SECTION A

INTRODUCTION TO RELIABILITY

1.0 INTRODUCTION

Reliability engineering is a professional discipline which combines knowledge in statistics and engineering for the purpose of quantitatively evaluating, predicting, measuring and improving the reliability of products. Reliability engineering procedures have been applied to a vast array of products, some of which include: machines (of all types), structures, computer software and materials to name just a few. What makes reliability engineering or any other engineering discipline usable for its practitioners are the analysis tools which are generated from the collective knowledge assembled within the discipline.

The material contained in this document emphasizes the various reliability analysis techniques which are available to those who must evaluate, model or predict the reliability of parts and systems. Although mechanical applications are emphasized in this document, many of the theories which are presented can be universally applied to other functional areas. It must be realized that these reliability analysis techniques only provide the means to an end. These analysis tools will prove useful as justification for the design changes, corrective actions and planning decisions which directly improve product reliability. As reliability practitioners, we should strive to provide the best justification possible when recommending design changes or planning future activities based on the expected performance of a product.

With this in mind, this document was developed by RAC engineers to meet the specific goals identified in Figure 1.0-1 and to provide a well rounded discussion of both part and system reliability analysis tools. The major sections of this document are the following:

Section A: Introduction To Reliability

Section B: Fundamental Statistical Concepts

Section C: Part Reliability Engineering

Section D: System Reliability Engineering

SECTION A: INTRODUCTION TO RELIABILITY

Goals:

- Establish part and system reliability engineering perspectives
- Define a "part"
- Define a "system"
- Establish basic terminology associated with each perspective

SECTION B: FUNDAMENTAL STATISTICAL CONCEPTS

Goals:

- Establish statistical concepts & terminology pertinent to reliability
- Discuss concepts of: the random variable, sample, population, probability, distribution of a random variable, and dispersion and central tendency numerics associated with a random variable
- Identify the random variables of reliability

SECTION C: PART RELIABILITY ENGINEERING

Goals:

- Discuss mechanical failure mechanisms
- Discuss mechanical failure theories and their utility
- Establish distribution statistics as a primary part failure data analysis procedure with emphasis on the Weibull failure model
- Identify and discuss the utility of other part reliability evaluation techniques such as interference analysis and life assessment models

SECTION D: SYSTEM RELIABILITY ENGINEERING

Goals:

- Establish the point process approach to system failure modeling
- Discuss important point process models such as Homogeneous Poisson Process (HPP) and Nonhomogeneous Poisson Process (NHPP)
- Discuss utility of failure mode evaluation tools such as Failure Mode, Effects and Criticality Analysis (FMECA) and Fault Tree Analysis (FTA)

FIGURE 1.0-1: SUMMARY OF DOCUMENT GOALS

1.1 Reliability Engineering Perspectives

Reliability engineering has developed two principal perspectives toward the analysis of reliability. These two principal perspectives are: part and system reliability engineering. Each perspective has evolved in order to evaluate different empirical and analytical reliability issues. Each also deals with different items of primary interest. Part reliability is concerned with the failure characteristics of the individual nonrepairable part to make inferences about the part population. System reliability is concerned with the failure characteristics of a group of typically different parts assembled as a repairable system. Past history has shown that the analysis of parts and the use of part reliability based theories has dominated the reliability discipline. Unfortunately, in some cases, this practice has led to the misapplication of part reliability theories to systems. But, this domination still exists even though many of the system reliability theories were well documented as far back as the mid-1960s (Reference [59]).

It is essential to realize that *two* principal perspectives exist and represent paths of analytical diversity within the study of reliability. Each perspective offers its own unique set of reliability terminology and statistical theories. It is the goal of this document to provide the reader with an accurate account of each perspective and to focus on the use of appropriate terminology and analysis techniques when evaluating parts and / or systems.

Reliability analysis techniques and terminology are not universally applicable but are a function of which perspective is in effect; part or system. In general, a segregated thought process, as shown in Figure 1.1-1, will serve the novice best when developing, interpreting, or communicating reliability information. There are numerous examples in reliability literature where incorrect evaluations have been performed because of confusion and misuse of reliability analysis techniques and terminology. Many of these misapplications could have been prevented with a better understanding of the differences between part and system evaluation procedures. Examples of these misapplications are identified and discussed in Reference [55].

