EFFECTIVE MEASUREMENT OF RELIABILITY OF REPAIRABLE USAF SYSTEMS

THESIS

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Abstract

The USAF generally does not know the reliability of its fielded repairable systems. The reported metric, Mean Time Between Failure (MTBF), is too lagging to be actionable in the best case, and is not representative of actual system reliability in the worst case. This thesis investigates the statistical techniques for measurement and analysis of the reliability of fielded repairable systems, which are very different than nonrepairables. To frame the investigation, a comparison is made between the generally accepted definitions and metrics and those used across the US Air Force (USAF). Reliability can be analyzed in four context areas: reliability prediction of nonrepairable and repairable items and reliability measurement of nonrepairable and repairable items. This research is focused on the latter. An algorithmic process for effective measurement of reliability of fielded repairable USAF systems, based on recurrent event analysis, is proposed and demonstrated using a non-parametric approach on USAF maintenance data. The approach provides a new capability that can identify even short term changes in system Rate of Occurrence of Failure (ROCOF), which can identify daily or hourly trends across the fleet subsystems. This new approach is compared to USAF calculations of MTBF over the same period.

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Louis J. Hogge

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EFFECTIVE MEASUREMENT OF RELIABILITY OF REPAIRABLE USAF SYSTEMS

I. Introduction

General Issue

The United States relies on complex systems to protect and project the national interest. These systems must be available to meet the operational need. The necessary system Operational Availability (A_o) is calculated from the overarching system requirements. The system reliability, maintainability, and logistics support requirements are subsequently derived from the A_o requirement.

The U.S. Department of Defense has renewed emphasis on reliability as the major contributor to system availability and to the operations and support costs associated with sustainment of the systems. In a recent memo the Director of Operational Test and Evaluation, Office of the Secretary of Defense, stated,

> "Poor reliability is a problem with major implications for cost. Sustainment costs have five to ten times more impact on total life cycle costs than do RDT&E costs. Unreliable systems have higher sustainment costs because, quite plainly, they break more frequently than planned. Poor reliability leads to higher sustainment costs for replacement spares, maintenance, repair parts, facilities, staff, etc. Poor reliability hinders warfighter effectiveness and can essentially render weapons useless." [1]

When systems do not meet the required availability due to less than expected reliability the logistics system must increase the flow of parts. The Department of

Defense (DOD) supply chain spends billions of dollars to purchase, manage, store, track, and deliver spare parts and other supplies to keep military equipment ready and operating. DOD reported that it managed more than 4 million secondary inventory items valued at more than $91 billion as of September 2009. Secondary inventory items include reparable components, subsystems, and assemblies other than major end items (e.g., ships, aircraft, and helicopters), consumable repair parts, bulk items and materiel, subsistence, and expendable end items (e.g., clothing and other personal gear). [2]

Effective Supply Chain Management (SCM) requires active control of system performance. Performance-based sustainment makes business sense when operation and support costs are significant higher than acquisition costs and sustainment costs can be reduced by smarter repairs. [3] Poor system performance (reliability) drives unnecessary repair actions and cost at the weapon system and commodity level. Repair is the single biggest customer of (buying components and subassemblies), and supplier to (selling repaired commodities), the USAF supply chain. The current USAF repair network includes over 150 managers, nearly 50,000 maintainers, and a $14 billion budget. [4]

To enforce the emphasis on system availability Chairman of the Joint Chiefs of Staff Instruction 3170.01F mandates use of Availability Key Performance Parameters (KPP) and Reliability and Ownership Cost Key System Attributes (KSA). [5] The Under Secretary of Defense (USD) for Acquisition, Technology, and Logistics (AT&L) issued a memorandum that defines the metrics and reporting requirements [6]. For the DoD the reportable metric quantifying materiel reliability is Mean Time Between Failure (MTBF) further defined as Operating Hours/Failures.

Reliability Definition

A widely accepted definition of reliability is the probability that a system or product will perform in a satisfactory manner for a given period of time when used under specified operating conditions in a given environment. [7]

Reliability will be segmented into four areas as presented in Table 1. Primarily, this thesis focuses on the Measurement of Recurrence Data (bottom right quadrant of Table 1).

Table 1. The Four Context Areas of Reliability Analysis

	Prediction (Estimation from Probabilistic Models)	Measurement (Data from Deployed Systems)
Life Data (throw away items, nonrepairable)	Traditional focus of reliability Based on design, part selection, and production quality	Mean Time To Failure (MTTF) Data fit to known distributions for comparison to prediction
Recurrence Data (repairable items, systems)	Reliability Block Diagrams Stochastic Point Process Models (HPP, NHPP, and many variations),	Arrival Interval Analysis Recurrent Event Data Analysis (nonparametric) Critical data is ordered sequence of times to failures.

Reliability can be predicted and measured. A reliability prediction is a probability calculation based on characteristics of the design. The reliability calculation is intended to affect the design to meet an availability requirement. A reliability measurement tracks failures as a function of time or usage. To compare the measured reliability to the predicted reliability definitions of the system or product, failure modes, period of time, operating conditions, and environment must be common or accounted for. The technique for comparison of measured reliability to predicted reliability attempts to model the failure occurrences as a parametric function related to the predictive model.

Problem Statement

The DoD and USAF measure of reliability is mean time between failure (MTBF) which is a discrete value calculated as the ratio of operational time to failures [8]. This definition of MTBF is an oversimplification that makes assumptions about the failure distribution that may not be accurate or intended. The necessary assumptions to state MTBF as the ratio of time to failures are not supported in the preponderance of applications [9] [10] [11]. To make credible judgments about the failure distribution the operating time to failure and environment must be tracked for individual items. The AF does not have a process or system to effectively or accurately track the performance of individual items or material. The AF is not applying effective processes or expertise to analyze the available field reliability data.

Effective measurement of reliability requires accurate time to failure, sequence of time to failures, and failure mode data. AF policy requires monitoring of component configuration and in-system performance [12] and detailed component histories but a general AF data system does not exist that effectively collects, retains, or provides access and analysis of weapon system component performance data and histories.

Research Objectives and Focus

The following objectives will guide this thesis. First this thesis seeks to summarize the research into the general (non-DoD) basis for the MTBF calculation, its use as a specification or measurement of reliability of fielded repairable systems/components, and alternative methods for measurement of reliability in this context (row 2 column 2 of Table 1). The thesis seeks to examine DoD and USAF measurement of reliability of fielded repairable systems and components data demonstrating expected shortfalls. Lastly, a more effectively derived measure is sought.

The focus of this research will be on the definition and nonparametric measurement of reliability of *repairable* USAF systems. As the field of reliability is expansive, this paper will not deal in detail with reliability prediction methods or with parametric statistical modeling of failure data.

The primary research question is, "Based on USAF repairable system recurrence data, how can reliability best be non-parametrically measured"?

Methodology Overview

1. A review of literature will examine the generally accepted definition of reliability and compare to the DoD reliability definition. The review will briefly examine the current state of reliability prediction and measurement in the four context areas shown in Table 1. The applicability of MTBF and Mean Time To Failure (MTTF) as the metric to define reliability of repairable and nonrepairable items will be examined.
2. The DoD and Air Force definition of MTBF will be considered. The AF use of MTBF as ‘the’ indicator of reliability of systems and commodities will be considered in the context of the current literature.
3. The accuracy and applicability of REMIS data as the authoritative source for AF reliability and maintainability data will be examined by using some specific data extraction and analysis cases. Some methods of REMIS data analysis that support reliability improvement will be presented.

Implications

Reliability of fielded repairable and complex systems in use in the DoD is generally not known. In most cases the reliability metric being reported (MTBF) is not accurate and in the worst case may not even be correlated to the actual system performance.

Preview

The DoD definition of reliability and the requirement for measurement of reliability is not coherent. MTBF is designated as the measure of reliability [13]. This paper will examine a more concise definition of reliability and the need for a less prescriptive requirement for the reliability metric. The current DoD emphasis is on reliability during design and test. Contracts require a comprehensive reliability program with defined metrics. Fault And Corrective Action Systems (FRACAS) are required. These specific requirements do not flow into, and are not generally measureable in, the Operations and Support phase of the programs.

The inadequacy of the AF Reliability reporting will be examined using some anecdotal cases. The process of the anecdotal cases will be related to the general case of REMIS inadequacy as a source for reporting component reliability or for root cause analysis of system reliability issues.

A suggestion for analysis of existing USAF maintenance data that would provide a more effective view of repairable system reliability and may lead to AF system reliability improvement will be presented.

II. Literature Review

Chapter Overview

The purpose of this chapter is to provide a reliability definition and review of the basis and effectiveness of Mean Time Between Failure (MTBF) as the measure of reliability. Brief background information on the topics context areas as shown in Table 1 is presented. A more detailed review of literature pertaining to the process for nonparametric analysis of recurrence data of deployed systems will be provided. This will be the context used for the methodology and data analysis chapters. The intent is to frame in the reader‘s mind that different data sets and different statistical processes are required in each context.

Reliability Definitions

Reliability of systems started to receive serious consideration with the increasing complexity of weapon systems during World War II. A widely accepted definition of reliability is traced back to the Advisory Group on the Reliability of Electronic Equipment (AGREE) formed by the U.S. Department Defense in 1952. A 1957 AGREE report defined reliability as the probability that a system or product will perform in a satisfactory manner for a given period of time when used under specified operating conditions in a given environment [14]. Note that this definition has four important elements: (1) reliability as a probability distribution, (2) defined satisfactory performance, (3) specific operating conditions, and (4) specific environment. All of these elements are critical to an unambiguous definition of reliability of a system or individual component.[7]

The definition of reliability in the DoD Guide for Achieving Reliability, Availability, and Maintainability and in MIL-STD-721 (cancelled 1995), Definition of Terms for Reliability and Maintainability, includes the four important elements of the definition above, 1. “the probability of” 2. “an item to perform a required function” 3. “under stated conditions” 4. “for a specified period of time.” [15] [16]

The USAF definition of reliability in Air Force Instruction 21-118, Improving Air and Space Equipment Reliability and Maintainability, omits the probability element and introduces the generalization of reliability as MTBF, “The ability of a system or component to perform its required functions under stated conditions for a specified period of time. Usually expressed as mean time between failures (MTBF).” [17]

The Under Secretary of Defense (USD) for Acquisition, Technology, and Logistics (AT&L) issued a memorandum defining reliability metrics and reporting requirements [6]. That memorandum defines Materiel Reliability as:

> Materiel Reliability is a measure of the probability that the system will perform without failure over a specific interval. Reliability must be sufficient to support the warfighting capability needed. Material Reliability is generally expressed in terms of a mean time between failure(s) (MTBF) and, once operational, can be measured by dividing actual operating hours by the number of failures experienced during a specific interval

The USD for AT&L definition is problematic. It states that Materiel Reliability is a specific probability value, of zero failures, over a specific interval. It does not mention specification/control of the operational conditions or environment.

The USD for AT&L memo and the USAF definition say that Materiel Reliability is generally expressed in terms of MTBF and describes operational Materiel Reliability as actual operating hours divided by failures in a defined interval. While the total life operating hours divided by total life failures is the literal value of the MTBF of a system, in practice the calculation is typically applied to a windowed period of the lifecycle operating time over failures (as suggested in the USD Memo) where the calculation may not be applicable. In a windowed period of time the operating hours divided by failures as the mean is only applicable to the exponential probability distribution where the failure rate is constant. That case is not applicable to repairable systems as will be discussed later in this chapter and demonstrated in chapter 3.

The first and third sentences of the USD memo are not complimentary. The material Reliability cannot be both, " … the probability that the system will perform without failure over a specific interval" and "expressed in terms of a mean time between failure(s) (MTBF) and, once operational, can be measured by dividing actual operating hours by the number of failures experienced during a specific interval." MTBF is a single number derived from the total lifecycle. It gives no information about the probability of failure in any specific interval unless the specific distribution is known.

It is important that the DoD/USAF definition of reliability be applicable and consistent across all four areas of reliability shown in Table 1. The original 1957 AGREE definition is consistent and applicable across the reliability field.

Reliability in Context

The practice of reliability prediction and measurement involves statistical modeling and analysis of data on time to occurrence of events of interest. When assessing reliability it is important to make the distinction between nonrepairable components and repairable systems, life data verses recurrence data [18] as represented by the rows of Table 1 (reproduced here).

Table 1. The Four Context Areas of Reliability Analysis

	Prediction (Estimation from Probabilistic Models)	Measurement (Data from Deployed Systems)
Life Data (throw away items, nonrepairable)	Traditional focus of reliability Based on design, part selection, and production quality	Mean Time To Failure (MTTF) Data fit to known distributions for comparison to prediction
Recurrence Data (repairable items, systems)	Reliability Block Diagrams Stochastic Point Process Models (HPP, NHPP, and many variations),	Arrival Interval Analysis Recurrent Event Data Analysis (nonparametric) Critical data is ordered sequence of times to failures.

