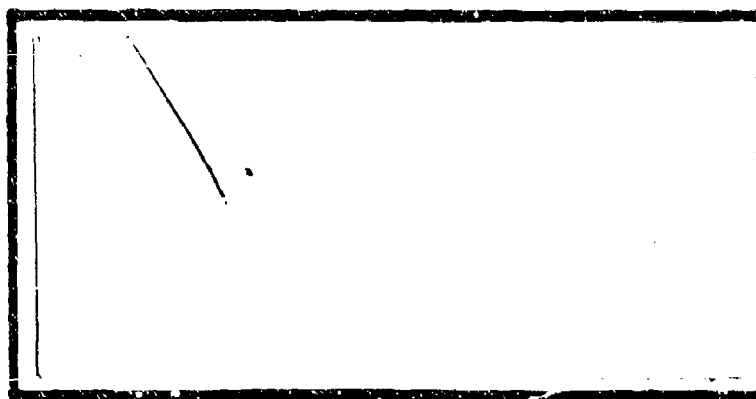AD-A202 625

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DEPARTMENT OF THE AIR FORCE

AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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EXPERTS' OPINIONS ON THE RELIABILITY
GAP AND SOME PRACTICAL GUIDELINES
ON RELIABILITY GROWTH

THESIS

Katherine C. L. Ma
Captain

AFIT/GSM/LSM/88S-17

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AFIT/GSM/LSM/88S-17

EXPERTS' OPINIONS ON THE RELIABILITY GAP

AND SOME PRACTICAL GUIDELINES ON

RELIABILITY GROWTH

THESIS

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Systems Management

Katherine C. L. Ma

Captain, USAF

September 1988

Approved for public release; distribution unlimited

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in many of the perplexing areas of reliability. It is
upon the shoulders of these "giants" that I was able to
capture a glimpse of the world of reliability.

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AFIT/CSM/LSM/88S-17

Abstract

Over the years, the reliability of fielded weapon
systems has consistently been less than what was predicted.
In the area of avionics equipment, the reliability gap
between "predicted mean-time-between-failures (MTBFs)" and
"field MTBFs" was reported to range from 7:1 to 20:1
(38:231). The inability to accurately relate factory
(whether specified, predicted, or demonstrated) reliability
to the field reliability of weapon systems/subsystems has a
significant impact on operational readiness and life cycle
costs.

To study the reliability gap between factory and field
reliability, this research is divided into three distinct
phases, with the following objectives:

1. To examine the existence of the reliability gap in
   airborne tactical radars.

2. To identify and analyze the major contributors to
   the reliability gap. Specifically, to identify the
   most significant contributors.

3. To explore practical guidelines on how to minimize
   the reliability gap. Specifically, to identify some
   practical guidelines on reliability growth.

To examine the existence of the reliability gap, this
thesis obtained the data from the Naval Air Systems Command
(NAVAIR) and examined the radars on Air Force and Navy
aircraft. Using experts'/practitioners' (DoD & Industry)

opinions, contributors to the reliability gap were identified. In addition, some practical guidelines on reliability growth management were also identified. This thesis consolidated some of the best currently available thinking on the major contributors to the reliability gap and some of the practical guidelines on reliability growth.

EXPERTS' OPINIONS ON THE RELIABILITY GAP

AND SOME PRACTICAL GUIDELINES ON

RELIABILITY GROWTH

I. Introduction

Over the years, the reliability of fielded weapon

systems has consistently been less than what was predicted

or demonstrated. In the area of avionics equipment:

> ...it has been reported that the ratio of an
> equipment's demonstrated MTBF (mean time between
> failure) to its field MTBF can range from 7:1 to
> 20:1. Even greater disparities are quoted when
> comparing predicted MTBFs to field MTBFs.
> [38:231]

The field reliability has generally failed to measure up

to the factory reliability (whether specified, predicted, or

demonstrated) (44:177). The inability to relate field

reliability to factory reliability has shown to have a

significant impact on system operational readiness

and life cycle costs (16, 40, 44, 48, 58).

This chapter introduces the research issues concerning

the existence, the major contributors, and the minimizing

approaches to the reliability gap between field and factory

reliability. The chapter begins with a discussion on the

background of the research topic followed by a description

of the specific problem. The scope and limitations of this research are then presented along with the research objectives, research questions, and potential benefits. The chapter concludes with an overview of the remaining chapters in this thesis.

Background

During the past few years, numerous studies have indicated a wide discrepancy between the field MTBFs, measured under actual operational environment, and the predicted MTBFs. In one of the studies:

> The U.S. Comptroller General states that 'one of the persistent problems with weapons systems has been the discrepancy between contractually specified reliability goals and those encountered in the operational environment'. U.S. Comptroller recommends that 'The services continue to strive to narrow the gap between contractually specified reliability and maintainability and those factors measurable under operational conditions'. In reviewing a current program, it notes that 'The test conditions are not fully representative of the operational environment. Only RELEVANT failures are counted. For example, one-time intermittent failures whose cause could not be determined were not counted. Failures caused by accidental damage, operator error, etc., were not considered. In the field, however, these items create significant workloads and spares demands, particularly in the avionics areas.' [54:5]

In the area of airborne avionics, Kern (38) studied the relationships between field and factory MTBFs (whether specified, predicted, or demonstrated values) of 16 different pieces of avionics equipment from 10 different aircraft and found the ratio of the disparity to range

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from 2.1:1 to 9.1:1 (38:201). Furthermore, Montemayor (54) studied the reliability gap between predicted and field reliability of airborne radars and found the ratio of predicted reliability to field reliability to be 5:1 (44:177). Table 1 summarizes some of the historical findings on the disparity between predicted or demonstrated reliability and field reliability.

Table 1. Historical Findings on the Difference Between the Predicted or Demonstrated Reliability and Field Reliability (44:177)

Equipment	Reliability Ratio Predicted : Field	Reliability Ratio Demonstrated : Field
Airborne Avionics	>20:1	
Airborne Transport	2.3:1	2.1:1
Airborne Composite	7.7:1	5.9:1
Airborne Fighter	9.1:1	6.7:1
Airborne Radars	5.0:1	

Specific Research Problem

The difference (gap) between the field and the factory reliability (whether specified, predicted, or demonstrated) has been documented in numerous studies. The ability to accurately predict the reliability of fielded weapon systems has shown to be useful in many areas. Among them is the

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ability to make "economic provision for repair costs, spare parts inventories, system availability, operational effectiveness...." (33:108). Within the military, there is a need to relate the factory reliability (whether predicted, specified, or demonstrated) to the actual field reliability in order to:

> ...establish realistic quantitative reliability and maintainability requirements and estimate weapon system readiness and maintenance resource demands. [44:177]

The inability to accurately predict the reliability of fielded weapon systems has been proven to be costly. Kolston (40) found that:

> ...initial spares provisioning and procurement of support equipment based on inaccurate predictions of reliability characteristics may result in non-optimum allocation of program resources, and, in turn, low levels of operational readiness. [40:245]

In examining the field reliability of deployed radars, Cougan and Kindig (16) found that without the proper reliability emphasis, more than 800 deployed radars "exhibited unacceptably low field reliability and operational readiness, accompanied by high life cycle costs" (16:121). Due to the increasing logistic support costs, there is an increased interest in identifying the causal factors to the differences, "as well as a requirement for better predictive methods for estimating field operational reliability" (38:231).