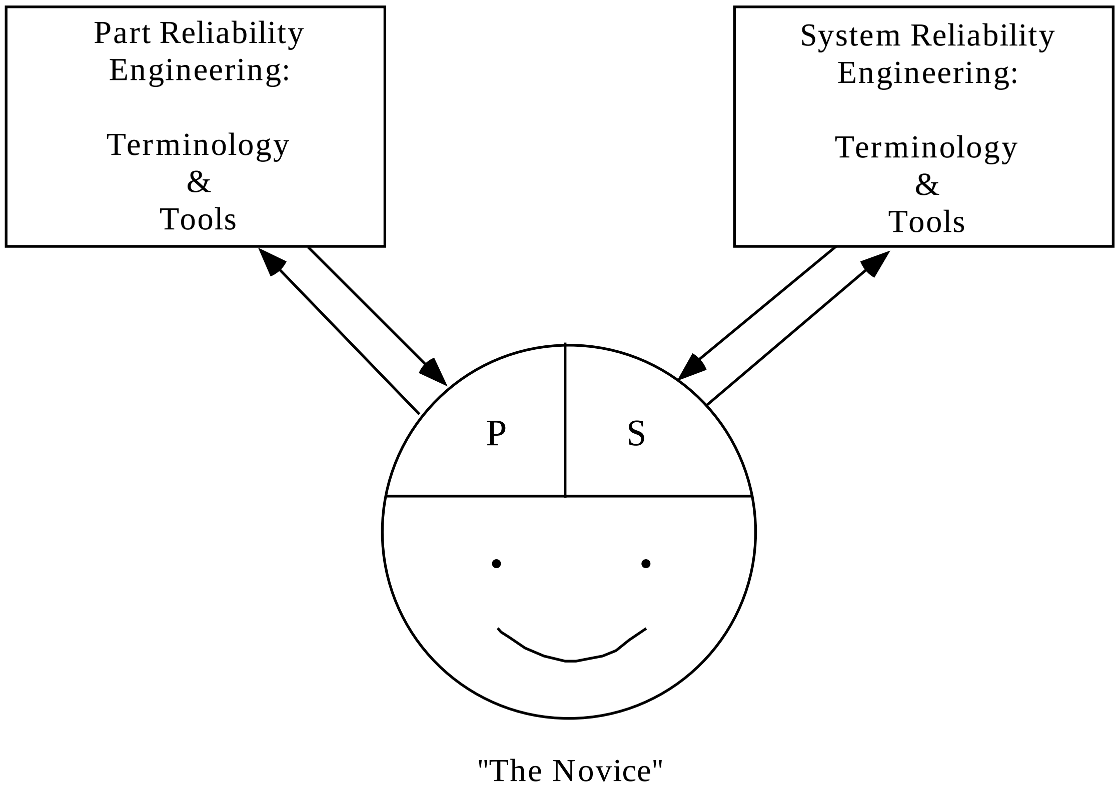


FIGURE 1.1-1: A "NOVICE" APPROACH TO RELIABILITY ENGINEERING CONCEPTS

Approaching a reliability task from the correct perspective is required to obtain valid results. It will also improve your ability to communicate the results to colleagues or the general reliability community. Figure 1.1-2 illustrates this concept and shows efficient lines of communication among the various members of the reliability community. Each member is enjoying a balanced perspective toward both part and system reliability.

Once the correct perspective has been established, the correct terminology can be applied. For example, one collects individual time-to-part failure (TTF) data for parts but collects time-between-successive system failures (TBF) data for a system. Understanding these subtle differences in terminology will improve our ability to develop, interpret and communicate reliability information. Figure 1.1-3 illustrates some common terms which are associated with either part or system reliability. All of the topics indicated in Figure 1.1-3 are discussed at various points throughout this document.