That distinction is often omitted as the terms and concepts are similar and the distinctions are subtle [19]. According to Meeker and Escobar [20] the important distinction is between data from, and models for, the following:

- The time of failure for nonrepairable units.
- The sequence of system failure times for repairable systems.

In a 1970 IEEE Transactions on Reliability editorial Mr. Ralph Evans stated, “After many years the reliability profession is still in sad shape with regard to understanding its basic concepts.” He closed the article with, “One cannot guarantee that wrong answers will be obtained if the proper model is not analyzed, but one can guarantee that the existing literature is very confusing and very few reliability engineers really understand the various kinds of models they invoke from time to time." [21] The editorial was republished in the June 2000 IEEE Transactions on Reliability to, "show that many things do not change, especially where people and their beliefs and problems are concerned." [22]

John Usher pointed out in 1993 that even though most complex systems are repaired, not replaced; the statistical methods and models that are appropriate only for nonrepairable systems are often used for reliability analysis [23]. He presents failure data from a repairable system and shows how application of the incorrect analysis (based on an iid assumption) provides a result that is opposite the correct result. The 1984 Ascher and Feingold book, *Repairable Systems Reliability. Modeling, Inference, Misconceptions and Their Causes* details many of the misconceptions and problems associated with treating repairable systems reliability data as if it were from a nonrepairable system [24]. Ascher and Christian Hansen presented a course, *Concepts and Models for Repairable Systems Reliability*, at the 2009 Centro de Investigacion en Mathematicas (CIMAT). The abstract for their course says they present the basic concepts and models for parts (nonrepairable) and systems (repairable) and, "stresses their up to infinite differences, rather than their superficially striking but relatively unimportant similarities." [25]

It is established that the appropriate statistical processes and data sets for reliability analysis depend on whether the subject is nonrepairable (life data) or repairable (recurrence data). These two contexts are further divided by the purpose of the analysis and the phase of the product lifecycle.

Parametric, or probabilistic, models are used to predict future performance and compare alternative designs in the absence of complete data. Nonparametric analysis of operational data is used to evaluate current and past reliability performance. The prediction of future performance based on a design process verses the performance measurement of a finite population of fielded units may be similar to the Deming categories of analytic verses enumerative studies. [26] Deming's analytic study category is statistical analysis of the processes that generate units over time. His enumerative category of statistical analysis uses data from identifiable units to make inferences about the larger population.

Life Data – Nonrepairable Components (Row 1 of Table 1)

Life data is associated with nonrepairable products or systems, a single time to event for each of a population of like units (same design, material, manufacturing processes), usually the end of life [27]. Most reliability literature has been devoted to the modeling and analysis of life data. Statistical software packages that facilitate analysis of life data are available and are widely used for reliability analytics.

For nonrepairable items the lifetime is a random variable. The failure of one item does not affect the performance of another item in the same population so the assumption that the lifetimes are independent is reasonable. If the population is produced to the same design, using the same processes and materials, it is also reasonable to assume the item lifetimes have the same distribution. These two assumptions lead to the basic assumption that the lifetimes are independent and identically distributed (iid). [19]

To assess the reliability of nonrepairable items the failures are tracked as a function of usage, usually hours. To make predictions about failures the data is then fitted to a Lifetime Distribution Model. Mathematical models of components and entire systems may be produced by combining models of many failure modes. The combination may be done by Monte Carlo simulation or by analytical methods. System models are useful for predicting spare parts usage, availability, maintainability, and support costs. [28]

The following definitions are from the Rigdon and Basu textbook, *Statistical Methods for the Reliability of Repairable Systems* [19]. Under the iid assumption the lifetimes have a corresponding cumulative distribution function (cdf) $F(t)$ that is the probability of an event T, that an individual component, or the ratio of the total population that, will fail by time t.

$$\text{cdf} \equiv F(t) = P(T \leq t)$$

Equation 1 Life Data, cumulative density function

The Reliability Function R(t), sometimes called the survival function, is the probability that an individual component will survive beyond t. Survival and failure are mutually exclusive so $R(t) = 1 - F(t)$.

The lifetime distribution model is a probability density function (pdf) $f(t)$.

$$\text{pdf} \equiv f(t) = \frac{d}{dt} F(t) = -\frac{d}{dt} R(t)$$

Equation 2. Life Data, probability density function

The hazard function is related to, but distinct from, the pdf.

$$h(t) = f\,(t\ |T>t)$$

Equation 3 Life Data, Hazard Function

The hazard function is the limit of the probability that a unit fails in a small interval given that it survived to the beginning of the interval. If the hazard function is increasing in a small interval it means that the probability of failure is increasing with the age of the system. The nonrepairable system is *wearing out.* A nonrepairable system with a decreasing hazard function is experiencing *burn-in* [19].

The pdf and the hazard function are important elements to define the reliability of a nonrepairable item. They define the expected life and the probability of failure in an interval.

Recurrence Data – Repairable Systems/Components (Row 2 of Table 1)

Recurrence data consist of times for any number of repeated events on a population unit, for example, repairs of a product. For a repairable system, a number of failures are expected for a single system [19]. Many systems and repairable components accumulate repeated repairs over time. In comparison to life data, analysis of recurrence data is underdeveloped.

A commonly used definition of a repairable system [24] is a system which, after failing to perform one or more of its functions satisfactorily, can be restored to satisfactory performance by an action other than replacement of the entire system. Data from repairable systems are usually given as ordered failure times $T_1, T_2, \ldots$ with data coming from a single system or from several systems of the same kind. [29]

Analysis of such recurrence data requires special statistical models and methods not generally covered in basic reliability books [27] [19]. Ascher and Feingold [24] wrote what may be the first book devoted to repairable system reliability in 1984. Their book presents the case that researchers and practitioners do not recognize or accommodate the crucial differences between the statistical treatments of repairable (life data) or nonrepairable (recurrence data) systems. They used examples to show that conclusions from data may be very wrong if times between failures are treated as statistically independent and identically distributed (iid) random functions when the assumption is not valid.

Stochastic point processes are used to assess the reliability of repairable systems. Failures are tracked as occurrences of events, or points, in time. The order and duration between points is critical.

The following definitions of functions for recurrence data are from the Rigdon and Basu textbook, *Statistical Methods for the Reliability of Repairable Systems* [19]. Assume that a random variable $N(t)$ represents the number of failures in the interval [0, t]. To specify a stochastic model for a point process there must be a joint distribution of the random variables $N(t_1), N(t_2), N(t_3), \ldots, N(t_n)$ and for any $t_1, t_2, t_3, \ldots, t_n$.

The Mean Cumulative Function (MCF) of a point process is defined to be the expected value at $N(t)$. This function is the pointwise average of all population curves passing through each t [27]. The MCF is often denoted by $\Lambda(t)$. Methods for estimation of the MCF are discussed later in this section.

$$\text{MCF} \equiv \Lambda(t) = E(N(t))$$

Equation 4 Recurrence Data, Mean Cumulative Function

When the MCF is differentiable the derivative is defined as the Rate of Occurrence of Failures (ROCOF). The ROCOF is the instantaneous rate of change in the expected number of failures. Methods for estimation of the ROCOF are discussed later in this section.

$$\text{ROCOF} \equiv \mu(t) = \frac{d}{dt}\,\Lambda(t)$$

Equation 5 Recurrence Data, Rate of Occurrence of Failure

The MCF and the ROCOF are important elements to define the reliability of a repairable system. They define the expected number of failures at time t and the probability of failure in an interval.

Reliability Prediction (Column 1 of Table 1)

Reliability Prediction refers to the use of probabilistic models, typically parametric, for the prediction of the reliability performance of nonrepairable items and repairable systems.

<u>Reliability Prediction in the Context of Life Data (Column 1 Row 1 of Table 1)</u>

The theoretical models used to describe unit lifetimes are Lifetime Distribution Models. The population is generally all unit lifetimes for all of the units manufactured based on a particular design, material, and manufacturing process [30]. A random sample of size *n* from this population is the collection of failure times observed for a randomly selected group of *n* units.

A lifetime distribution model can be any *probability density function* (or pdf) *f(t)* defined over the range of time from *t* = 0 to *t* = infinity. The corresponding *cumulative* *distribution function* (or cdf) *F*(t) gives the probability that a randomly selected unit will fail by time *t*.

The pdf *f(t)* has only non-negative values and eventually either becomes 0 as *t* increases, or decreases towards 0. The cdf *F(t)* is monotonically increasing and goes from 0 to 1 as *t* approaches infinity. In other words, the total area under the curve is always 1. This is means that a single randomly chosen unit will fail in infinity. The entire population will fail in infinity.

The most commonly used distributions used to model life data are the exponential, Weibull, and gamma. [19] I will not discuss the Weibull or gamma functions in this paper but characteristics of the exponential distribution have a direct relationship to the later discussion of Mean Time Between Failure (MTBF).

Two theorems, 4 and 5, from the Rigdon, Basu text [19] state the two unique characteristics of the exponential distribution. The exponential distribution has the memoryless property and it is the only continuous distribution with the memoryless property. The exponential distribution has a constant hazard function and is the only distribution with a constant hazard function. The memoryless property means that the probability of failure is not dependent on age. The probability of an old unit surviving in the next interval is equal to the probability that a new unit will survive in the same interval. As shown in the text [19] the result of a constant hazard function is that the mean and the hazard are reciprocal of each other.

Reliability Prediction in the Context of Recurrence Data (Column 1 Row 2 of Table 1)

The difference between the statistical processes applicable to Life Data and Recurrent Data derives from the observation of a single failure per system, usually the end of life, for nonrepairable systems and multiple numbers of failures per system for repairable systems. Due to the multiple failures in a repairable system the iid assumption for the times between failures is usually not valid. [19]

In some limited cases the recurrence data may be iid so a Homogenous Poisson Process (HPP) could model the ROCOF function. While the bathtub hazard function (life data Weibull distribution) may look identical to a recurrence data HPP the interpretations are different. The bathtub hazard function is an expression of the conditional probability of the only failure of the system. The bathtub ROCOF shows that a system will have many failures early in its life, followed by a period of constant ROCOF and then the ROCOF will increase as the system ages and failures are more frequent. [19]

In a paper presented at the IEEE 2005 Reliability and Maintainability Symposium, Mettas and Zhao of the Reliasoft Corporation said two models commonly used for analysis of repairable systems data are the perfect renewal process (PRP) and the nonhomogenous Poisson process (NHPP) [31]. The PRP corresponds to an assumption of perfect repairs where the system is as-good-as-new after repair. The NHPP corresponds to minimal repair where the system is as-good-as-old after repair. The NHPP assumption is that the system after repair is in no better condition than immediately before the failure. Most repairs do not fit either of the extremes of the PRP or NHPP but are some complicated intermediate. A general renewal process (GRP) model attempts to analyze complex repairable systems with varying degrees of repair. The Mettas and Zhao paper provides an overview of existing repairable system models and proposes a formulation for estimating parameters of the GRP and for development of confidence bounds.

There are many other models and variations of models presented in academic literature. There are eight different models discussed in the Mettas and Zhao paper. These models attempt to accommodate such variations as preventive maintenance effects, incorporate the results of simulations such as Monte Carlo, compensate for small sample sizes or few failures, … . However, as Guo, Ascher and Love [32] point out, too much attention is paid to the invention of new models with little thought as to their applicability. Too little attention is paid to necessary data collection and consideration of the usefulness of the models for solving real reliability problems. These models are difficult to apply to engineering problems either because of the strong assumptions or the model complexity.

Reliability Measurement (Column 2 of Table 1)

Reliability Measurement refers to the analysis of field data to monitor and assess the reliability performance of systems in operational use.

The failure rate of a nonrepairable component applies only to the first failure times of the population of parts. [30] The population of nonrepairable parts will decrease over the lifetime as individual parts fail and are replaced until all have failed. A nonrepairable population is one for which individual items that fail are removed permanently from the population. While the system may be repaired by replacing failed units from either a similar or a different population, the members of the original population dwindle over time until all have eventually failed.

A repairable system can be returned to operational condition by adjustment or replacement of parts. The rate at which failures occur during system usage (and are then repaired) is defined as a Rate Of Occurrence Of Failure (ROCOF) or "repair rate". It is incorrect to talk about failure rates or hazard rates for repairable systems. These terms apply only to the first failure times (life data) for a population of nonrepairable components. [30]

Reliability Measurement in the Context of Life Data (Column 2 Row 1 of Table 1)

The purpose of measuring the reliability of nonrepairable items is to assess the quality of the product and for comparison to the expected life. Life data is often used to support predictive analysis by fitting measured data to statistical models.

There are life data models that are applicable to very precise Fault Report And Corrective Action Systems (FRACAS) data and models that are intended to compensate for less precise data. Dr. Abernathy's Fifth Edition of the New Weibull Handbook presents a comprehensive treatment of the two most widely used life data analysis models, the Weibull and the Crow-AMSAA, as well as a good overview of most models currently used for life data analysis.

