability. Therefore one must compare the area under the curve both before and after the time of the desired maintenance action to determine the payback. Sometimes there is a dramatic failure rate increase followed shortly thereafter by a swift decrease. In such a case, there may not be area enough under the curve to warrant the investment of a time directed task (see figure 7).



Shaded portion represents reliability gains achievable with an overhaul at five years.

Figure 7. Reliability Effect Possible with 5 Year Overhaul

Oftentimes newly manufactured components and newly restored components are thought of as *apples* and *apples* when they should be considered *apples* and *oranges*. SUBMEPP analysis has shown that reliability after overhaul is not always equivalent to the reliability of a newly manufactured component. To compare the two, the analyst would choose *not* to restart the lifecycle clock of a component when it had a planned renewal. This will cause the application to graph reliability beyond the renewal age. If the component's planned overhaul was effective in improving the health of the component, one would see a sudden reliability improvement as exhibited in figure 8. If no change were observed, one would conclude that although replacement with a new component would affect reliability, overhaul of the existing component would not. SUBMEPP recently analyzed an air dehydrator. Age and Reliability graphs for the dehydrator showed that the component did experience increased failure rates as it aged and corrective maintenance was not improving the situation. Because of backup capabilities, the failure modes in question did not have significant consequences, however consideration was given to restoring the unit from a cost containment perspective. The system engineer took the additional step of comparing the effectiveness of past overhauls to the reliability exhibited by a new component and found that little improvement would be gained from an overhaul.