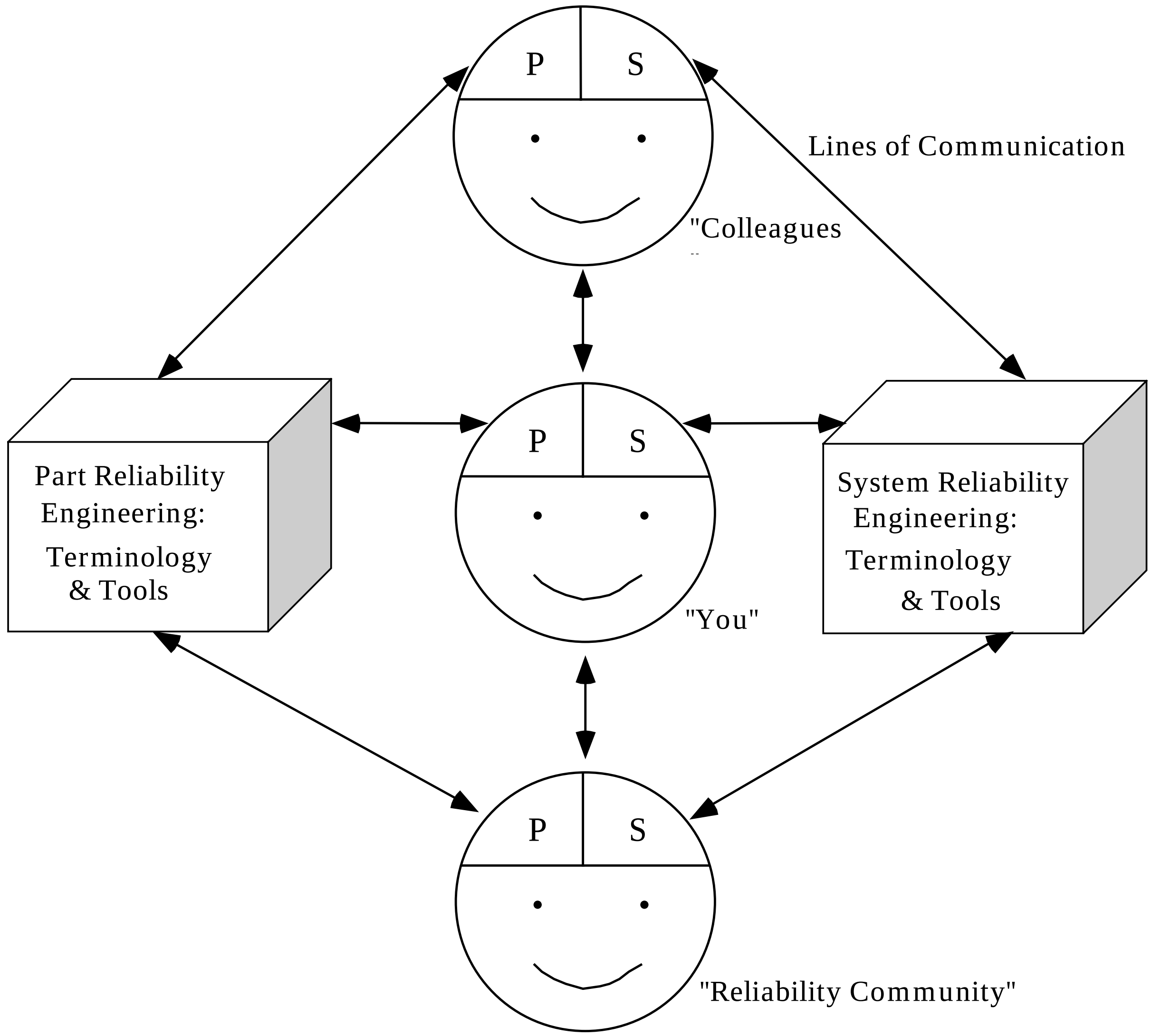


FIGURE 1.1-2: INTERPRETING AND COMMUNICATING RELIABILITY ENGINEERING INFORMATION WITH SUCCESS - HAVE A BALANCED PERSPECTIVE