Life data analysis is often oversimplified by applying the most basic distributions without verifying, or even stating, the underlying assumptions. Reliability analysis of life data requires careful planning and execution. Mistakes can be costly in terms of time and money, wrong decisions made can be detrimental to system operation. [20]. Abernathy warns that it is tempting to plot a single Weibull for systems from poorly defined populations and multiple failure modes. This misapplication will show a β close to one, roughly equivalent to using mean-time-to-failure (MTTF) and exponential reliability, and masking infant mortality and wear out modes. The results are not meaningful for individual failure modes. This method was common and is still used by those unaware of the advantages of newer methods for system models. [28]

Meeker suggest a general strategy for analysis of life data [20]:

1. Begin with graphical analysis without making any distributional or model assumptions.
2. Fit one or more parametric models depending on the purpose of the study and the amount/source of data.
3. Asses the adequacy of the model.
4. If there are no "obvious departures from the assumed model, one will generally proceed, with caution," to predict future outcomes with statistical intervals showing uncertainty and variability.
5. Display results graphically including estimates, predictions, and uncertainty bounds.
6. Assess the adequacy of the model assumptions and provide the conclusions with the reliability results.

Reliability Measurement in the Context of Recurrence Data (Column 2 Row 2 of Table 1)

Recurrence events are analyzed over a period for a single repairable system or for multiple similar systems. Early repairable system data analysis techniques, 1952 to 1991, focused on times to first occurrence, times to second occurrence …, or times between occurrences. [24] [33] . Later methods use parametric counting process models and analysis for the number of occurrences. [19] [20] Estimation of the model parameters requires iterative procedures or special software. There is a significant body of literature on the subject but parametric methods are computationally intensive and not intuitive.

Necessary assumptions are rarely stated, investigated or justified [9]. Nelson provides a less complex method for nonparametric analysis of recurrent data that is also applicable to cost and other "observed values" of events. The process is nonparametric in that it does not specify a point process model for the recurrence rate. The Nelson process is based on the Mean Cumulative Function (MCF). [27] Trindade and Nathan present a tutorial of a practical application methodology of the MCF analysis based on their work with Sun Microsystems [34].

To apply nonparametric analysis of recurrent event data analysis each unit of the population is described by a cumulative history function for the number of event recurrences over time. Figure **1** depicts a single unit's cumulative history function:

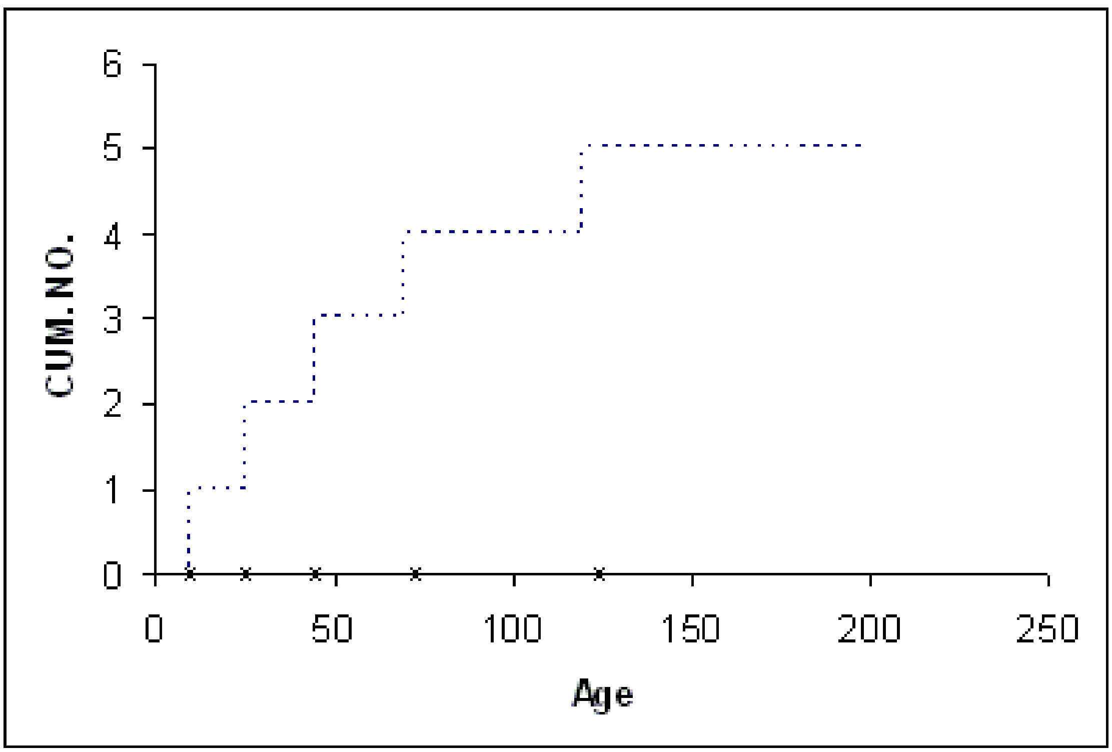

Figure 1 Cumulative Number of Failures of a Single System [35]

The nonparametric model for the population is the cumulative history functions of all units of the population. At a time *t*, the units have a distribution of their cumulative number of events. This distribution differs at different times *t* and has a mean *M(t)* called the MCF . The MCF is the pointwise average of all cumulative history functions as shown in Figure 2.

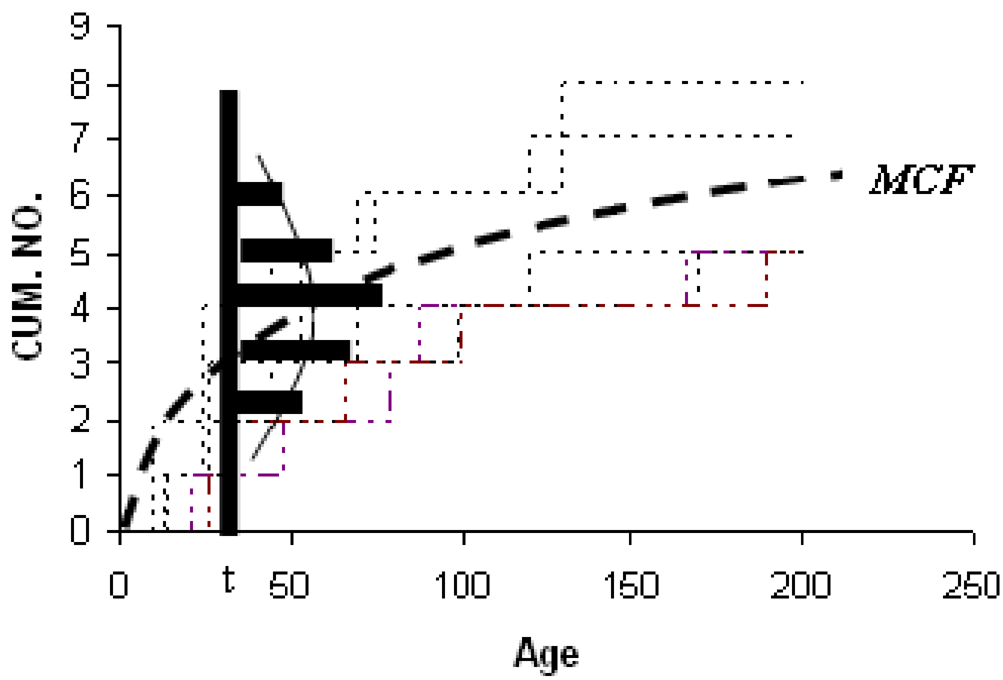

Figure 2 MCF and Population Distribution at Time *t*. [35]

When the data is uncensored (all units in the population are still operating at the point in time) the MCF values at different recurrence times are estimated by calculating the average of the cumulative number of recurrences of events for each unit in the population at that point in time. Suppose that the cumulative value for a sample unit *i* by time t is $Yi\ (t)$, $i = 1, 2, \ldots, N$. Then the estimate of the MCF at time t is simply the average of the cumulative values at age t. [35]

$$M(t) = [Y_1(t) + Y_2(t) + \cdots + Y_N(t)]/N$$

Equation 6 Estimate of MCF or *M(t)*

When the data is censored (some units in the population stopped operating prior to t_i) the censoring times must be considered as explained by Nelson. [27]

Rate of of OCcurance Of Failure (ROCOF) can be estimated from the estimate of the MCF by calculating the slope of the MCF at t.

The Trindade and Nathan process is explained and adapted to the purpose of this paper in Section 3. It will be applied to a set of real USAF historical maintenance data to demonstrate the utility and applicability.

Applicability of MTBF

Mean Time Between Failure (MTBF) is only applicable to repairable systems/components. It is often incorrectly used interchangeably with Mean Time To Failure (MTTF) of nonrepairable items.

MTBF is a reliability “buzz word”. Numbers are used without an understanding of what they truly represent. Basic and necessary assumptions are not stated. While MTBF may be an indication of reliability, it does not necessarily represent the expected service life of a nonrepairable product or the expected failure free period of a repairable system. Ultimately an MTBF value is meaningless if ‘failure’ is undefined and assumptions made in the calculation are not stated or are unrealistic.

The only completely accurate way to calculate MTBF for a nonrepairable product (actually MTTF for nonrepairable product) is to wait until every unit in the population has failed, or for a repairable system wait until the system is retired, and then do the calculations. This is obviously impractical so MTBF is generally estimated. Assumptions are required to estimate MTBF. This can lead to numbers that don't have a value in themselves but have some value in a relative sense. That is, the reliability of two products or systems can be compared IF calculated in EXACTLY the same way and IF ALL the same assumptions are made and validated.

A common misconception about MTBF is that it is the expected period between system failures. It is not uncommon to see MTBF numbers on the order of a million hours. It is unrealistic to believe that a system could operate continuously for more than 100 years without failure.

MTBF does not mean the expected failure free period, the useful life, or the average life. So what does it mean? As with many questions, the answer depends on the context.

Definition: The expectation of the operating time between failures. [36] The general expression for MTBF is given by:

$$E\{t\} = \text{MTBF} = \int_0^{\infty} x\, f(x)\, dx_0{}^{\infty} = \int_0^{\infty} R(x)\, dx,$$

where R(t) denotes the reliability (performance).

Equation 7 Mean Time Between Failure (MTBF)

When the system Rate of OCcurrence Of Failure (ROCOF) is constant with iid failure times the operating times between failure recurrences can be represented by the Homogenous Poisson Process (HPP) model [20]. Remember that the HPP of a repairable system or systems is often confused with the exponentially distributed failures of nonrepairable systems. If that mistake were made to calculate the MTBF of an HPP failure recurrence distribution for a repairable system the units would be the correct giving the appearance of a correct result. But the underlying data would not be correctly applied, the number would not be accurate, and the conclusion would be wrong. This will be demonstrated in Chapter III.

The HPP assumption (actually the exponential distribution) is widely used, although inappropriately, in the development of preventive maintenance strategies for repairable systems. In many cases, the MTBF is used to determine a preventive maintenance interval for a component. However, the use of the MTBF metric implies that the data were analyzed with an HPP since the mean will only fully describe the recurrence rate when the HPP is used for analysis. The use of the HPP, in turn, implies that the component has a constant ROCOF. This now begs the question of why anyone would preventively replace a component that has a constant ROCOF and does not experience wear-out over time! With a constant ROCOF assumption, preventive maintenance actions do not improve the reliability of the component, but rather waste time and parts

Once a MTBF is calculated based on the HPP assumption, what is the probability that any one particular repairable system will be operational at time equal to the MTBF? We have the following equation:

$$R(t) = e^{-t/MTBF}$$

But when t = MTBF

$$R(t) = e^{-1} = 0.3677$$

This tells us that the probability that any one particular system will operate without failure to its calculated MTBF is only 36.8%.

Inadequacy of MTBF as a Measure of Reliability for Repairable Systems

MTBF is the most often cited measure of reliability of repairable systems. MTBF is literally the total operating time divided by all failures. The common concept of MTBF assumes a one pass lifecycle, or a perfect repair process, where all failures come from a single population distribution. This assumption is predicated on an assumption of a Homogenous Poisson Process (HPP). For the assumption to be valid each failure is statistically independent and identically distributed (iid). Under this assumption the mean completely characterizes the distribution and the ROCOF is constant. The validity of the assumption is rarely checked or stated. [34].

Trindade and Nathan say the popularity of the MTBF metric is due to its simplicity and its ability to cater to the *one number syndrome* [9]. The exponential failure distribution assumption makes analysis very simple but it does not apply to most real systems. If this model were applicable to automobiles the reliability would not be dependent on mileage. If a product wears out or becomes less reliable it obviously does not have a constant failure rate. Using the MTBF when it is not appropriate can lead to missed failure trends and wrong conclusions about the reliability of the systems. [9]

USAF Calculation of MTBF as a Measure of Reliability

The U.S. Air Force defines MTBF in Technical Order 00-2-2, Maintenance Documentation., Mean Time Between Failure (Inherent). Inherent refers to a Type 1 failure or actual failure of the item.

MTBF-1 (INHERENT) = FLYING HOURS * QPA * UF / INHERENT FAILURES

NOTE: The Usage Factor (UF) is the ratio of end items with the WUC configuration to the end items accruing Flying Hours. The Quantity Per Assembly (QPA) is the number of the WUC items installed per end item.