In the interest of maximizing the operational readiness and optimizing the life cycle costs, this research investigates the reliability gap. Figure 1 presents the generic reliability gap between the factory and field reliability. The existence of the gap is well documented in numerous studies. Research is needed to identify the causal factors to the gap, and to explore ways of minimizing the gap, and consequently increase operational readiness and optimize life cycle costs.

```
R
E
L          PREDICTED                  ↑
I                                     |
A                                     |
    SPECIFIED                         |
B      OR                            Gap
    DEMONSTRATED                      |
I                                     |
L                                     |
I          FIELD                      ↓
T
Y

    └────────────────────────────────────
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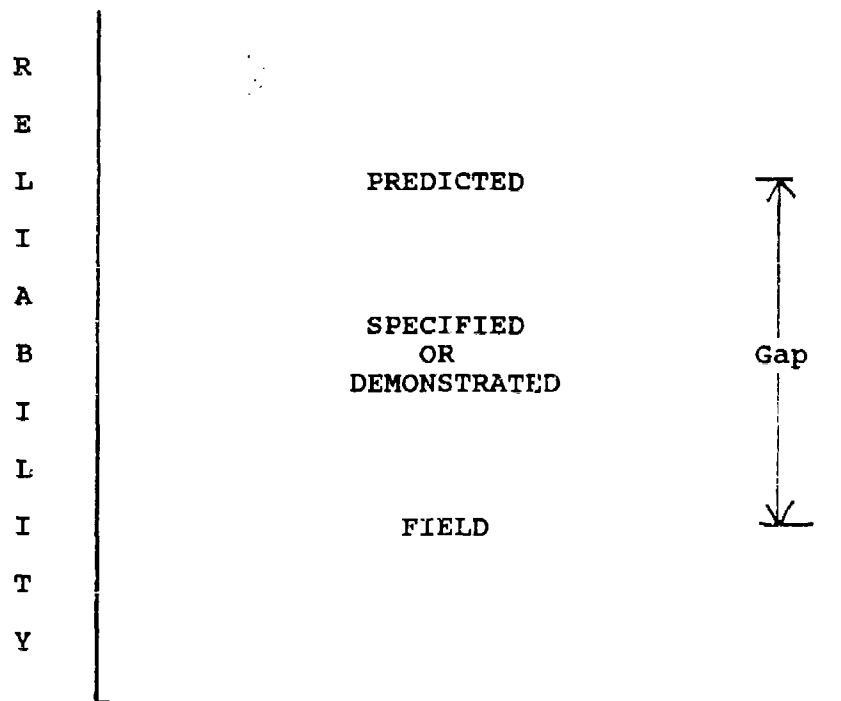
A TYPICAL SYSTEM

Figure 1. The Reliability Gap

Research Scope

The extent of this research will be divided into three
distinct phases. In the first phase, tactical airborne
radars will be examined to present the existence of the
reliability gap. The courtesy slide from NAVAIR consists of
Air Force as well as Navy aircraft. It is the researcher's
intent that this part of the study be used primarily to
better understand the reliability problems. Consequently,
specific systems will not be named. In the second phase,
interviews will be used to collect experts'/practitioners'
opinions to identify and rank order the major contributors
to the reliability gap. Reliability experts/practitioners
from the Army, Navy, Air Force, and Industry will be asked
to participate in this part of the study. Personal, as well
as telephone, interviews will be conducted. In addition, a
second round of interviews will be conducted to validate the
findings from the first round. Finally, in the third phase,
practical guidelines (experts'/practitioners') will be
examined on how to minimize the gap. Specifically, some
practical guidelines on reliability prediction and
reliability growth will be examined. The data source for
this phase will be the experts'/practitioners' opinions,
various studies conducted by the experts/practitioners, and
appropriate historical studies.

Research Limitations

The limitations associated with the scope of this research are as follows:

a. The selection of the participants in each category (Army, Navy, Air Force, and Industry) of the interviews will be based on the availability of the experts/ practitioners and will not necessarily be proportionately representative of the population at large. Consequently, a similar study using another sample from the target population could produce different results.

b. The data obtained in this study will be derived from personal and telephone interviews of experts. As a result, data obtained in this manner are subjective in nature and could not be quantitatively verified. Whenever interviews are involved, there exists the possibility of interjecting bias. The researchers can interject bias into the process by their presence, by the way questions are presented, or by a host of other factors (26:165-167). Although success could not be verified, every effort will be made to eliminate or reduce bias.

c. Alternative techniques will be selected to minimize the reliability gap and the techniques selected are by no means all-inclusive. The intent for this phase of the study is to draw on the expertise of the interviewees in order to explore the practicalities of the proposed theories.

Research Objectives

The objective of each phase of this study is as follows:

Phase I. To examine the existence of the reliability gap in tactical airborne radars on Air Force and Navy aircraft.

Phase II. To identify and analyze the major contributors to the reliability gap. Specifically, to identify the most significant contributors.

Phase III. To explore ways on how to minimize the reliability gap. Specifically, to identify some practical guidelines on reliability growth.

Research Questions

The questions, each pertaining to its respective objective of this study, are as follows:

1. Does the reliability gap exist in tactical airborne radars?

2. What are the major contributors to the reliability gap? Specifically, what is the relative importance of the major contributors and what are the most significant contributors?

3. What are some of the practical guidelines on how to minimize the reliability gap? Specifically, what are some of the practical prediction techniques and some practical guidelines, i.e., the growth model, the initial reliability, the growth rate, and the effectiveness factor?

Potential Research Benefits

The purpose of this study is to examine and analyze the reliability gap between the field and factory reliability.

In addition, this thesis identifies some practical guidelines in the area of reliability growth. This study offers the following potential benefits, with a common goal of maximizing operational readiness and optimizing life cycle costs.

1. The identification of the most significant contributors to the reliability gap can help decision makers to better allocate their resources.

2. The comparative (DoD vs Industry) perspective of the most significant contributors can serve as a guide to better understanding the reliability gap.

3. This research suggests some possible solutions to the most significant contributors which can be implemented in the future to minimize the reliability gap.

4. This study contains an extensive literature review on the issues of the reliability gap and traditional ways of reliability assessment.

5. This study consolidates some of the best currently available thinking on the major contributors to the reliability gap and some of the practical guidelines on reliability growth.

Overview

The remaining chapters of this thesis will describe in detail how the objective of each phase of this study will be accomplished. Chapter II presents an exhaustive literature review on the issues of reliability as they pertain to this research, while Chapter III describes the data requirement, data collection, and the data analysis of this research. Chapter IV presents the findings and Chapter V summarizes this research effort and makes recommendations for future studies.

II. Literature Review

Introduction

Research of this study begins with the investigation of the reliability gap between the factory (whether specified, predicted, or demonstrated) and the field reliability. This chapter begins with the definition of reliability, followed by the development of reliability engineering and the understanding of the problems of unreliability. Description of the reliability gap and traditional ways of assessing reliability are examined. In addition, some practical questions and answers associated with the research problem--the reliability gap--are also presented. This chapter concludes with a summary of the literature review.

Definition of Reliability

In order to have a clear understanding of the theme of this study--the reliability gap--it is first very important to understand the meaning of the term called "reliability."

Reliability is defined 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. [8:14]