Reliability Terminology

Part Reliability

- Time-to-Part Failure of the ith part (TTF_i)
- Mean Time to Failure (MTTF)
- Failure Distributions
- Exponential Failure Model
- Weibull Failure Model
- Force of Mortality (FOM) or Hazard Rate, h(x)
- Wearout
- Order Statistics $\left(TTF_{(1)},\ TTF_{(2)} \ldots TTF_{(n)}\right)$
- Spacing Between Order Statistics (i.e., the time between ordered TTF)
- "x" for the age of a part

System Reliability

- Time-Between - Successive System Failures $\left(TBF_i\right)$ or Interarrival Times
- Mean Time Between Failure (MTBF)
- Arrival Times $\left(TTSF_i\right)$ or time to the i^{th} system failure
- Failure Process
- Point Process Model
- Homogeneous Poisson Process (HPP)
- Non Homogeneous Poisson Process (NHPP)
- Rate of Occurrence of Failure (ROCOF)
- Deterioration
- Chronological Ordering
- Laplace Trend Test
- "t" for the age of a system

FIGURE 1.1-3: SIGNIFICANT RELIABILITY TERMS AND THEIR ASSOCIATION

1.2 Functional Categories of Reliability

Reliability has been segregated into functional categories. Functional categories have been identified in numerous discussions of reliability and include: mechanical, electronic, structural and materials to name just a few. These categories are significant because they identify specific specialty areas within reliability. They represent a natural transition to more detailed areas of expertise and are typically associated with the standard engineering disciplines such as mechanical and electrical engineering. As illustrated in Figure 1.2-1, these functional areas can be viewed as specialty "spin-off" areas from the main body of reliability engineering.

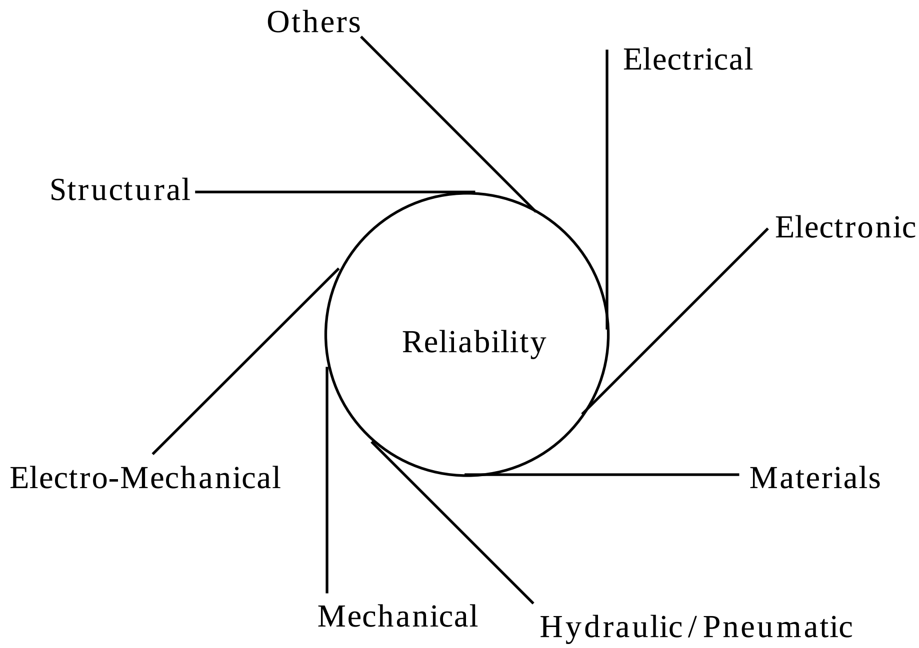


FIGURE 1.2-1: FUNCTIONAL AREAS OF RELIABILITY

The functional areas of reliability have been greatly enhanced because of the enormous knowledge base which currently exists in each of the related engineering disciplines. In order for reliability models to be meaningful, engineering variables must be transitioned into reliability variables such that no engineering theories are violated. In this way, reliability engineering practices will enhance present engineering procedures.

Mechanical reliability is a specific functional area of reliability engineering which specializes in the application of reliability principles to mechanical parts and systems with mechanical parts. Here the analyst can use his or her engineering expertise of mechanical failure mechanisms, mechanical failure theories, material properties, stress concentrations, fatigue theory, fracture mechanics or other related topics to improve the reliability of parts and systems. The functional area of mechanical reliability will be emphasized throughout this document in the form of mechanically oriented discussions and examples.