Equation 8 USAF Definition of MTBF

MTBF, as defined by the AF, is a discrete number calculated from fleet *total* of flying hours and failures. The discrete number does not give any insight into the characteristics of the distribution beyond the arithmetic mean.

Using fleet total flying hours for the calculation causes significant loss of accuracy (increased confidence interval) as the sample size decreases. Small sample sizes are common to small fleets, few failures, or short sample periods.

The practical usage of USAF MTBF is for windowed periods of the total lifecycle. Often metrics are reported in quarterly or annual intervals.

This application is a lagging indicator. No information is available until the end of the period, significant latency in the data availability. If an attempt is made to shorten the period to reduce the latency the number of events in the period decreases. At some point the MTBF is undefined (zero events in the period).

The magnitude of the MTBF is dependent on the choice of period interval and location. The calculation for the selected interval is inaccurate due to left and right data censoring. Left and right data censoring is where units of the population operated for a significant time without failure before (left censoring) and after (right censoring) the data interval. It is obvious that as the data analysis period is reduced relative to the expected failure free period of the systems the censoring error becomes large.

The USAF uses maintenance data to document the system failures. There is no method within that data system to define specific failure modes, correlate repair actions across levels of maintenance, or track the numbers of systems in use at any given time. Operating time is not accurately tracked below the end item level. This creates a conglomeration of failures (hardware, software, test deficiency, …) tracked in a single distribution. It provides no ability to drill done below the end item level for root cause analysis.

Clearly there is a need for better USAF reliability metrics that account for trends and allow for drill down to root cause.

Summary

According to John Usher [23] even though most complex systems are repaired, not replaced, when they fail many reliability practitioners use statistical methods and models that are only appropriate for nonrepairable systems. Ascher and Feingold [24] discuss serious issues with treating repairable systems reliability data as if it were from a nonrepairable system.

The USAF not only uses the wrong metric to assess the reliability of fielded repairable systems, the wrong metric is calculated incorrectly. There is an applicable process available, which can be used with existing USAF data, to provide a more effective measure of repairable system reliability.

III. Methodology

Chapter Overview

To demonstrate that the calculation of MTBF is not an effective measure of field repairable USAF systems an illustrative set of maintenance data will be used to represent the failure history of similar systems. This set of data will be used to show that the MTBF calculation is completely dependent on the time interval and location of the data sample and is not necessarily a characteristic of the system's reliability.

The graphical and nonparametric analysis process presented by Dr. Nelson [35], further refined and used by Sun Microsystems Inc. for reliability analysis of their products [9], will be applied to historical USAF maintenance data. The output of that analysis process will be compared to the MTBF calculations (Equation 8) from the same data, in the same period, to show the relative merits. The example is similar to one used in Dr. Nelson's book, Recurrent Events Data Analysis for Product Repairs, Disease Recurrences, and Other Applications [27].

The Adapted Recurrent Events Data Analysis Process

The process below is a generalized adaptation of the more statistically rigorous process presented by Dr. Nelson in his text [27]. This process more closely follows the algorithmic analysis process presented by Trindade and Nathan of Sun Microsystems [9].

1. Obtain a data set of ordered event recurrence intervals from each system. The events are a function of usage such as operating time, cycles, calendar days, … .
2. Plot the recurrence events on a cumulative timeline. This graphical analysis technique will show obvious trends or outliers in the data.
3. Plot the cumulative event functions for each system of the population or of a statistically valid random sample of systems.
4. Plot the Mean Cumulative Function (MCF) and confidence bounds for the data set.
5. Plot the ROCOF of the systems. The recurrence rate is the derivative of the MCF at a point in time. Because there is no closed form solution to the derivative of the MCF the Recurrence Rate will be approximated by calculating the slope of the MCF at the point in time.

The analysis process can be completed for relatively small data sets using a spreadsheet program such as MS Excel. MS Excel was used to for the notional example in this chapter. For larger data sets a more specialized program is useful. To process the very large USAF maintenance data sets MS Excel was used to combine, format, and correlate the necessary data. JMP was used to calculate the MCF and confidence interval. The JMP data was exported back into excel for plotting. JMP does provide output plots but they are image files with few formatting options for reporting.

Recurrent Events Data Analysis Methodology Example

Dr. Nelson uses a five population staircase history function to introduce and explain the concepts of a nonparametric population model (cumulative history functions of all units) and Mean Cumulative Function (MCF) [27]. I will use the same technique and similar data for five identical systems, each operating for 100 hours, to illustrate the adapted recurrent events analysis process. The USAF calculation of Mean Time Between Failure (MTBF) is calculated (Equation 8), for two intervals, 20 and 50 hours, and overlaid on the cumulative failure functions

1. **Obtain a set of ordered event recurrence intervals from each system (or from each similar system).**

. The cumulative failure events of a notional sample of five similar systems, each operating for 100 hours, are shown in Table 2.

Table 2 Cumulative Failures as a Function of Time

	0	10	20	30	40	50	60	70	80	90	100
System A	0	1	1	1	1	1	1	1	1	2	2
System B	0	0	1	2	2	2	2	2	2	3	4
System C	0	0	0	1	1	1	1	2	3	3	3
System D	0	0	0	0	1	1	2	2	2	2	2
System E	0	0	0	0	0	0	0	0	0	0	1

2. Plot the recurrence events on a cumulative timeline.

The data from Table 2 was used in JMP to create the event plot in Figure 3. This plot may provide a quick graphical illustration of the systems' reliability. The small data set does not readily support an iid assumption. While the HPP may be a reasonable model for each system it appears that the systems are not identical (different MTBF) so a HPP may not represent the stochastic point process for the failures of these multiple systems. The assumption of a constant ROCOF and the use of a windowed calculation of MTBF (period less than total failure/usage) would not be appropriate for this data set. But fitting to a parametric model is not necessary for cause analysis.

The plot of failure recurrences as a function of cumulative time provides a quick top level indicator of issues that impact system availability that may not be hardware reliability issues. From Figure 3 it can be seen that System E operated without failure to 100 hours. System B had two sets of clustered failures. As the system failures events are only reported every 10 hours the second failures of the System B clusters may have been a very short time after repair.

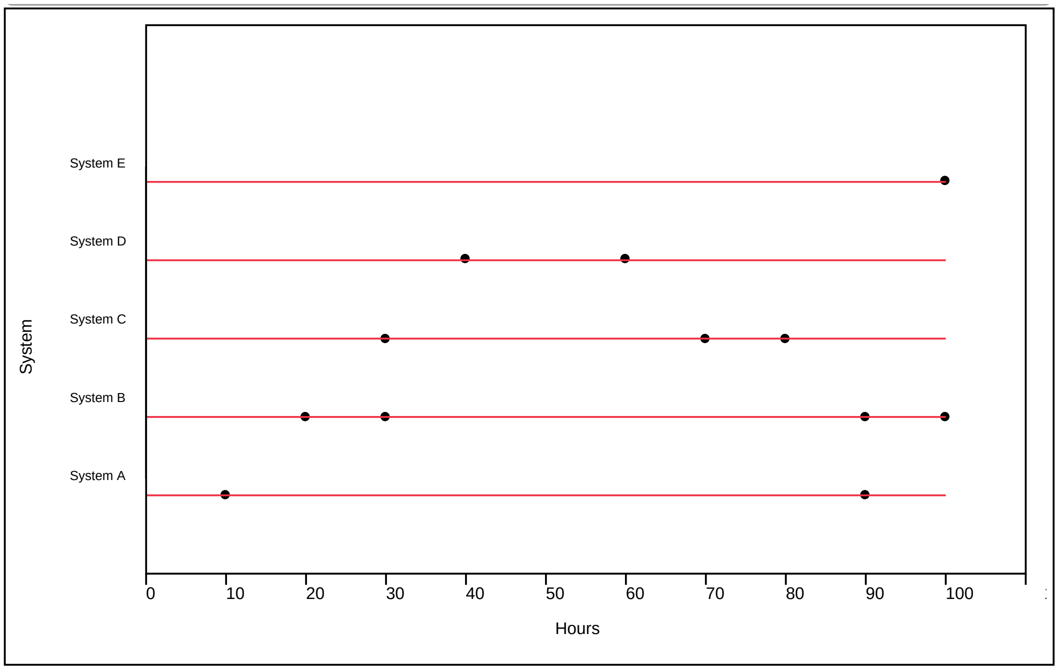

Figure 3 JMP Event Plot

3. **Plot the cumulative event functions for each system of the population or of a statistically valid random sample of systems.**

A cumulative plot is a simple graph that can be constructed from a set of events-of-interest for a repairable system. This plot can be constructed for all failures, outages, system failures due to specific failure modes etc. A cumulative plot can be constructed for just one system, for a statistical sample, or for all systems in a population. The cumulative plot in Figure 4 is a plot of the number of failures on each system versus the operating hours of the system. The cumulative plot reveals the sequence of events with operating time. For example, System A had one failure at 10 hours and was failure free to 90 hours. System E operated for 100 hours before failure.

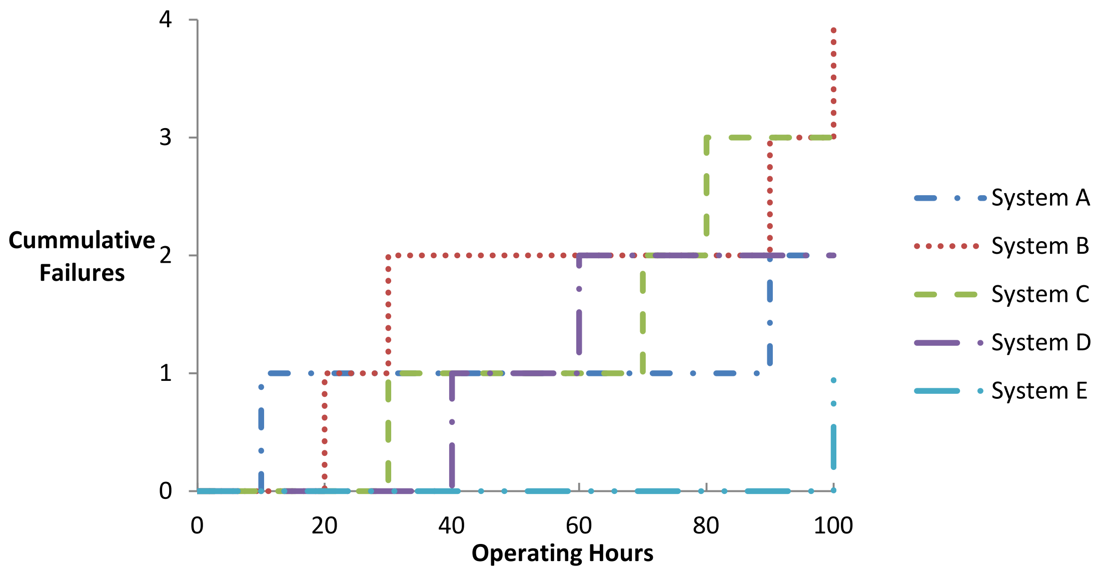

Figure 4 Plot of Cumulative Failures of Five Similar Systems

4. Plot the Mean Cumulative Function (MCF) and confidence bounds for the data set.

The MCF is a useful construct to plot the average behavior of large populations of repairable systems/items. The MCF is constructed incrementally at each recurrent event by calculating the mean quantity of recurrent events of the population of systems at risk at that point in time. The number of systems at risk is the number of systems that are operating and providing information. [9]

Information can be obscured by data censoring and truncation. One could also have interval or window censoring that is dealt with extensively in [9]. The MCF accounts for systemic gaps in data by appropriately normalizing by the number of systems at risk.

The example in Figure 5 shows the MCF for the five similar systems. The calculation at each point of interest would be in the manner of these samples:

$$\text{MCF}(10) = \frac{4(0)+1(1)}{5} = 0.20$$

$$\text{MCF}(50) = \frac{1(0)+3(1)+1(2)}{5} = 1.00$$

$$\text{MCF}(100) = \frac{0(0)+1(1)+2(2)+1(3)+1(4)}{5} = 2.40$$

For this trivial example the 95% confidence interval was calculated using the built-in confidence function in MS Excel. The more sophisticated recurrence analysis algorithm in JMP fits a distribution to the recurrences of the population of systems at the point in time and determines the confidence interval from that distribution. Dr. Nelson provides procedures for calculating point-wise confidence bounds [27].

A quick look at this MCF plot with confidence intervals shows the systems that are out of the ‘normal’ range. While these are not necessarily outliers in the strict statistical sense it is a strong visual indication of problem systems/items. [9] From Figure 5 it can be seen that System A fails early, outside of the confidence interval, then recovers. System B is always at near the top of the confidence interval and is out of the interval 40 out of 100 hours and again at the end of the observation period. System B would be an excellent candidate for specific root cause analysis. Notice that System E is out below the confidence bounds for the entire period. It would be good to examine that system to see why it is so reliable.