PROBABILITY, the first element in the reliability definition, implies that any attempt to quantify reliability involves the use of statistical methods. Usually, it is quantified in terms of the relative frequency of occurrence of an event, that is, the ratio of the number of times that the event occurs (successes) to the total number of opportunities for occurrence (trials) of the event (35:74). For example, the probability of survival of an item for 80 hours is 0.75 indicates that "we can expect the item will function properly for at least 80 hours, 75 times out of 100 trials" (8:14). It is also important to realize that the observed probabilistic quantities of a certain parameter are not the true values of that parameter, but are values distributed around some expected value (33:111).

SATISFACTORY PERFORMANCE, the next element in the basic reliability definition, indicates that:

> ... specific criteria must be established which describe what is considered to be satisfactory system operation. A combination of qualitative and quantitative factors defining the functions that the system or product is to accomplish, usually presented in the context of a system specification, are required. [8:15]

TIME, the third element of the reliability definition, is recognized as one of the most important elements in the basic definition of reliability since it represents:

> ...a measure against which the degree of system performance can be related. One must know the 'time' parameter in order to assess the probability of completing a mission or a given function as

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scheduled. Of particular interest is being able to predict the probability of an item surviving (without failure) for a designated period of time. Also, reliability is frequently defined in terms of mean time between failure (MTBF), mean time to failure (MTTF) or mean time between maintenance (MTBM); thus, the aspect of time is critical in reliability measurement. [8:15]

Time seems to be a relatively simple parameter; some of the underlying complexities of time are explained by Shelly and Stovall (62) in these words:

The 'T' part of MTBF in the laboratory might be equipment on chamber-time, official test-time, or various combinations. The 'T' in the field MTBF might be flight time, equipment operating time, equipment standby plus operating time, or various combinations. [62:322]

SPECIFIED OPERATING CONDITIONS, the fourth element of the basic reliability definition, include:

...environmental factors such as the geographical location where the system is expected to operate, the operational profile, temperature cycles, humidity, vibration, shock, and so on. Such factors must not only address the conditions for the period when the system or product is operating, but the conditions for the periods when the system (or a portion thereof) is in a storage mode or being transported from one location to the next. Experience has indicated that the transportation, handling, and storage modes are sometimes more critical from a reliability standpoint than the conditions experienced during actual system operational use. [8:15]

In determining systems or products reliability, all these elements are essential. By examining the basic definition of reliability, it can be realized that the study of reliability is rather complex. The complexity involves

the uncertainties associated with the study of probability and statistical analysis.

The study of statistical analysis is concerned with the "collection, organization, and interpretation of data according to well-defined procedures" (35:3). Well-defined in the sense that the rules of organization and interpretation are clearly spelled out so that, given the same data, any researcher applying the same analytical techniques will get the same conclusions (35:10).

However, the application and interpretation of statistics in reliability are not as straight forward as public opinion polls or measurement of human IQ scores. In these applications:

> ...most interest is centered around the behaviour of the larger part of the population or sample, variation is not very large and data are plentiful. In reliability we are concerned with the behaviour of unlikely combination of load and strength, variability is often hard to quantify and data are expensive. [58:4]

Reliability analysis may contain many sources of uncertainty and variability which may be more difficult to analyze than other disciplines of statistical analysis. However, O'Connor (58) emphasized how people can make a difference in reliability analysis:

> ...the reliability engineer or manager is not, like an insurance actuary, a powerless observer of his statistics. Statistical derivations of reliability are not a guarantee of results, and these results CAN be significantly affected by actions taken by quality and reliability engineers and managers. [58:5]

Reliability is defined in terms of four essential elements: Probability, satisfactory performance, time, and specified operating conditions. Knowing the essential elements of reliability is important in understanding the research problem---the reliability gap.

The study of reliability has been in existence for quite a number of years. In fact, the study of reliability analysis has its roots back in the 1940s, during WWII (37:5).

Development of Reliability Engineering

Reliability analysis is "an indirect outgrowth of the problems with electronic systems designed during the early 1940s for use in the war effort" (37:5). Over the years, there seemed to be a direct relationship between the complexity of military electronic systems and the problems that were generated. As we transitioned into the age of solid-state electronics technology, the problems were compounded by new designs, new manufacturing processes, and perplexing logistics support issues. All these problems translated into reduced availability and increased ownership costs (58:9).

In 1952, the Department of Defense (DoD) established the Advisory Group on Reliability of Electronic Equipment (AGREE) to investigate the reliability problem (37:5). In 1955, the AGREE established a program consisting of nine

tasks: numerical reliability requirements, tests, design procedures, components, procurement, packaging and transportation, storage, operation, and maintenance. The task groups, comprised of personnel from both the military and industry, "were asked to submit their findings in the form of a report after they had considered all aspects of their assigned tasks" (1). In the area of testing, the task group generated a report which concluded that integral activities are needed in the development cycle in order to break the spiral of increasing development and ownership costs. The report emphasized the need to test new equipment for several thousand hours in high-stress, cyclical environments in order to discover design problems early so they can be corrected before production. The report also recommended that formal demonstrations of reliability, using statistical methods, be instituted as an acceptance condition of equipment by the procuring agency. The DoD accepted and reissued the AGREE report on testing as US Military Standard (MIL-STD) 781, Reliability Qualification and Production Approval Tests. The reliability engineering effort developed quickly. The AGREE and reliability program concepts were soon adopted by the National Aeronautics and Space Administration (NASA) and many major companies (58:10).

In 1965, the DoD issued MIL-STD-785, Reliability