1.3 Concept of a Part

Essential to the understanding of material contained in this document is the significance of what characterizes a "part" and what characterizes a "system". A "part" will be defined as a nonrepairable item which can only fail once and is then discarded. A part can be categorized as a simple part or a complex part. A simple part consists of a single component. For example, o-rings, belts, bolts, springs or gears can be considered simple parts. A complex part consists of more than one component. For example, a ball bearing, relay, thermostat, fuse or spark plug can be considered complex parts because, upon failure they are typically discarded, but unlike simple parts, do contain multiple components.

Figure 1.3-1 graphically portrays the time-to-failure (TTF) associated with a group of identical parts tested to failure. Note how parts exhibit no life after first failure and are considered nonrepairable.

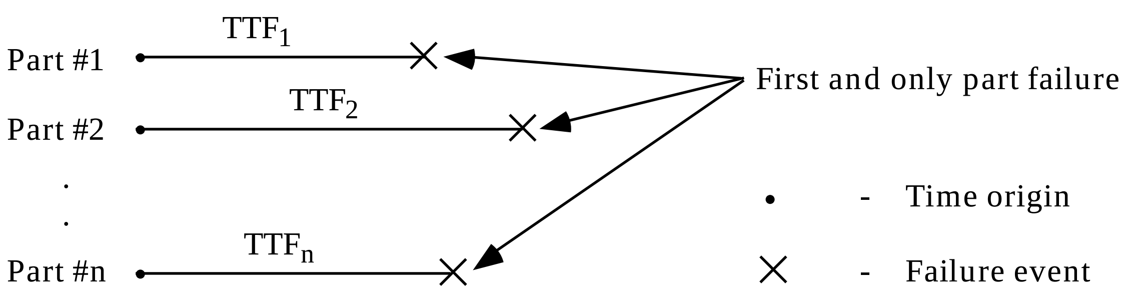


FIGURE 1.3-1: ILLUSTRATION OF PART FAILURE FOR A SAMPLE OF N IDENTICAL PARTS

Probabilistic failure models $\left(f_P(x),\ F_P(x),\ R_P(x)\right)$ can be generated from a sample of identical parts which have failed such as those illustrated in Figure 1.3-1. These probabilistic models define the reliability characteristics of each part in the sample. As the sample size, n, approaches infinity (∞), the reliability characteristics approach their true values. The true values being representative of the entire part population. The probabilistic models associated with TTF data are discussed in Section B and the procedures for probabilistic modeling of TTF data are discussed in detail in Section 6.0.

1.4 Concept of a System

Unlike a part, a system has a particular characteristic which makes it unique, namely, the ability to experience successive failure events over its lifetime. This sequential series of failure events can be illustrated on a continuous time line as shown in Figure 1.4-1 and is called a failure process.

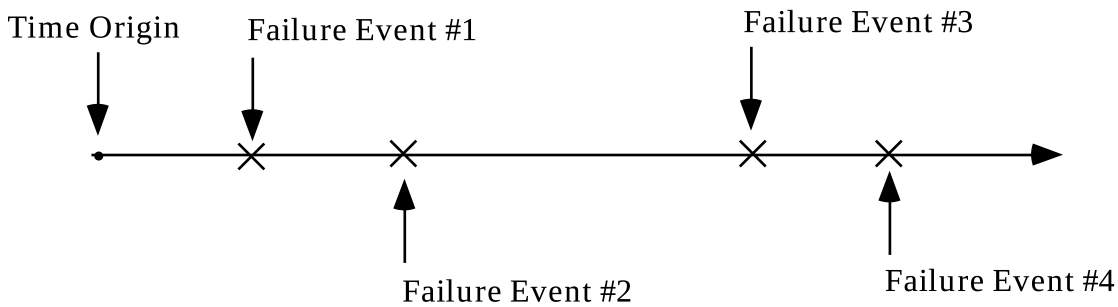
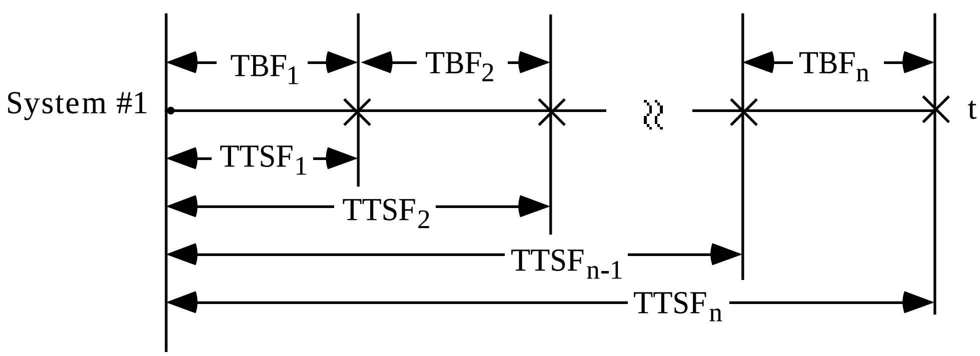