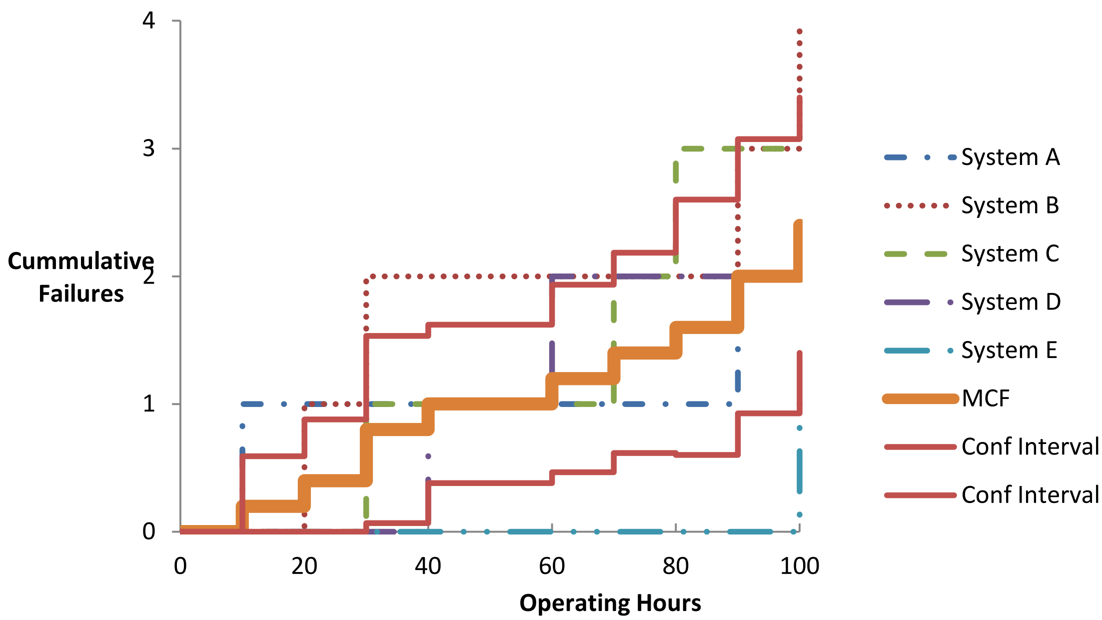

Figure 5 Plot of the MCF for Five Similar Systems with 95% Confidence Interval

5. **Plot the ROCOF of the systems.**

The ROCOF is approximated by calculating the slope of the MCF at the point in time. It is expressed in events per unit of time per population unit. The ROCOF plot in Figure 6 is simply the slope of the MCF points as calculated by MS Excel and is a poor approximation due to the small sample size. It demonstrates the concept to be applied in section IV.

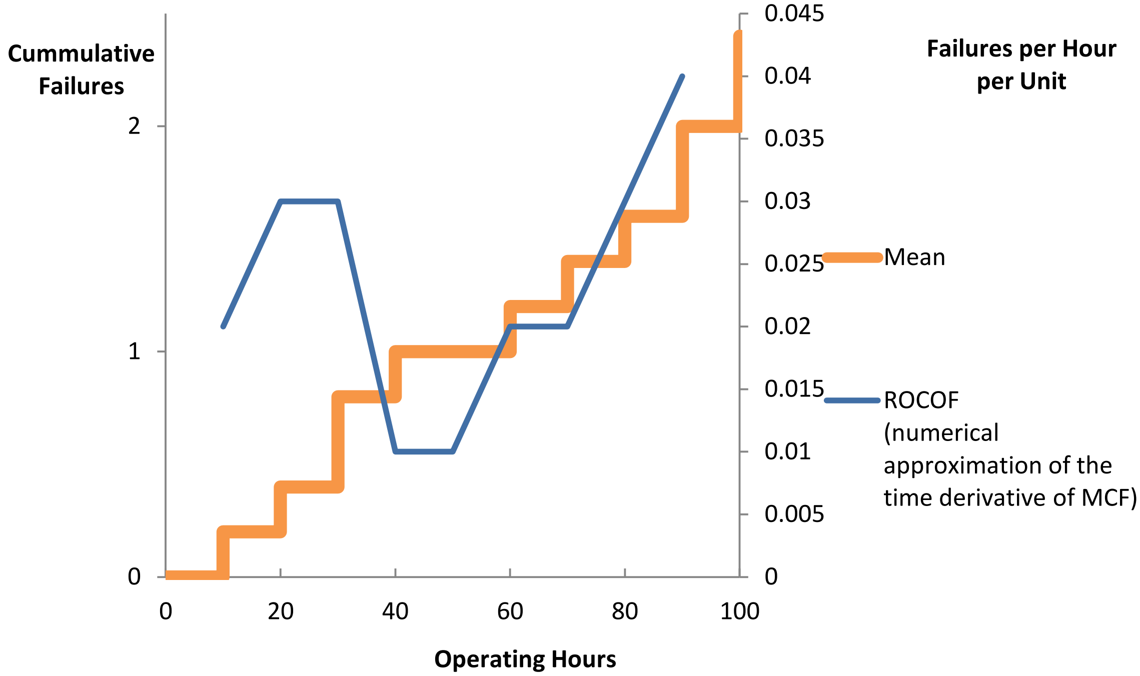

Figure 6 ROCOF for Five Similar Systems

ROCOF Compared to USAF Calculation of MTBF as a Measure of Reliability

The USAF calculation of Mean Time Between Failure (MTBF) using Equation 8, is calculated for two intervals, 20 hours and 50 hours. These values are overlaid on the cumulative failure functions in

Figure 7 to demonstrate the process that will be used with actual USAF data in section IV.

For comparison of the USAF calculation of MTBF to the ROCOF the inverse of MTBF will be used. As discussed in section II the USAF incorrectly uses MTBF as the measure of reliability (often cited as a 'failure rate') in a period. The incorrect usage is related to the assumption of the special case of the HPP where the failure rate is constant and the inverse of the MTBF. This leads to the use of failures/time as the failure rate but even in the special case of the HPP the strict definition of failure rate is the inverse, in units of time/failures, the same units as the ROCOF.

If the MTBF is used as the measure of reliability for this population of systems it can be seen that there is no information available until the end of the period. This makes a significant lag in the data availability. If an attempt is made to shorten the period for additional resolution the events in the period decrease. At some point the MTBF is undefined (zero events in the period). It can also be seen that the magnitude of the MTBF is dependent on the choice of period interval and location. The calculation for the selected interval is inaccurate due to left and right data censoring. Left and right data censoring is where units of the population operated without failure for a significant time before (left censoring) and after (right censoring) the data interval.

Incorrect analysis of the reliability of this population of systems on the basis of the 20 hour MTBF would say that the 'failure rate' of the population of systems initially is 0.01 failures per hour. After 20 hours of usage the failure rate would increase to 0.015 failures per hour. The lowest failure rate would be at 60 hours and the highest at 100.

Analysis of the reliability of this population of systems on the basis of the 50 hour MTBF would say that the 'failure rate' of the population of systems initially is 0.02 failures per hour and increases slightly to 0.028 at 100 hours.

The ROCOF by comparison more closely follows the time of the actual system failures and provides better resolution and accuracy.

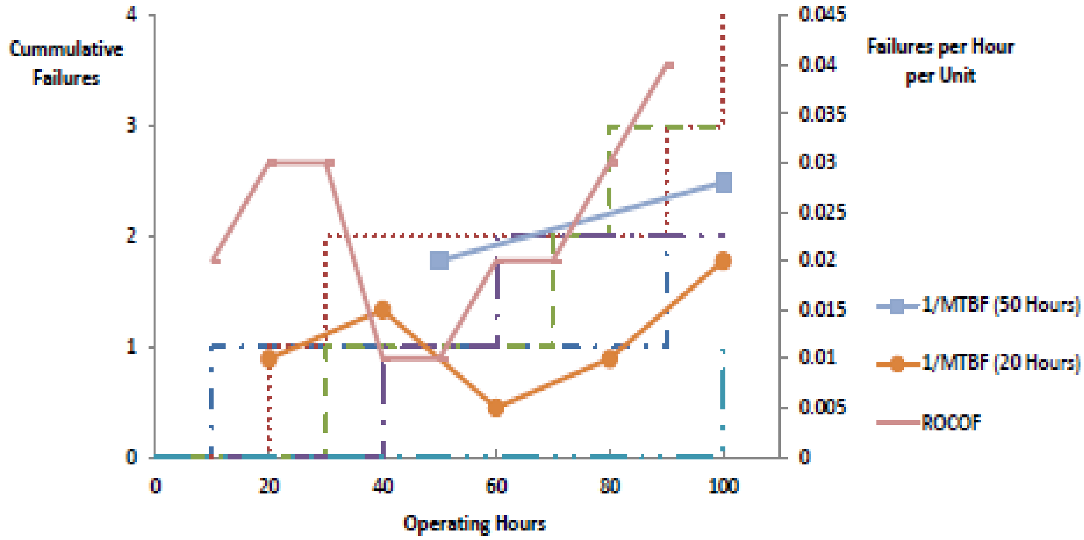

Figure 7. USAF Comparison of MTBF Derived 'Failure Rate' and ROCOF Over Two Different Periods (20 and 50 Hours)

Summary

The notional data presented in this chapter illustrates the concepts that will be applied to the real USAF maintenance data in the next chapter. The adapted recurrent events data analysis process will show that near-real-time information can be obtained about the reliability performance of a population of fielded repairable systems. The process also allows analysis of the reliability performance of items, or changing subsets, within the population relative to others in the population and to their own history.

IV. Analysis and Results

Chapter Overview

The data required for recurrent event analysis of USAF systems are generally collected but the necessary data elements are not linked together. Usage hours are accurately collected at the end item level so subsystem failure recurrence times are available. But usage time is not generally tracked on subassemblies or components. Some data subassembly/component data can be correlated by associating removal/install times with the usage of the end item but there is no standard serialization schema and no error checking so data accuracy is very poor using that method.

The demonstration presented in this chapter is analysis of two years of organizational (flightline) maintenance data for three subsystems of a weapon system in four basic configurations. The four weapon system basic configurations will be called A, B, C, and D. The subsystems that are mostly common across each configuration will be identified by their three digit Work Unit Code (WUC) 14A, 74A, and 74C. There are some limitations to using two years of data from a weapon system that was fielded more than 15 years ago and continues in-service after the two year period. Those limitations will be discussed in context.

The data was exported from LIMS-EV, combined and formatted in MS Excel. Recurrence calculations were done using the commercially available statistical analysis software JMP. JMP has Reliability and Survival functions that include recurrence data analysis. JMP produces the Event Plot (Figure 3and Figure 8) and calculates the MCF with Upper and Lower 95% Confidence Levels (UCL and LCL).

The subsystem recurrence data is available via LIMS EV but is not easily accessible nor is it exportable in a directly useable format. More than 600 worksheets were created to assemble and format the necessary data for the demonstration (24 months, four weapon system configurations, three subsystems) in this chapter. The volume of data and the large amount of manual data manipulation makes the probability of error near one. In spite of the likelihood of error the analysis does provide business intelligence and actionable evidence of issues effecting weapon system availability.

1. Obtain a set of ordered event recurrence intervals from each system (or from each similar system).

Reports were exported from LIMS-EV to obtain the necessary usage data for the weapon system. To accurately identify trends in the data it is necessary to monitor the failure recurrence data on a daily basis. LIMS-EV limits data exports of daily data to a maximum of one month. The data for failures and for operating hours are different reports so must be exported separately. To get two years of data for four weapon system configurations and three subsystems on each configuration required 576 individual exports from LIMS-EV (24 months * 4 configurations * 3 subsystems * 2 hour and failure reports) The LIMS-EV interface is very quirky, often timing out before a query can be set up, similar queries output in different formats, so query sizes must be small. The process is detailed in Attachment A.

2. Plot the recurrence events on a cumulative timeline.

The sequential time-to-failure data set for three subsystems of each instance of the weapon system over two years was imported into JMP. The built-in JMP Recurrent Event Analysis was used to plot the recurrent events on a cumulative timeline, Figure 8, and to calculate the MCF and confidence bounds.

Figure 8 is a sample of the population of a USAF weapon system end items' cumulative events timeline plotted in operating hours. The events are failures of a subsystem of common design across the weapon system. Each timeline represents the failure history of a serialized end item. The vertical lines on the timeline represent the failures.