Programs for Systems and Equipment. This document mandated
the integration of reliability engineering activities with
the traditional engineering design, development, and
production activities. It was realized that an integrated
approach was:

> ...the only way to ensure that potential
> reliability problems would be detected and
> eliminated at the earliest, and therefore the
> cheapest, stage in the development cycle. [58:10]

Numerous studies were conducted to show the cost benefit of
higher reliability as a result of early development effort,
demonstration of specified levels of reliability in
accordance with MIL-STD-781, and production testing. The
concept of life cycle cost was introduced as part of the
cost benefit analysis (58:10).

As the struggle for more reliable systems or products
continues, there is a need to better understand reliability.
The next section will address the reasons for unreliability
and the problems associated with it.

Understanding the Problems of Unreliability

As far back as 1955, in the early years of reliability
engineering, RCA conducted a study and presented the
findings in the Proceedings of the Conference on "The
Reliability of Military Electronic Equipment," August 1956.
The summary of the study contained 10 major conclusions

about reliability and Appendix A contains 7 of the 10 conclusions. What is so amazing is that most of the conclusions still apply today, 33 years later! Especially interesting is the conclusion that "RELIABILITY TAKES TIME....time is the mortar which binds this whole structure of reliability together...." (Appendix A).

Like vintage wine, reliability takes time. The problems we have had with unreliability over the years, is it possible that we have been "drinking the wine before its time?"

There are many reasons for unreliability. Lloyd and Lipow (14) stated that the root cause of the problems is "due to the dynamic complexity of system development concurrent with a background of urgency and budget restrictions" (41:3). The dynamic complexity to which they refer is the emerging technology in an ever-changing environment. They noted that:

> ...devices and systems are not perfect; they do not operate in the same manner in all circumstances. Our total knowledge may be insufficient about any item so that when it is placed into an environment, about which we also have insufficiency of information, failure occurs. [41:4]

However, they mentioned that if sufficient time is given, we will acquire the knowledge to change the situation through the process of evolution. They expressed the problem in these words:

Were we able to let the evolution take place at a
natural pace, our reliability problem might be
relatively minor. Unfortunately, there is an
urgency which prevents us from giving sufficient
time to all of the many considerations. The
evolutionary process conflicts with the
'revolutionary' atmosphere. Before we have time to
experience, synthesize, and apply our knowledge we
are developing another system or device. [41:4]

To help understand the problem of unreliability,

Stovall (65) made the following conclusions:

---The consumer desires a higher reliability than:
   (a) he is willing to pay for, or
   (b) he knows how to obtain from the producer.

---The manufacturer is frequently unwilling to
   spend the money necessary to achieve high
   reliability because of zero profit margin
   brought about by the low quote necessary to get
   the business.

---Cost/schedule is a trade-off against the
   achievement of high reliability; reliability
   is usually compromised with both consumer and
   producer being parties to the decision to
   establish cost/schedule as the number one
   priority.

---More often than not, the supplier does not know
   how to achieve higher reliability than he
   achieved in the past, and he does not have the
   reliability management skill to elevate his
   capability.

---There are manufacturing shortcomings at all
   levels: prime contractor, supplier, and sub-
   tier supplier. Although the same may be said
   for the design, it is easier to design high
   reliability than it is to produce it.

---For high piece-part count equipment, subsystems
   are so complex with so many interfaces with
   other subsystems that there is an inherent low
   reliability.

---Frequently, the operational facility does not
have the necessary maintenance/repair
capability for complex systems to sustain
original hardware reliability.

---Reliability, as delivered from the producer is
frequently directly related to the future
business potential. Today's action is strongly
influenced by the potential for tomorrow's
sale. [65:594]

In the early 1980s, Air Force Logistics Command (AFLC)
did a study on the cost of unreliability. The study found
that:

...parts failures accounted for 75% of support
equipment costs in aircraft procurement accounts
and at least 20% of the Air Force budget. The
study also showed that the impact of improving
reliability was significant. In fact, for a
composite of fighter aircraft, doubling the mean
time between failure (MTBF) would reduce the spares
requirement by some 80%. [32:5]

Reliability is not a simple concept. It is defined in
terms of four essential elements: probability, satisfactory
performance, time, and specified operating conditions.
Reliability analysis/engineering is not a new science
(though some may still consider it an art); it has been in
existence since the 1940s. Over the years, there have been
numerous studies on the puzzling concepts of reliability/
unreliability. With the stage set, this study will now
explore the research problem--the reliability gap.

The Reliability Gap

The inability to relate the factory (whether specified,
predicted, or demonstrated) and field reliability has proven

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to be costly. It has been shown that the "inaccurate predictions of reliability characteristics may result in non-optimum allocation of program resources, and, in turn, low level of operational readiness" (40:245). Before examining the composition of the reliability gap, it is necessary to define the reliability indices used to measure reliability. In his study, Kern (Hughes Aircraft) described the terms as follows:

> The required MTBF is established on considerations of mission requirements, cost, previous experience, etc. The predicted MTBF is an analytical assessment of the inherent reliability based on equipment design characteristics, while demonstrated MTBF assess inherent reliability on the basis of the failure/operating time experience of a specific sample of equipment under controlled laboratory test conditions. The field MTBF, on the other hand, is an assessment of the achieved operational reliability of the equipment in actual operation. [38:231]

Kern addressed that in theory, since all four MTBFs measure the same parameter, they should be alike. But in practice:

> ...it has been reported that the ratio of an equipment's demonstrated MTBF to its field MTBF can range from 7:1 to 20:1. Even greater disparities are quoted when comparing predicted MTBFs to field MTBFs. [38:231]

With four types of reliability indices, there are six possible combinations of reliability gap: Predicted vs Specified, Predicted vs Demonstrated, Predicted vs Field, Specified vs Demonstrated, Specified vs Field, and

Demonstrated vs Field. Figure 2 presents a graphic
description of the reliability indices for two typical
systems.