FIGURE 1.4-1: SYSTEM FAILURE PROCESS: TIME LINE OF SYSTEM FAILURE EVENTS

The time line is typically representative of system operating time. Comparing Figure 1.3-1 and Figure 1.4-1 reveals the differences between part failures and system failures, namely, a part can only fail once but a system can fail numerous times. This significant difference will form the basis for further statistical pursuit within each of these areas.

The notation given to the various time segments of the system failure process is identified in Figure 1.4-2.



n	=	total number of system failure events
TBF_i	=	time between successive system failure events or interarrival times
$TTSF_i$	=	time to system failure events or arrival times

FIGURE 1.4-2: TIME SEGMENT NOTATION FOR SYSTEM FAILURE PROCESS

Other references on repairable system reliability and time series analysis have used other notation for both arrival times (e.g., T_i and x_i) and interarrival times (ex., X_i). NPS-2 has selected a slightly more representative set of notation as illustrated in Figure

1.4-2 in order to improve the distinction between part and system variables. This essential notation will also be summarized in the next section.

1.5 Essential Notation

The following is a list which summarizes the most significant notation to be used throughout this document. Some of the notation has already been introduced in previous sections and should be reviewed again at this time. Much of this terminology is consistent with other published works and this will hopefully improve the utility of the material to follow. A glossary of reliability terms is also provided in Appendix A.

Parts

P	-	represent the random variable: time to part failure, a primary random variable in part reliability engineering
$\{TTF_1, TTF_2 \ldots TTF_n\}$	-	set of time to part failure data from n identical parts
$TTF_{(1)}, TTF_{(2)} \ldots TTF_{(n)}$	-	time to failure data from n identical parts which is ordered by magnitude such that $TTF_{(1)} \leq TTF_{(2)} \leq TTF_{(n)}$ (i.e., order statistics)
$TTF_{(i+1)} - TTF_{(i)}$	-	spacing between ordered time to part failure data
x	-	age of a part, typically considered the operational age
$f_P(x)$	-	density function which describes a set of time to part failure data from n identical parts where n › ∞
$F_P(x)$	-	cumulative distribution function which describes a set of time to part failure data from n identical parts where n › ∞
$h_P(x)$	-	hazard rate or force of mortality (FOM) of time to part failure
$R_P(x)$	-	part reliability or probability that the part survives to age x

Systems

S_i	-	represents a system random variable which is the time between the (i-1)st and ith system failures extracted from a population of system failure processes
TBF_i	-	time between the (i-1)st and ith system failures, also the ith interarrival time of one system failure process
T_i	-	represents a system random variable which is the time to the ith system failure or the ith arrival time
$TTSF_i$	-	time to the ith system failure also the ith arrival time from one system failure process. A value of random variable T_i
t	-	total system age, typically considered the operational age
TBF_1, TBF_2 ... TBF_n	-	represents the natural order of interarrival times of one system failure process which has "n" failure events

General

f(x)	-	probability density function of a random variable, X
F(x)	-	cumulative distribution function of a random variable, X
h(x)	-	hazard rate or force of mortality of a random variable, X
R(x)	-	survivor function or reliability function of a random variable, X