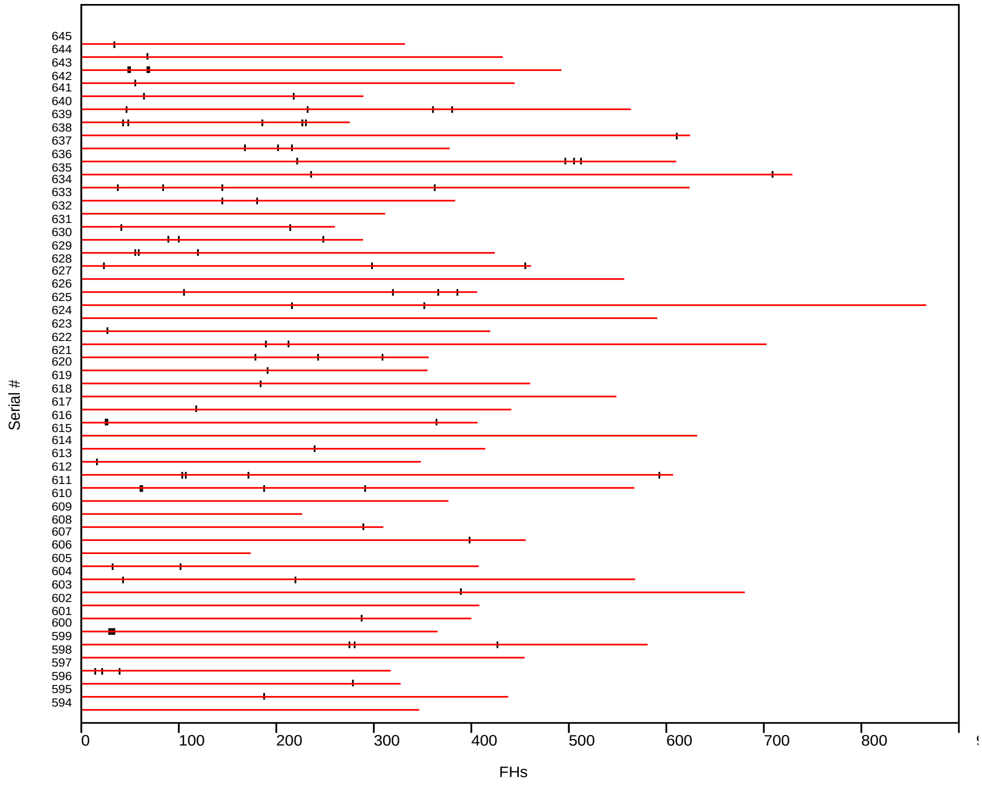

Figure 8 Event Plots of Subsystem Failures for a Sample of the Weapon System End Item Population.

The differences in the failure distribution across the population and the clustering of failures on individual end items suggest that the failure distribution for the population is not iid. Without an interval estimate of the HPP intensity parameter [19] the HPP would not be an appropriate assumption for failures of this subsystem; a constant ROCOF would not be an appropriate assumption. But as with the illustrative set of data shown in Figure 3, fitting to a parametric model is not necessary for cause analysis.

Important conclusions can be made from a quick review of the data presented Figure 8. The subsystem operates without failure for long operational periods on many end items. Other end items have a relatively large number of failures and many of the failures across the sample are clustered. The long periods of operation without failure would suggest that there is not a problem with inherent reliability of the subsystem hardware design or implementation. The clustered failure pattern on some end items would suggest poor fault isolation procedures or training or components used to repair the subsystem have a significant number of dead-on-arrivals. To identify the root causes of failures in this subsystem a similar analysis of the recurrent failure event histories of the subsystem components would be valuable.

3. Plot the cumulative event functions for each system of the population or of a statistically valid random sample of systems.

Figure 9 and Figure 10 are plots of the MCF of failures of two different subsystems respectively with a design common across the USAF weapon system. The weapon system is divided into four subset configurations due to the large size of the weapon system population. The MCF of the subset configurations are plotted with the MCF of the weapon system. These four subset configurations are operating at the same time at different locations and in different commands across the USAF.

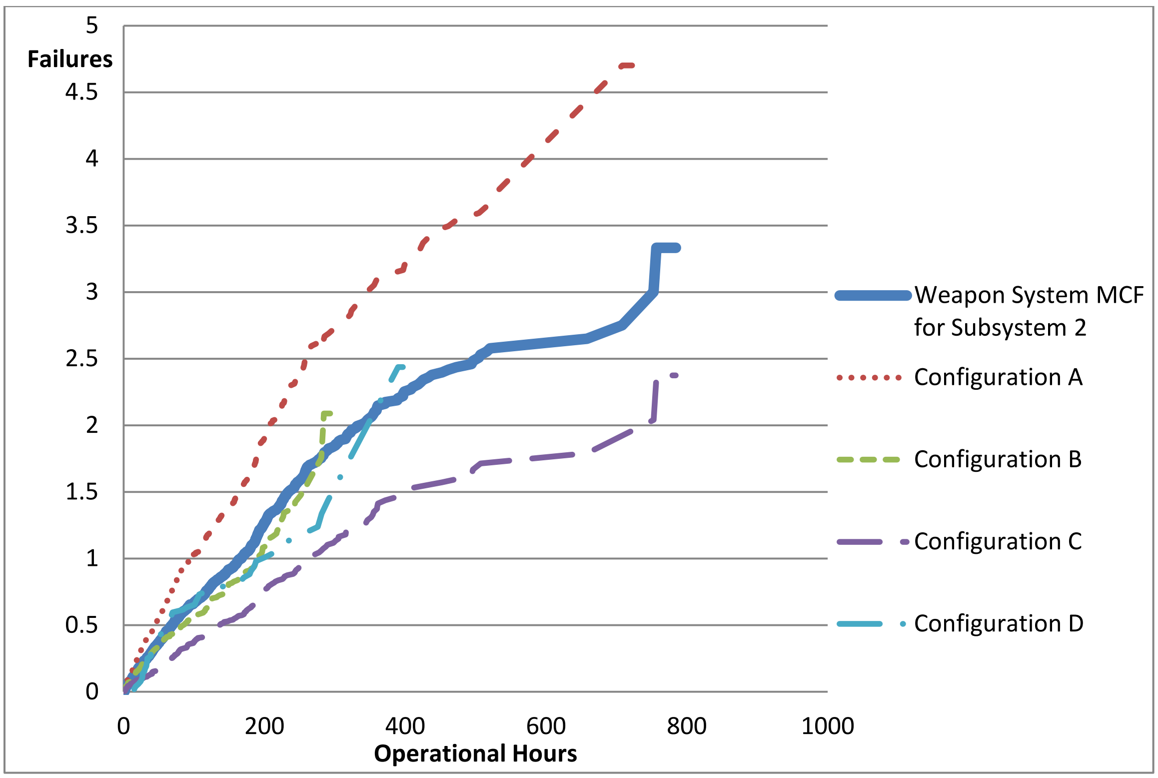

Figure 9 Plot of MCF of Subsystem 2 for the Weapon System and Subset Configurations

Figure 9 and Figure 10 demonstrate the capability to examine and compare the relative reliability performance of individual end items or subsets of the population.

In Figure 9 it is seen that Configuration A has a significantly higher numbers of failures per hour and drives the weapon system MCF. This subsystem is the same across all four configurations so stands to reason that an external factor is driving the failures of subsystem 2 in configuration A. It is possible that a nonmaterial change to configuration A would make an improvement in the weapon system reliability. Figure 10 shows consistent reliability across all four weapon system configurations for subsystem 1.

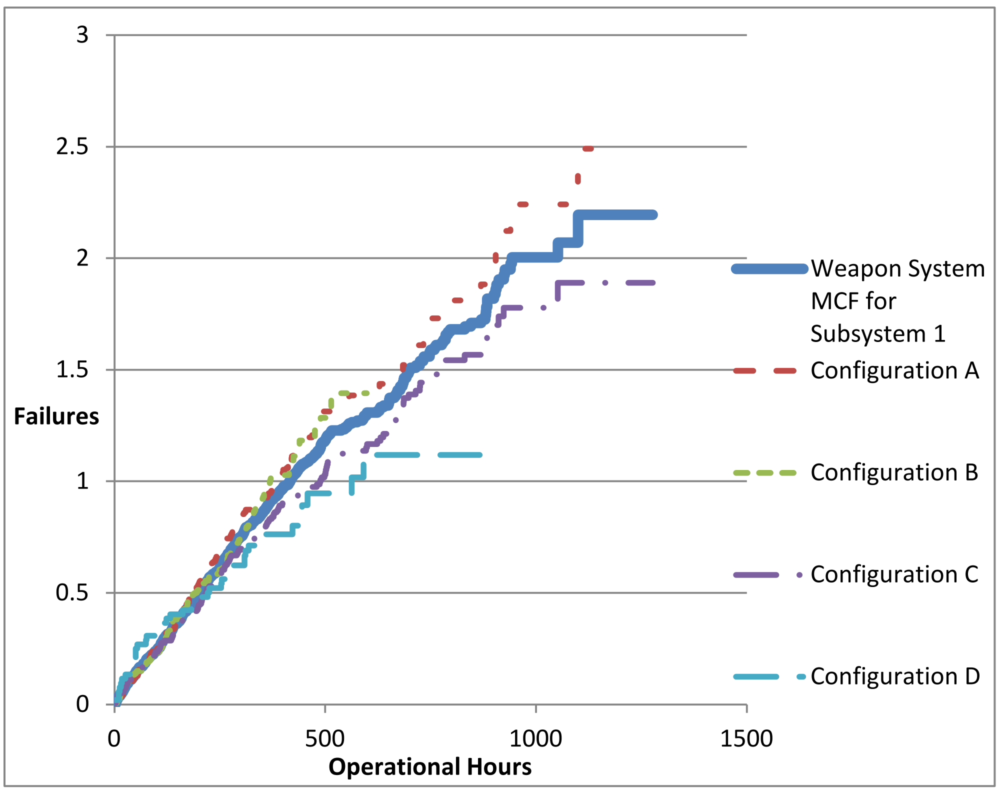

Figure 10 Plot of MCF of Subsystem 1 for the Weapon System and Subset Configurations

4. Plot the Mean Cumulative Function (MCF) and confidence bounds for the data set.

Figure 11 demonstrates the MCF of one subsystem of a USAF weapon system. The confidence interval is calculated by JMP as an Upper Control Limit (UCL) and Lower Control Limit (LCL) by fitting a distribution to the cumulative failures of all end items in the population at each failure time. In this case the interval is 95%. The MCF normalizes for population size so the confidence interval increases with the operational hours due to the smaller population that accrues that many hours. The same characteristic results in more stepwise character of the MCF as the population size decreases and individual failures have a relatively larger impact on the mean.

This plot allows a prediction to be made about failures as a function of operating hours. From the data shown in Figure 11 the first failure of subsystem 2 of an individual end item occurred between 370 and 470 hours and the second occurred between 940 and 1050 hours 95% of the time.

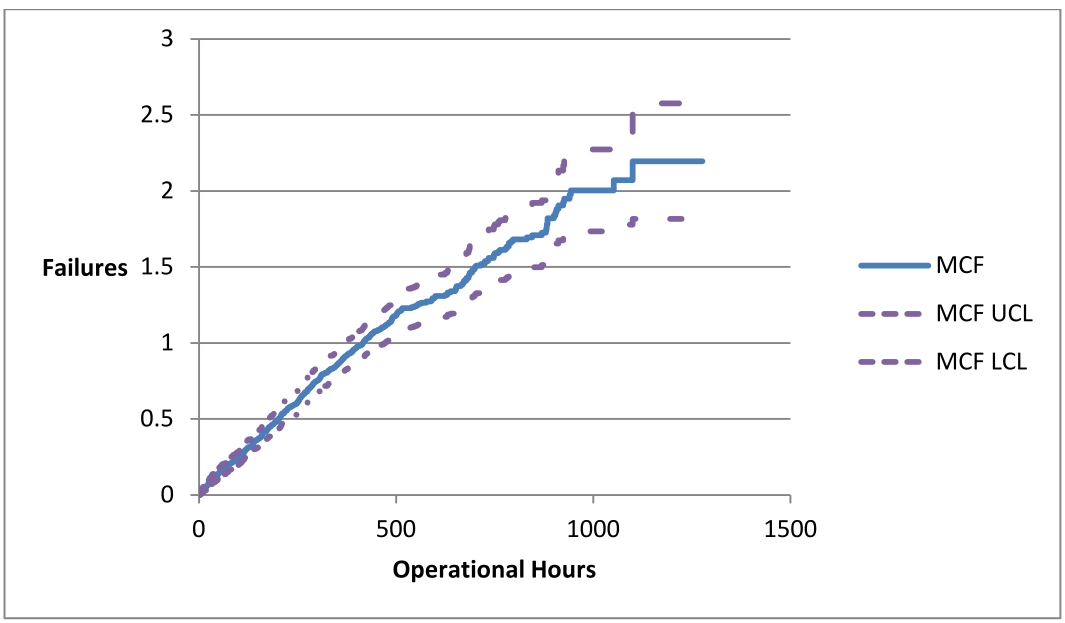

Figure 11 MCF for Subsystem 2 with 95% Confidence Limits

5. Plot the ROCOF of the systems.

There is no closed form solution to the derivative of the MCF so the ROCOF is approximated by calculating the slope of the MCF at the point in time. The ROCOF data presented in these charts was calculated by using the MS Excel slope function across seven data points, three before and three after each calculation point. This results in more smoothing at the right end of the Figure 12 as the sample size decreases and the interval between data points increases.