```
R  │ PREDICTED                            PREDICTED
   │
E  │ — — — — — — — — — — — — — — — — — — — —
   │
L  │ DEMONSTRATED                         SPECIFIED
   │
I  │ (LABORATORY)                         (REQUIRED)
   │
A  │ — — — — — — — — — — — — — — — — — — — —
   │
B  │ SPECIFIED                            DEMONSTRATED
   │
I  │ (REQUIRED)                           (LABORATORY)
   │
L  │ — — — — — — — — — — — — — — — — — — — —
   │
I  │ FIELD                                FIELD
   │
T  │ — — — — — — — — — — — — — — — — — — — —
   │
Y  │
   │
   └──────────────────────────────────────────
```

SYSTEM A   SYSTEM B
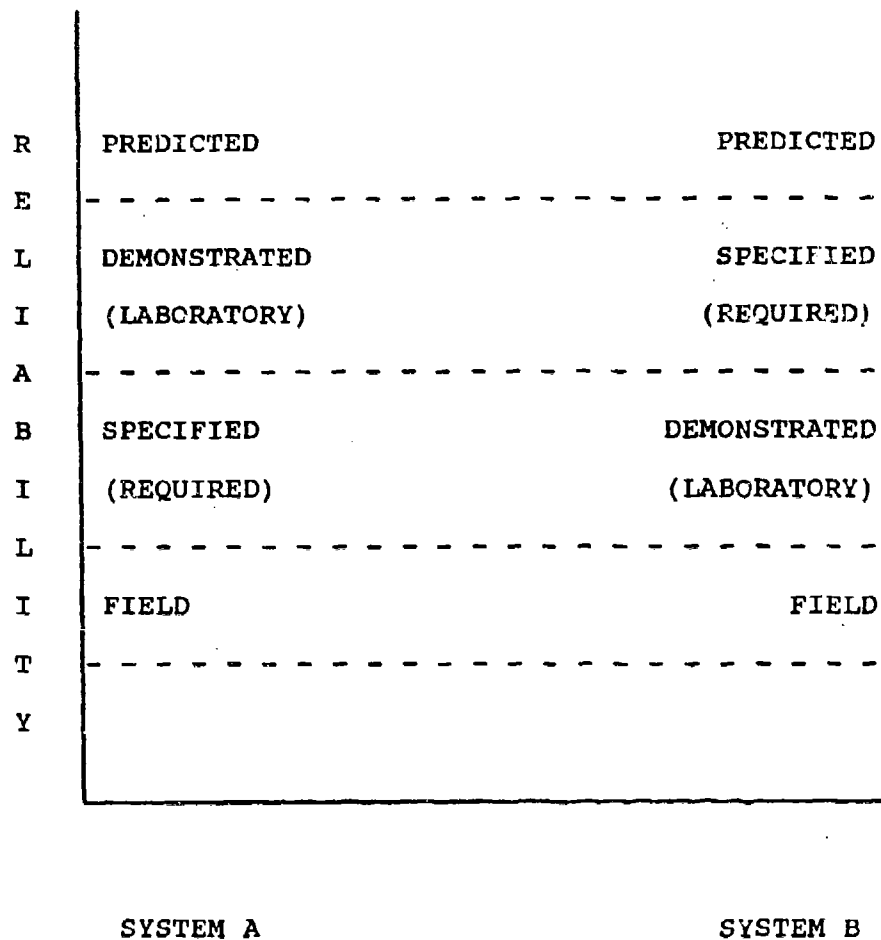
Figure 2. The Reliability Indices

The following paragraphs will address the reliability
gap of each combination. In some cases, the contributing
factors of the reliability gap for the particular
combination may be described under the same paragraph.

Predicted vs Specified vs Demonstrated vs Field MTBF.
Since some of the factors are similar, this paragraph will
also describe the factors under the combinations of
Predicted vs Field and Specified vs Demonstrated. Kern
examined 16 different pieces of avionics equipment from 10
different USAF aircraft and attributed the differences to
"definitional factors, operational factors, or environmental
factor." After removal of the definitional factors, he
concluded that:

> ...about half of the remaining differences are
> accounted for by operational factors and the
> remainders are due to the combined influence of
> environmental and other factors. [38:231]

Kern described the "definitional factors" as:

> ...inherent to the differences in the failure
> criteria and time base used by the two
> communities: the AFLC which collects and
> analyzes the data; and the engineering community
> (AFSC and Industry) which establishes requirements,
> performs predictions, and conducts reliability
> demonstration tests. The definitional differences
> are composed of two parts, one related to the time
> base used for MTBF assessment, the other to the
> failure criteria used for assessment purposes.
> [38:241]

Kern cited that the primary "operational factors" are:

> ...those related to maintenance and handling and
> equipment use. The study shows that non-
> operating failures make a significant
> contribution to the assessed field MTBF for
> avionics equipment. It is estimated that between
> 20% and 60% of the failures recorded during
> operational deployment of avionics equipment are
> actually non-operating failures. This suggests
> the need to establish several separate measures of
> MTBF, each directed at a specific objective. One
> would be used to determine the inherent reliability
> (based on operating hours), one to determine field
> operational reliability (based on flight hours),
> and another to determine logistic support
> reliability (based on calendar time, i.e., months
> or years). [38:241]

Under "environmental factors", Kern observed that:

> ...when the field MTBF data are separated by
> aircraft type (fighters vs. bombers), the
> differences in assessed field operational MTBFs
> suggest that it may not be valid to use a single
> environmental factor for aircraft without regard to
> the type of aircraft. Possibly the currently
> published environmental factors given in MIL HDBK-
> 217B should be adjusted by an appropriate modifier
> to reflect differences in aircraft type. [38:241]

Predicted vs Specified MTBF. Muglia, et al., (56)
studied the reliability gap by comparing MTBF prediction
techniques (including those in MIL-HDBK-217 A/B) and based
the analysis on 13 years of actual data analysis from
Hoffman Electronics Corporation's (HEC) reliability experience
of Tactical Air Navigation (TACAN) systems. The study
concluded that the:

> ...estimated system Mean-Time-Between-Failure
> (MTBF) can vary from 0.16 to 6.5 times that
> specified. The method for estimating MTBF is

responsible for this variance. Customer
specifications, the engineer's experience, and
management desires often dictate the MTBF
prediction techniques to be used. [56:510]

Muglia's study emphasized further that:

System prediction techniques become a relatively
ineffective guide to product reliability
measurement if management does not support the
reliability engineering concepts. More
specifically, management must allow time and funds
for testing, repair, and design correction where
necessary to eliminate thermal and electrical
design deficiencies, manufacturing deficiencies,
and testing and handling deficiencies. [56:513]

Predicted vs Demonstrated MTBF. When Lynch and Phaller

(43) examined the disparity between predicted vs test

(demonstrated) MTBF, they studied an Electronic

Countermeasures (ECM) system consisting of four major units

containing 5,527 electronic parts for seven years. Based on

their study, Lynch and Phaller concluded that certain

assumptions inherent in the MIL-HDBK-217 prediction models

were largely responsible for the difference. Specifically,

the assumptions made at the part level have a significant

impact on the reliability prediction and they found that the

largest areas of disparity between predicted MTBF and test-

observed MTBF were the assumptions made for:

(1)   the quality of design and/or constructions
      techniques used in initially designing and
      laying out the parts, and

(2)   the adherence to the established and specified
      production process control procedures in
      producing the parts. In the models presented
      in MIL-HDBK-217, it is assumed that certain

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standards are followed in these areas based on the requirements specified. The adherence to these requirements manifest themselves primarily in the MIL-HDBK-217 component quality factor which is subject to wide variation (120 to 1 for hybrids). There are also equivalent assumptions regarding system design and quality practices which can affect this disparity.... [43:121]

Demonstrated vs Field MTBF. In 1974, the "Joint Logistics Command (JLC) sponsored a Reliability Test Committee as part of its Electronics Systems Reliability Workshop" (2:30). The Committee was comprised of experienced reliability personnel from both the Department of Defense (DoD) & Industry. Their task was to better understand the underlying causes of the discrepancies between laboratory and field reliability in electronic systems. The Committee classified their findings into four general categories:

---DIFFERENCES IN FAILURE DEFINITIONS. In laboratory testing, the basic reliability measure is derived from relevant failures, those that cause loss of function in the equipment under test. In operational use, the basic measure is maintenance action, which may not be related to the loss of function in the equipment being investigated, but is induced by an external source; thus, there may be more maintenance actions than relevant failures.

---POOR DEFINITION OR SIMULATION OF THE OPERATIONAL USE ENVIRONMENT. Present laboratory testing is oriented heavily toward temperature environments, with some consideration to vibration and voltage cycling. In actuality, humidity is important to seaborne systems, random vibration to jet aircraft, and shock to army mobile units, yet these environments are

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not specified for laboratory reliability
testing. Unless these factors have been
carefully considered in design, the testing is
inadequate.

---MISINTERPRETATION OF TEST PLAN RESULTS. Many of
the present test plans in the existing standards
are designed to efficiently demonstrate a
minimum acceptable MTBF at high confidence
levels. However, the confidence with which the
specified MTBF is demonstrated is a variable
dependent on the test length and, therefore, is
a cost-of-testing consideration. Unless the
user understands the difference between these
two parameters, unforeseen results could occur.

---INADEQUATE FAULT ISOLATION TECHNIQUES. Existing
military electronic systems have grown very
complex. But the gains in technology have been
devoted to increased performance, with inadequate
emphasis being placed on design for ease of
maintenance. When failures later occur in
operational use, fault isolation becomes
extremely difficult. Consequently, the
maintenance personnel under pressure of
operational readiness are forced to resort to
cannibalization and 'shotgun' techniques. The
penalty is maintenance-induced faults and large
percentages of 'no defect found' in equipment
returned to depots. However, the added cost for
this fault isolation capability in the design is
a deterrent in the acquisition phase of a
competitive environment. [2:31]

Shelley and Stovall also studied the relationship
between the field and laboratory MTBFs. By using various
adjustment factors, they introduced the translational model
to establish a mathematical relationship between field and
demonstrated reliability. They concluded that:

(1) It is not possible to consistently predict the
field MTBF from laboratory data, and vice
versa. The individual predictions will
invariably be high or low. However, if one
counts all laboratory discrepancies (except
those due to test equipment), there is an even
chance that the field MTBF will be greater
than the laboratory MTBF.

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(2)   Prediction accuracy and correlation are greatly
        improved when the laboratory/field MTBF
        numbers are based upon several failures, i.e.,
        statistical fluctuation is a real hazard. One
        can seldom be accurate by attempting to
        project field performance from lab performance
        when the laboratory MTBF is based on a few
        (say 2 or less) failures, and conversely.

(3)   A major reason for differences between
        laboratory and field reliability is failure
        definition combined with the human element.
        In the field, there is a strong inclination to
        count discrepancies as failures unless it is
        very obvious that there was no failure. In
        the laboratory, there is a strong inclination
        to exclude a discrepancy unless it is very
        obvious that there is a failure as
        contractually defined.

(4)   The relatively good correlation of reject data
        and the very poor correlation of accept data
        provides strong evidence that the problem of
        poor correlation is more people-related than
        test requirement-related.

(5)   It was not conclusively shown that the
        translation between laboratory and field
        MTBF's can be improved by the use of
        adjustment factors, as determined in this
        study. The translation model was not
        disproved, but it is apparent that better
        information is needed in order to confidently
        utilize the model. [62:330]

In addressing the difference between field reliability
and factory reliability, whether specified, predicted, or
demonstrated values (44:177), MacDiarmid (Rome Air
Development Center) mentioned several studies. These
studies tried to clarify the issue by introducing:

> ...the notion that there is a set of factory
> reliabiity and maintainability terms called
> 'contract' terms and a set of field R&M terms
> called 'operational' terms that are defined
> differently and serve different purposes. [44:177]

In addition, MacDiarmid summarized the results of the
Boeing study on translating operational R&M parameters to
contractual ones, and vice versa:

> The Boeing results do not attempt to find a simple
> degradation factor relationship between a field
> MTBF and a contract MTBF as others have often done,
> but instead they recognize that the difference in
> contractual and operational parameters are in
> concept, measurement method, and usage and provide
> means to relate them.   [44:182]

In trying to understand the disparity between field and
factory reliability, Lynch and O'Berry (42) collected over
two years of data, observed over 500 systems deployed at 10
operational sites.   They concluded that the most significant
factor affecting field reliability is "composed of much more
than the elements of temperature, vibration, altitude, etc.,
that are simulated in a typical MIL-STD-781 test" (42:242).
They found that the environment beyond those identified in
MIL-STD-781 to be maintenance- and logistics support-related
and it includes:

> ...maintenance personnel, shop management, program
> management, support equipment, prime system and
> support equipment spares, planning and operations,
> and the complex interaction among them....
> [43:242]

From their field experience, they also found that
"...only 20% of the field problems encountered were hardware
reliability problems" (42:242).

Balaban (4) identified the limitations associated with field data collection systems and contributed the difference between field and test (demonstrated) reliability to three classes:

> ---Analysis and Test Weaknesses. During the development and production phases, reliability engineers must deal with many ambiguities and make many assumptions that will subsequently represent weaknesses in their efforts. For analysis effort, these include modeling an evolving design or a set of design options; developing assumptions related to equipment interfaces, environments, built-in test (BIT) capabilities; using historical data derived from incompatible hardware, software, support, or environmental elements; and estimating the nature and capability of the equipment's support environment. Even though system predictions are based on the best data available, the analyst works under numerous limitations that affect the quality of the resulting estimate. For test efforts, the results must be tempered by the effects of in-process and subsequent design changes; the use of nonrepresentative hardware; and test environments that are nonrepresentative or lack BIT or interface software, test equipment, manuals, or appropriately qualified operators or support personnel. There is always a trade-off between test length, test timing, and test realism. These compromises limit the quality of the resulting estimate.

> ---Improper Assumptions. Independent of the problems that beset the analysis and test efforts.... This can include changes in the physical operating environment (e.g., the avionics bay is or is not vibration-free), in usage assumptions (e.g., the mission length is changed), and in support concepts (e.g., the type or amount of test equipment to be used).

> ---Variability of Results. Similar hardware, operated under supposed similar conditions, can exhibit widely varying reliability characteristics. This variability underscores the difficulty of developing point estimates of reliability characteristics during development and test activities. [4:123]

Summary on Reliability Gap Discussion. The existence of
the reliability gap can be attributed to a host of factors.
A summary of the major contributing factors, along with
their references, is presented in Table 2.

Table 2. The Reliability Gap: Literature Review Summary

Major Contributing Factors	References
Definitional	2, 29, 38, 44, 62
Operational, Usage	2, 4, 38, 44
Environmental	2, 29, 38, 42
Prediction Techniques ---including those in 217	56, 62
Prediction Assumptions ---specifically those in 217	4, 43, 62
Misinterpretation of Test Plan Results	2
Inadequate Fault Isolation Techniques	2
Analysis & Test Weaknesses	4
Improper Assumptions	4
Variability of Results	4
Reliability Measurement Methods	44
Management Support	56
Statistical Variability	62
Human Performance	62

Traditional Ways of Assessing Reliability

The development of highly complex weapon systems involves considerable amount of risks. The ultimate risk is in the development of highly complex, state-of-the-art weapon systems that do not meet the operational requirements. In order to minimize the risks, various techniques were used to track the reliability value throughout the development process. These techniques also help decision makers to pinpoint specific problem areas early in the development phase, make better decisions in terms of trade-offs, and consequently make the overall development process more cost effective.

This section of the literature review is divided into three portions: Reliability Prediction, Reliability Testing, and Reliability Growth. The basic concepts of each, along with its objectives, are presented in the following paragraphs.

Reliability Prediction. This portion addresses the underlying objective of reliability prediction, reliability models (definition, limitations, and applications), and the standard references for reliability prediction and the limitations of MIL-HDBK-217.

Reliability Prediction Objectives. The underlying objectives of reliability prediction are to maximize operational readiness and optimize life cycle costs (40:245).

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In addition, making a reliability prediction is also used to gain advance knowledge of the reliability of a new system or product. The advance knowledge of reliability "could allow accurate forecasts to be made of support costs, spares requirements, warranty costs, marketability, etc." (58:122). From an engineering point of view, reliability prediction is invaluable as part of the design processes for comparing options and to identify critical reliability design features (58:122).

Reliability Models. Various reliability models have been used in an attempt to predict the reliability of systems and subsystems with more accuracy.

Definition. In order for reliability to be accepted as a science, it has to satisfy two conditions:

1. ...the general structure of its formulae must be consistent with the general structure of the other formulae of science itself, and

2. ...they must be so interpreted to yield results that can be confirmed by observations. [33:110]