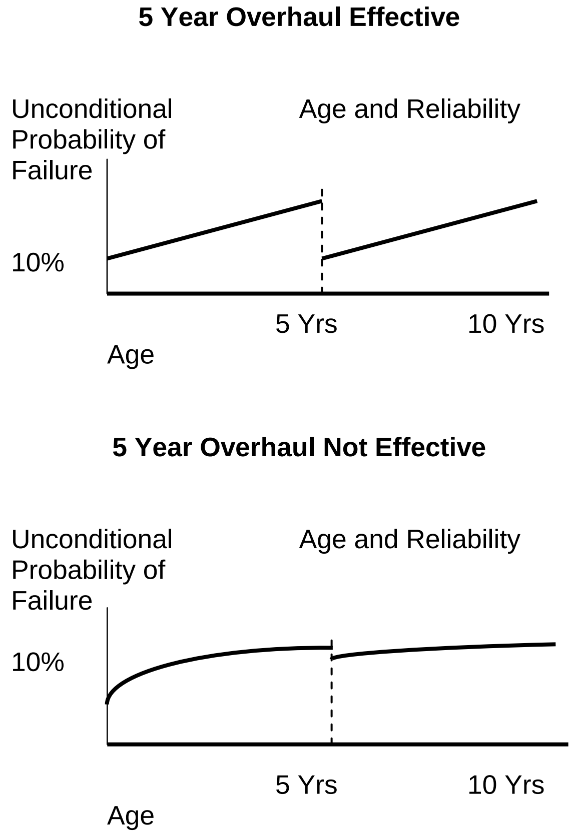


Figure 8. Various Reliability Effects with 5 Year Overhaul

Case Study

Soon after the development of the feedback data analysis application, a SUBMEPP combat systems engineer analyzed *Trident* class torpedo tubes. Torpedo tubes are comprised of barrels, breech and muzzle doors, latches, linkages, slide valves, rotary actuators, power cylinders, safety interlocks, indicators and numerous other sub-assemblies. The class maintenance plan for the torpedo tubes included a time based maintenance action to replace hydraulic power cylinders every 160 months. Each torpedo tube has five cylinders. Functional failures for these components are mission critical as they render a tube inoperable, or degrade performance to an unacceptable level. Even though there are multiple torpedo tubes, a full complement of operational torpedo tubes is deemed necessary for readiness. Two of the power cylinders operate the torpedo tube slide valve. Over half of the observed discrepant conditions associated to inoperability of the slide valve were attributed to the hydraulic power cylinders and only one of those discrepancies was judged to be a functional failure. The predominant mode of failure was external leakage of hydraulic fluid and as previously stated, these were judged to be non-functional failures. They were potential functional failures if left untreated. Figure 9 displays the Age and Reliability curve for the slide valve power cylinders. The failure pattern is random with no correlation with time. In fact, the regression line has a slightly negative slope of 0.0003X. There is no evidence indicating that the valves should be replaced at 160 months. Moreover, the engineer found that existing condition monitoring tasks were applicable in monitoring and maintaining system health. Periodic pressure and cycle time tests are able to detect degradation before performance is compromised, and allow sufficient time for repair or replacement of cylinders. Age and reliability findings for the remaining power cylinders were similar. The engineer deleted the requirement to replace torpedo tube power cylinders at 160 months and this lifecycle cost avoidance for *Trident* class submarines was determined to be $2.3 million. If the current reliability trend holds consistent over the submarine lifecycle, that avoidance will be actual savings.

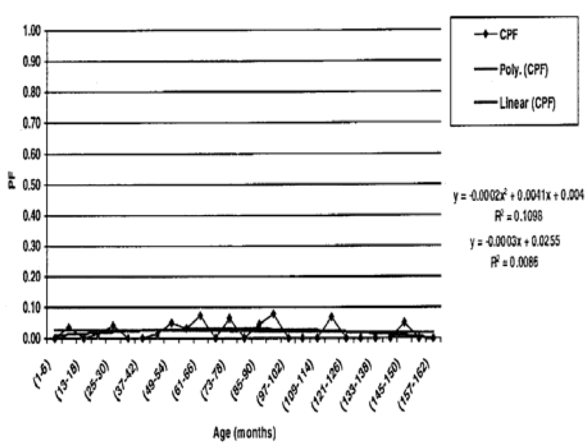


Figure 9. Age and Reliability Graph for Torpedo Tube Slide Valve Power Cylinders

CONCLUSION

The vast majority of steady state random failures exhibited by the sample of submarine components analyzed by SUBMEPP support the 1961 finding that “reliability and overhaul time control are not necessarily directly associated topics”. At the conclusion of an RCM analysis it has been uncommon at SUBMEPP to prescribe time directed component renewals. Prescription of condition monitoring tasks has been the prevalent strategy to maintain safe operation and required asset functionality. The once held belief that time is the best guide in scheduling major equipment overhauls should no longer be ascribed to. More appropriately, maintenance professionals should continue the evolution of devising conditioning monitoring parameters to better assess component health. Advents in technology are making this easier with each passing day. Whenever possible, the component should communicate to the maintainer when maintenance is appropriate or necessary. However, the findings of this paper should not dissuade one from analyzing the effects of time on component reliability. Age and reliability correlations do exist for many components and as components in various systems, platforms and facilities experience ages never before observed or studied, past results are subject to change. Moreover, maintenance engineers must always be on guard to prevent safety-related failures, which haven’t occurred, but could occur at older lifecycle ages. Material condition assessment is appropriate for these instances. Maintenance plans must periodically be revisited to assess past decisions and to devise new strategies based on current best practices and new technologies. In the end, there is no substitute for an in-depth, thorough and comprehensive review of maintenance feedback data.

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BIOGRAPHY

Tim Allen is a Reliability Analyst Leader at Submarine Maintenance Engineering, Planning and Procurement (SUBMEPP), a Naval Sea Systems Command field activity located in Portsmouth, NH. He has worked at SUBMEPP for the past sixteen years. As a member of the Reliability Centered Maintenance group, he co-developed SUBMEPP's Feedback Data Analysis System. Tim trains system engineers in the principles and methodologies of RCM and works collaboratively with them to engineer maintenance plans. He was previously an engineer for submarine atmospheric and seawater systems. Tim received a Bachelor of Science in Mechanical Engineering Technology at the University of Maine in 1986. In 1997, Tim received a Master of Business Administration degree at New Hampshire College.