The ROCOF of subsystem 1 of a USAF weapon system is plotted against operating hours, Figure 12, and calendar days, Figure 13. The plot against operating hours shows impacts to the ROCOF that are related to systems usage. The plot against calendar days shows impact to the ROCOF due to events that are external to the systems. [9]

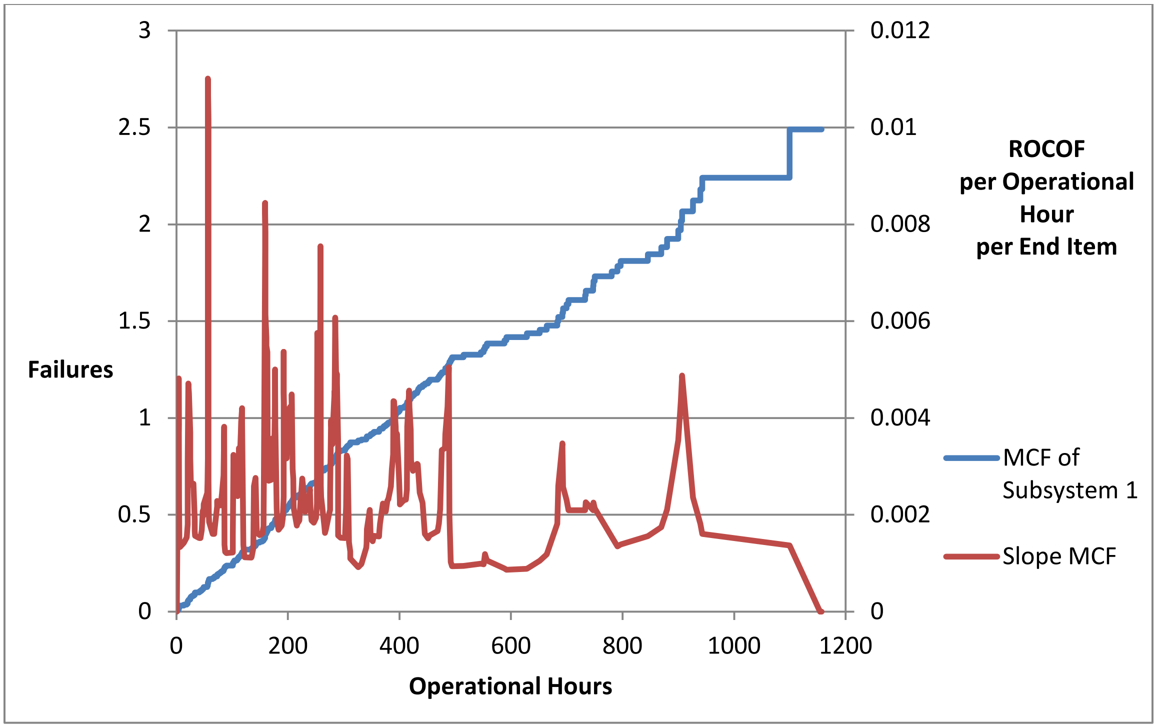

Figure 12 ROCOF Plotted Verses Operational Hours

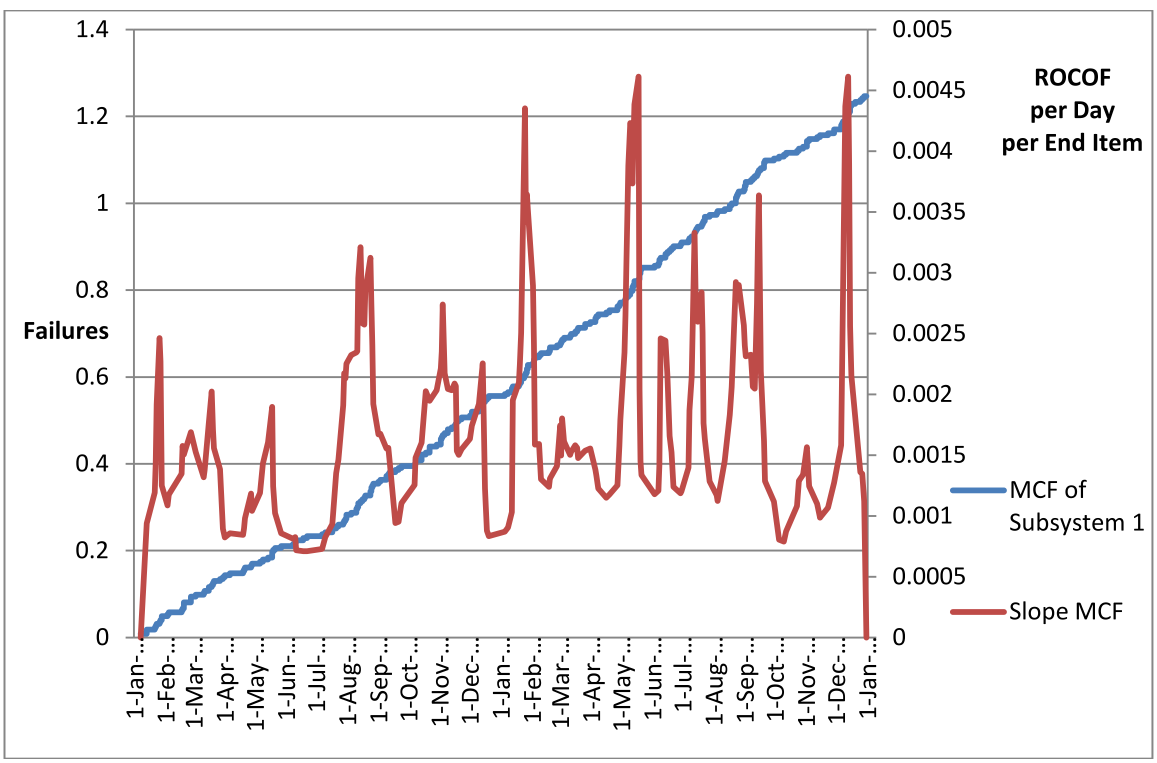

Figure 13 Plot of ROCOF Verses Calendar Date

ROCOF Compared to USAF Calculation of MTBF as a Measure of Reliability

The USAF requires annual reporting of MTBF for weapon systems. The purpose of the reporting is to monitor the reliability performance of the weapon system. The MTBF is often incorrectly analyzed as a failure rate because the units, hours/failures, seem plausible. By definition the failure rate units are the inverse, failures/hours. The inverse of the USAF calculation of MTBF will be used to make the units consistent for comparison with the ROCOF.

Two years of the MCF and ROCOF for a subsystem of a USAF weapon system and the inverse of the USAF calculation of quarterly and annual MTBF are plotted in Figure 14. This plot demonstrates the improved response of the ROCOF compared to the MTBF derived ‘failure rate’.

From the plot it can be seen that using 1/MTBF as the failure rate obscures much of the deviation in the ROCOF. Many weapon system subsystem are repaired by replacing very expensive repairable units. Each spike in the ROCOF represents tens of thousands of dollars worth of replacement parts. As seen in the event timeline in Figure 8 the failures are often clustered creating spikes in the ROCOF. Root cause analysis can identify mitigations and save millions of dollars for replacement parts and improve weapon system availability by reducing the amount of unscheduled maintenance. But the root cause analysis cannot be done if the problem is obscured by using MTBF as the measure of reliability.

It appears from the plot that the magnitude of the 1/MTBF is larger than would be a trend-line through the ROCOF. The magnitude is not a pure comparison as the MTBF calculation is scaled by the operating hours in the period while, in this plot, the ROCOF is a function of calendar time.

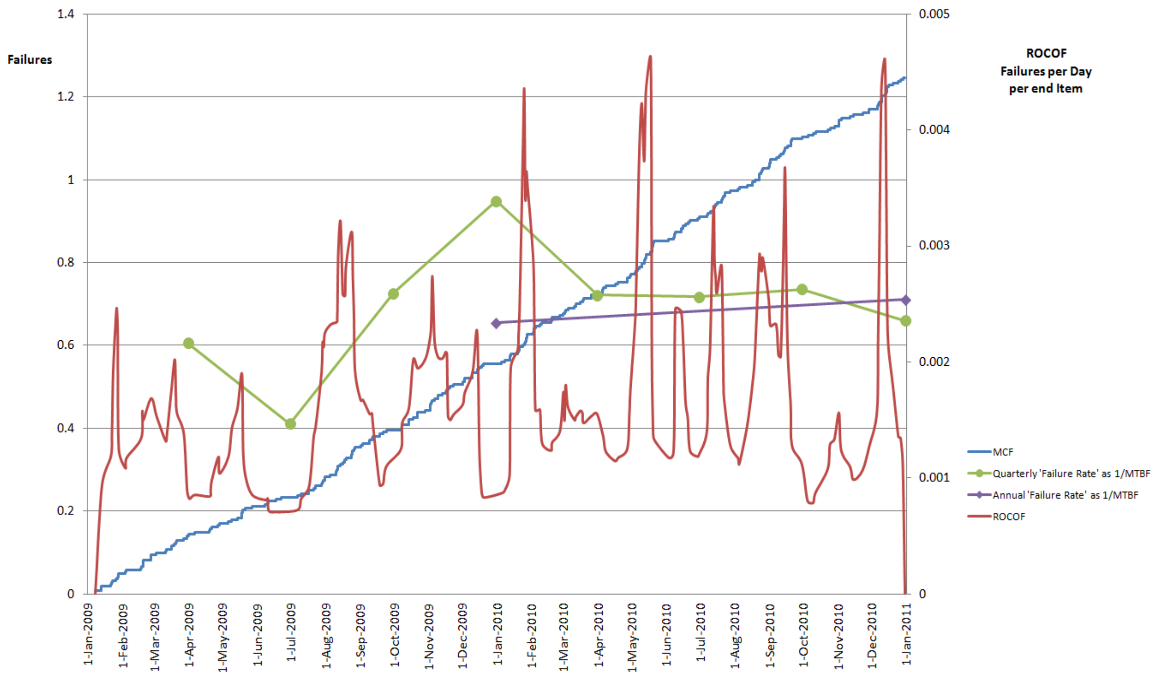

Figure 14 Comparison of ROCOF vs. Annual and Quarterly MTBF 'Failure Rate'

Data Censoring

Censored data is also sometimes referred to as truncated or suspended data. Two types of censoring can occur in the data set. Right censoring occurs when the time to failure of a specific unit is not known due to the data period ending before failure. Left censoring occurs when the system was operating for some time before data is collected. At the start of the data period the population has some unknown operating time and unknown failure history.

The demonstration presented in this chapter utilized two years of failure data for a USAF weapon system that has been fielded for more than fifteen years. A complete set of recurrent event data for the weapon system is not available. An arbitrary starting point was chosen within the range of available data. This created a false point in time where all end items in the population appear to have been fielded at once with zero operational hours. The actual time to first failure in the period of analysis is not known for any items in the population. The time from the beginning of the period of analysis to the first failure in the period is used in the calculation of MCF per operating hour as if it were the actual time to first occurrence. The left data censoring is a source of error in the magnitude of the MCF and ROCOF. The MCF and ROCOF would appear to be higher than they actually are for low operating hours due to the time to first failure being truncated for all items in the population. The error decreases as the data analysis period increases beyond the ‘typical’ failure free period of the end items. Figure 15 illustrates the order of magnitude of the left censoring error in this chapter. The MCF calculated from one year of data increases at a much faster rate than the MCF calculated from two years of data.

The weapon system continues to be in use so end items have continued to accrue operating time after the period of analysis data. The time to next failure after the last failure in the data analysis period is unknown. This is right data censoring. Right censored data is not included in the calculation of MCF by JMP. Right censoring could be a significant source of error if there are a significant number of end items in the population that have long failure free periods relative to the data analysis period. This would make the MCF appear higher than it really is due to the most reliable systems being omitted from the MCF calculation. Ideally the MCF and ROCOF would be updated regularly. This periodic extension of the period of analysis would keep decreasing the percentage of the error.

The USAF calculation of MTBF is more susceptible to both left and right data censoring than the calculation of MCF. A calculation of MTBF for the first year of the data analysis period would have the same left censoring error as the MCF but would also have a similar error from right censoring. The percentage of error becomes larger as the period of calculation of MTBF decreases until the point where the number is undefined (zero failures in the period).