Thus mathematics, with its formulae serving as laws or models, has been used as the language of reliability (33:110).

A reliability model is:

A mathematical relation, that on the basis of deductive or inductive reasoning can be expected to exist between some measure of a failure process, and one (usually time) or more explanatory factors. [33:111]

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<u>Limitations</u>. Since reliability is defined in

terms of probabilities, further limitations are involved

with data interpretation and sampling variation. As

described by Harris and O'Connor:

> ...in dealing with probabilistic quantities we no
> longer consider their true value as being precisely
> predicted, but rather as being distributed around
> some expected value, and it is this expected value
> that we attempt to predict, and hopefully to gain
> some insight into its distribution... [33:111]

Another limitation is the assumption of the use of

independent and identically distributed (IID) random

variables. O'Connor addressed the reasons why the

assumption of IID exponential in a repairable system can be

very misleading. O'Connor cited a total of 14 reasons; some

of the reasons are as follow:

1. The most important failure modes of systems are
    usually caused by parts which have failure
    probabilities which increase with time (wearout
    failures).

2. Failure and repair of one part may cause damage
    to other parts. Therefore, times between
    successive failures ARE NOT NECESSARILY
    INDEPENDENT.

3. Repairs often do not 'renew' the system.
    Repairs are often imperfect or they introduce
    other defects leading to failures of other
    parts.

4. Repair personnel learn by experience, so
    diagnostic ability (i.e., the probability that
    the repair action is correct) improves with
    time. Generally, changes of personnel can lead
    to reduced diagnostic ability and therefore
    more reported failures.

5. Reported failures are nearly always subject to human bias and emotion. What an operator or maintainer will tolerate in one situation might be reported as a failure in another, and perception of failure is conditioned by past experience, whether repair is covered by warranty, etc.

6. System failures might be caused by parts which individually operate within specification (i.e., do not fail) but whose combined tolerances cause the system to fail.

7. Many reported failures are not caused by part failures at all, but by events such as intermittent connections, improper use, maintainers using opportunities to replace 'suspect' parts, etc. [58:89-91]

An overriding criticism about the concept of reliability modeling is the one involving human performance.

> Even if sufficient failure data were available to overcome the deficiencies of statistical reliability models (an impossible situation in the practical reliability engineering context) the human element can still invalidate the predictions made. [58:126]

Dhillon (24) mentioned that H. L. Williams was the first person to recognize the importance of human-element reliability in system-reliability predictions (1958). Dhillon also cited the study of A. Shapero and pointed out that "human error is the cause for a large proportion (i.e., from 20 to 50%) of all equipment failures" (24:2).

Application. Recognizing all the limitations associated with reliability prediction models, it is still possible and useful to make reliability predictions for systems under the following circumstances:

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1. The system is similar to systems developed, built, and used previously, so that we can apply our experience of what happened before.

2. The new system does not involve significant technological risk (this follows from 1).

3. The system will be manufactured in large quantities, or is very complex (i.e., contains many parts), or will be used over a long time, or a combination of these conditions applies, i.e., there is an asymptotic property.

4. There is a strong commitment to the achievement of the reliability predicted, as an overriding priority. [58:127]

For example, credible reliability predictions can be made for a new TV receiver or cassette player. However, for new, highly sophisticated, state-of-the-art equipment, the reliability predictions are not as credible (58:127).

Reliability Prediction Standards References and the Limitations of MIL-HDBK-217. Reliability prediction is not a simple task and it is almost an impossible task for new, highly sophisticated, state-of-the-art equipment. MIL-STD-756, Reliability Prediction, is the most commonly used standard reference for reliability prediction. The prediction plan is identified as part of the reliability program plan. In order to compare options and validate the concept, MIL-STD-756 requires that an initial reliability prediction be performed as early as possible as part of the feasibility study.

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MIL-STD-217, Reliability Prediction for Electronic

System, is the standard reference for electronic equipment

parts count and stress analysis (58:150). The literature

search indicated that the predictions used in MIL-STD-217

have not been credible. The limitation of MIL-STD-217 is

that it assumes independent, identically exponentially

distributed times to failures for all components. However,

O'Connor measured five reasons why MIL-STD-217 is acceptable

in most work, because:

1. A constant failure rate (CFR) assumption makes system reliability prediction relatively easy, since an additive (parts count) method can be used.

2. For most maintained equipment, as repairs are carried out and as modules and components are exchanged, after a period the system might consist of parts with different ages. Also, maintenance induces failures, which tend to have a constant rate of occurrence. Therefore, there might be an overall tendency to a CFR.

3. It is much easier to calculate an assumed CFR from data on systems than to derive the parameters of a two-parameter (e.g., Weibull) distribution. Also, the data are seldom numerous enough to allow derivation with adequate statistical or engineering confidence.

4. For logistics planning purposes, e.g., avionics spares planning for a fleet of aircraft, the CFR model is adequate both for prediction and for monitoring of performance. MTBF is the function usually used in such cases.

5. Predicted reliability is subject to such wide margins of error that the IID/CFR assumptions do not make much difference. [58:189]

Reliability prediction for new, highly sophisticated,

state-of-the-art systems must be based on the

"identification of objectives and assessment of risks, in that order" (58:127). Throughout the development process, objectives must be determined to see whether they are realistic. Appropriate models and data are used to quantify the objectives and assess the risks. The reduction of risks can be accomplished through analysis and tests (58:128). Testing is crucial to the development of complex systems because it provides decision makers with the feedback information to make intelligent trade-offs.

Reliability Testing. This portion addresses the objectives of reliability testing. Two types of reliability testing, reliability demonstration and reliability development testing, will be discussed in detail.

Reliability Testing Objectives. The objectives of reliability testing is to reduce the risks of development of highly complex systems and to identify the reliability characteristics as early as possible during the development program because "the effect of failures on schedule and cost increases progressively, the later they occur in the development program" (58:261). Reliability testing is critical in the development of complex, highly sophisticated systems where the risks are high. Testing is essential because designs are seldom perfect and "designers cannot usually be aware of, or be able to analyze, all the likely causes of failure of their designs in service" (58:260).

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Demonstration Testing. It is also known as

Reliability Qualification Test (RQT), or Design Approval

test (55). It is defined as:

> A test conducted under specified conditions, by,
> or on behalf of, the government, using items
> representative of the approved production
> configuration, to determine compliance with
> specified reliability requirements as a basis for
> production approval. (Also known as a
> 'Reliability Demonstration,' or 'Design Approval'
> test.) [55:130]

MIL-STD-781 is the standard method used for formal

reliability demonstration testing. MIL-STD-781 test plans

are based on the assumption of a constant failure rate.

The practical problems associated with MIL-STD-781 testing

are as follows:

1. RELIABILITY IS NOT AN INHERENT PHYSICAL
   PROPERTY OF A SYSTEM, AS IS MASS OR ELECTRIC
   CURRENT. The mass or power consumption of a
   system is measurable (also within statistical
   bounds, if necessary). Anyone could repeat