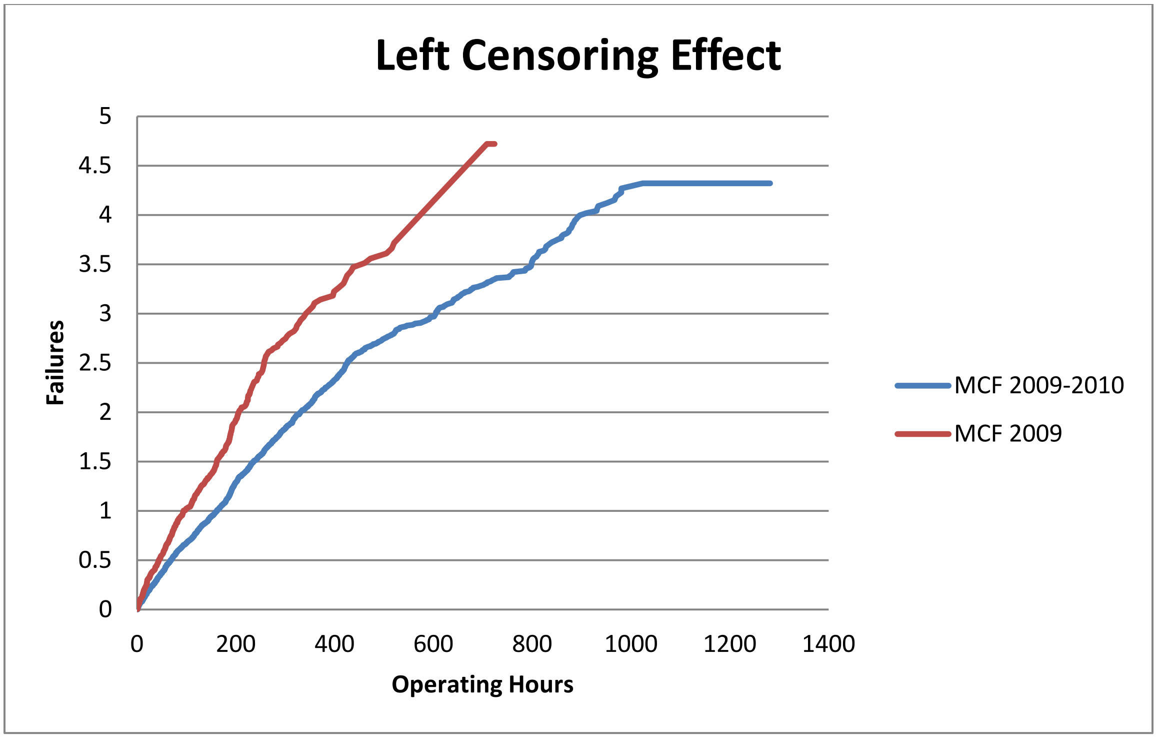

Figure 15 Illustration of MCF Error Due to Left Data Censoring

Investigative Questions Answered.

"Based on USAF repairable system recurrence data, how can reliability best be non-parametrically measured?"

Reliability of fielded USAF repairable systems should be measured using the basic operations of recurrent event data analysis advocated by Nelson [27], and the recurrent events data analysis process adapted from Trindade and Nathan [9] as presented in Chapter III and demonstrated in Chapter IV. This measurement process could be implemented using existing USAF maintenance data but would be much more effective with an enterprise reliability data architecture to support it.

Summary

It has been shown that the USAF calculation of MTBF is not an effective measure of fielded repairable systems. The basic assumptions that are necessary for the USAF calculation of MTBF to be applicable (iid) are rarely reasonable for fielded repairable systems. USAF guidance and policy does not mention that there are assumptions that must be verified and stated nor are alternatives measures discussed.

When MTBF is applied inappropriately it is a lagging metric that misses developing trends and short term spikes in ROCOF. If the period of the MTBF calculation is shortened to reduce latency the error increases due to left and right data censoring. If the period is extended to reduce censoring the smoothing and latency increases.

The nonparametric recurrent event data analysis process of this chapter shows that the reliability of fielded repairable systems and the first level of indentured subsystems can be measured in near real time. The technique does not require complex statistical models that require parameterization. Complex numerical techniques are not required to solve specialized mathematics. No new data elements or sources of data are required.

However there are complications to using the nonparametric recurrent event data analysis process in the current environment. The existing USAF data is not readily available in the quantity and format necessary. There is a substantial time investment to set up the necessary data and it must be updated regularly to take advantage of the near real time issue identification capability. Today that investment must be made for every system to be considered. As much of the lifecycle failure event history as possible should be included in the analysis period to minimize the left censoring error.

V. Conclusions and Recommendations

Chapter Overview

The DoD has increased the emphasis on reliability in order to reduce sustainment costs and weapon system availability. But the emphasis is on the development phase where there is a mandatory and formalized reliability program. There are millions of dollars to be saved and significant improvement available in A_o by improving the reliability of fielded legacy weapon systems. There is little focus on reliability in the sustainment phase. The very definition of reliability in the USAF does not have relevance to fielded repairable systems. MTBF is defined as the metric to report the status of weapon system reliability but it does not provide the intended information and is likely calculated incorrectly.

The opportunity exists to utilize existing data to measure the reliability of fielded repairable systems. Anecdotal evidence suggests valuable reliability improvement can be made, without redesigning systems, by accurate and timely analysis of the MCF and monitoring of fielded repairable system ROCOF.

Conclusions of Research

Effective measurement and improvement of weapon system reliability in the sustainment phase requires accurate and timely data documenting the lifecycle of individual items and specific material. Effective measurement and improvement of weapon system reliability in the sustainment phase requires expert application of pertinent analysis to that data.

There is no USAF policy or guidance for the analysis of reliability data after fielding. The USAF definition of reliability is not coherent with the desired operational outcome or rigorous statistical analysis. The policy and guidance does not make a distinction between the context areas as presented in Table 1. There may be areas of reliability expertise and effective reliability data analysis within the USAF sustainment community but it is dependent on the priorities of the weapon system management.

MTBF is not an effective metric for the reliability of fielded repairable systems if the purpose for measurement is for reliability improvement. The USAF calculation of MTBF for a windowed period of the lifecycle is not the mean operational time between failures in the period due to left and right data censoring. It is a lagging indicator that tends to obscure important trends and indicators in the data.

A method for non parametric analysis of recurrent events is well defined in literature. It is applicable to reliability of fielded repairable systems. The USAF has data available that could be used for recurrent event analysis at least to the first level of indenture below the end item. However the lack of operational time tracking of serialized items below the end item level limits the ability to apply the process at lower levels of indenture.

Significance of Research

It appears that the USAF reliability program is not a priority. There is no person responsible for reliability at the AF level. It is not clear who is responsible for reliability in AFMC. There is no USAF standard architecture for reliability data collection or analysis. The requirement for measuring fielded system reliability is identified as the responsibility of the PM in several AF documents.

USAF reliability metric is typically reported on an annual basis at such a high level that no one realizes the wrong metric is used and the wrong metric is calculated incorrectly. The error generally does not have an impact because the data is not actionable. If an effort is made to improve reliability the metric cannot track results.

The correct data analysis process for fielded repairable USAF systems is available. The process has the capability to identify specific poor performing end items and subsystems for improvement. The process has the capability to compare the respective reliability of subsets of weapon system population based on such parameters as location, using command, different configurations, … . This capability allows root cause identification and accurate measure of the impacts of reliability improvement efforts or other modifications.

Recommendations for Action

Conduct a study to determine if the effort and expense being invested in the acquisition reliability programs are producing the intended result in the fielded systems. The DoD has renewed emphasis on reliability in order to reduce sustainment costs but the focus has been on reliability prediction and test during the development phase of programs, column 1 of Table 1. Studies have characterized the success or failure of reliability programs by the Operational Test and Evaluation (OT&E) results. No attempt has been made to examine if successful OT&E reliability results correlate with effective reliability of the fielded system.

Adopt the standard definition of reliability with the four important elements; 1. “The probability of” 2. “an item to perform a required function” 3. “under stated conditions” 4. “for a specified period of time.” [15] [16]. Remove all reference to calculation of reliability metrics (MTBF) from the definition of reliability.

Suspend the use of MTBF as ‘the’ measure of reliability. The use of MTBF as the only measure trivializes a very complex topic. The correct measure depends on the context of the requirement and the data source as described in Table 1. The USAF has many initiatives to improve reliability for many purposes. There must be experts available to recommend the appropriate analysis and measure depending on the context.

Reliability of fielded USAF repairable systems should be measured using the basic operations of recurrent event data analysis advocated by Nelson [27], and the recurrent events data analysis process adapted from Trindade and Nathan [9] as presented in Chapter III and demonstrated in Chapter IV. Make the recurrent events analysis process available with access to the relevant data. The USAF has positioned LIMS-EV as the single source of truth for enterprise data. LIMS-EV should have a view for sustainment data that is an interface to recurrent event analysis capability to the lowest repair level of serialized items. The research for this thesis required much manual data correlation and formatting. All of that could be done within GCSS-AF and made available across the enterprise.

Recommendations for Future Research

1. It is possible to mechanize the recurrent event analysis process and output notifications of reliability issues (MCF trends or ROCOFspikes). The USAF office, AF/A4ID sponsored a pathfinder project to demonstrate the capability to automate recurrent event analysis. The project produced an IT tool that analyzed massive amounts of maintenance data comparing the current state with historical data to automate near real time identification of abnormal events. [37]

2. Accurate sequence and time to failure data is not generally available below the first level of indenture for USAF weapon systems. It appears that the operating time data attribute is available in the USAF maintenance data collection system for all serialized items. But it appears that it is not a required element, that there is no data there unless manually entered by the technician. The required data is available within the USAF enterprise and accurate population of that data element could be automated as it is for end items.

USAF serialized maintenance data is currently entered manually with no error checking. Research for this thesis reviewed serialized history for components and found that there are significant numbers of incorrect serial numbers in the data. One very critical and expensive component has 20% more serial numbers in the system than items in the inventory. This creates a maintenance record for items that do not exist and omits valuable data from the record of existing items.

Many USAF subsystems are made up of complex, irreplaceable, repairable units. Some of these units are worth millions of dollars and cost hundreds of thousands to repair. To accurately measure the reliability of those items the data gap must be bridged.

The existing data architecture could be researched and compared to the data elements necessary for effective reliability measurement for all. The user interface and GCSS-AF interfaces could be researched to identify sources and impacts of errors.

Summary

The DoD and USAF definition of reliability and the required reporting metric should be reconsidered. The definition should be broad enough to include all of the context areas presented in Table 1 and the required metrics should be tailored to the specific context. MTBF is not an effective metric for measurement of repairable USAF systems.

The DoD intention is to improve reliability in sustainment but all of the effort is aimed at acquisition programs. The USAF can work toward the DoD goal of reducing sustainment costs and improving weapon system A_o by improving reliability without limiting the improvement to current and future acquisition programs. The reliability of fielded repairable systems may be improved with effective measurement and analysis.

Nonparametric recurrent event data analysis is the correct process to use for assessment of the reliability of fielded repairable systems. The necessary USAF data to implement the process at the subsystem level is currently collected. Many weapon systems have historical records of the data. But the data is not readily accessible to reliability analysts. The required knowledge, software tools and resources are not generally available across the USAF enterprise. But as this paper has shown, limited analysis can be done if the weapon systems managers want to invest the resources.

Appendix A

Data Extraction from LIMS-EV [Code 3 Breaks]

LIMS-EV Weapon System View

WUC Tab

1. At Time Increment: select ‘By Month’ (Select month with slider).
2. At Time Increment: select ‘By Day’ (Adjust to desired period with calendar pop-up.)
3. Select desired population as appropriate.
4. At Hours/Numeric/Mean Time buttons select ‘Numeric’.
5. At Metric: select ‘Code 3 Breaks’.
6. At WUC Digit: select ‘3 Digit’.
7. At Driving WUC/LCN/Ref Des: select appropriate WUC.
8. Click the Update button.
9. At the data table View By: select ‘3 Digit WUC’.
10. Check the Transpose Grid box.
11. At the data table Export Grid dropdown select ‘View – metrics selected in the grid’.
12. Save the export file.
13. Repeat from 1 for each month until the desired period is exported.

Data Extraction from LIMS-EV [Flying Hours]

LIMS-EV Weapon System View

Utilization Tab

1. At Time Increment: select ‘By Month’ (Select month with slider).
2. At Time Increment: select ‘By Day’ (Adjust to desired period with calendar pop-up.)
3. Select desired population as appropriate.
4. At Rate/Hours/Numeric buttons select ‘Hours’.
5. Click the Update button.
6. At the data table View By: select ‘Serial Number’.
7. Check the Transpose Grid box.
8. At the data table Export Grid dropdown select ‘View – metrics selected in the grid’.
9. Save the export file.
10. Repeat from 1 for each month until the desired period is exported.

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Vita

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14. ABSTRACT
The USAF generally does not know the reliability of its fielded repairable systems. The reported metric, Mean Time Between Failure (MTBF), is too lagging to be actionable in the best case, and is not representative of actual system reliability in the worst case. This thesis investigates the statistical techniques for measurement and analysis of the reliability of fielded repairable systems, which are very different than nonrepairables. To frame the investigation, a comparison is made between the generally accepted definitions and metrics and those used across the US Air Force (USAF). Reliability can be analyzed in four context areas: reliability prediction of nonrepairable and repairable items and reliability measurement of nonrepairable and repairable items. This research is focused on the latter. An algorithmic process for effective measurement of reliability of fielded repairable USAF systems, based on recurrent event analysis, is proposed and demonstrated using a non-parametric approach on USAF maintenance data. The approach provides a new capability that can identify even short term changes in system Rate of Occurrence of Failure (ROCOF), which can identify daily or hourly trends across the fleet subsystems. This new approach is compared to USAF calculations of MTBF over the same period.

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