   the measurement with any copy of the system
   and would expect to measure the same values.
   However, if we measure the MTBF of a system in
   one test, IT IS UNLIKELY that another test
   will demonstrate the same MTBF, quite apart
   from considerations of purely statistical
   variability. In fact, there is no logical or
   physical reason to expect repeatability of
   such experiments.... Of course, if a large
   number... were tested we would be able to
   extrapolate the results with rather greater
   credibility and to monitor trends....
   However, MIL-STD-781 testing cannot be
   extended to such large quantities because of
   the costs involved.

2. MIL-STD-781 testing is often criticized on the
   grounds that in-service experience of MTBF is
   very different to the demonstrated figure. In

addition, in-service conditions are almost
always very different of the environments of
MIL-STD-781 testing, despite any attempts to
simulate realistic conditions.

3. MIL-STD-781 testing is not consistent with the
    reliability test philosophy..., since the
    objective is to count failures and to hope
    that few occur. An effective reliabiity test
    programme should aim at generating failures,
    SINCE THEY PROVIDE INFORMATION ON HOW TO
    IMPROVE THE PRODUCT. Also, a reliability test
    should not be terminated solely because more
    than a predetermined number of failures occur.
    MIL-STD-781 testing is very expensive, and the
    benefit to the product in terms of improved
    reliability is sometimes questionable.
    [58:282-283]

Development Testing. It is also known as

Reliability Development Growth Test (RDGT). It is defined

as:

A series of tests conducted to disclose
deficiencies and to verify that corrective actions
will prevent recurrence in the operational
inventory. (Also known as, Test-Analyze-And-Fix,
'TAAF' testing). [55:130]

MIL-STD-781D (53) describes how development reliability

tests should be managed and integrated with other

development tests.

The standard was developed to place more emphasis
on testing to detect weaknesses in the product,
rather than on formal reliability demonstration
methods in which the test objective is (from the
supplier's point of view) to have as few failures
as possible. [58:273-274]

The development of highly complex, state-of-the-art

systems involves a lot of uncertainties and risks. In order

to minimize the risks, development testing programs are

incorporated to ensure that system reliability and
performance requirements are met. Over the years, it has
been recognized that "a comprehensive approach to
reliability growth management throughout the development
program" (51:4), is necessary to minimize the high risks
associated with the development of highly complex systems.

Reliability Growth (Improvement). This portion of the
literature review addresses the basic concepts of
reliability growth, reliability growth management
(definition and the managers' role), and reliability growth
analysis (purpose, development, selection for the "optimum"
growth model, and application).

Basic Concepts. MIL-HDBK-189 defines reliability
growth as "the positive improvement in a reliability
parameter over a period of time due to changes in product
design or the manufacturing process" (51:3). In their
article, Morris and MacDiarmid referenced P. H. Mead's study
on reliability growth of electronic equipment, which stated
that there are three distinct ways in which reliability can
grow:

> Growth Mode 1. By operating each equipment (or
> portion of it) to expose and eliminate rogue
> components or manufacturing errors.

> Growth Mode 2. By familiarization, increased
> operator skill and general "settling down" in
> manufacturing, use and servicing.

Growth Mode 3. By discovering and correcting
errors or weaknesses in design, manufacturing
or related procedures. [55:130]

Morris and MacDiarmid explained further that:

Reliability or electronic equipment can improve
both at the collective and individual equipment
level. Burn-in improves the reliability of the
equipment subjected to it while design changes
improves (or degrades) the reliability of all
equipment subject to the changes. Each of the
three growth or evolution modes can be made more
effective by planned activities. [55:130]

Reliability growth occurs in complex systems; however,

the misconceptions concerning reliability growth cannot be

overlooked. Clarke (14) cited cases where "reliability

demonstration test data have been improperly used to portray

reliability growth" (14:407). According to Clarke:

...to effect a growth in inherent reliability,
one or more of the basic design or process
(manufacturing methods or quality) parameters must
be improved. It is generally recognized that a
realistic reliability prediction, based upon these
parameters is a good approximation of the inherent
reliability for a particular design and the
practical upper limit for reliability growth.
[14:407]

Growth Management. MIL-HDBK-189 defines it as:

The systematic planning for reliability achievement
as a function of time and other resources, and
controlling the ongoing rate of achievement by
reallocation of resources based on comparisons
between planned and assessed reliability values.
[51:3]

It is emphasized in MIL-HDBK-189 that the various

techniques identified in reliability growth management "do

not, in themselves, manage. They simply make reliability a

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more visible and manageable characteristic." To ensure

goals are achieved, top management decisions are required

to:

> ---Revise the program
> ---Increase testing
> ---Fund additional development effort
> ---Add or reallocate program resources
> ---Stop the program until interim reliability goals
>   have been demonstrated   [51:5]

Growth Analysis. Why is there a need to do

reliability growth analysis? Under the test-analyze-fix

process, the system configuration is constantly changing.

Test data on the system for a fixed configuration are

limited. Consequently:

> ...direct estimates of system reliability for a
> fixed configuration would generally not enjoy a
> high degree of confidence and may, therefore, have
> little practical value. [18]

Faced with the difficulties of directly estimating

system reliability, reliability growth models are usually

used. Reliability growth models are defined as mathematical

formulae, usually as a function of time, used to represent

the system reliability during the development phase. The

objectives of most reliability growth models are:

> (1)   Inference on the present system reliability,
>
> (2)   Projection on the system reliability at some
>   future development time. [18]

Development of Growth Models. During the

early development phases, new products are often found to be

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less reliable than later in the field, when failures are discovered and improvements have been made and incorporated as a result of failures observed and corrected. This phenomenon of displaying reliability improvement (growth) of products in service was first analyzed by J. T. Duane (25). In 1962, he presented a report on the empirical relationship of the MTBF improvement he observed on a number of items used on aircraft. Duane observed that the cumulative MTBF (total time divided by total failures) plotted against total time on log-log paper gave a straight line. The slope of the line gives an indication of the rate of MTBF growth. The steeper the slope, the faster the improvement, and the sooner the products will become more reliable. Duane observed that the typical range for the growth rate was between 0.2 and 0.4, and that the value was correlated with the intensity of the reliability improvement effort (58:285-286).

In addition to reliability growth models for hardware, some researchers have also explored the reliability growth models for software. In his study on reliability growth models, Balaban mentioned that a number of software reliability models have been developed over the years.

The study of software reliability growth models is beyond the scope of this research. Unless otherwise specified, the discussion on reliability growth model in this study is limited to hardware only.

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The Optimum Growth Model. Numerous studies have been conducted to search for the "ideal" model. Over the years, Rome Air Development Center has conducted and/or sponsored several studies on the issue. The selection of the optimum reliability growth model is beyond the scope of this research. This study will, however, include the findings of three of the studies. These three studies were chosen because of the extensive amount of research effort that was involved.

In 1975, Schafer (Hughes Aircraft Company) examined six models and fitted 270 data sets (186 ground equipment and 84 airborne equipment) to those models. The findings were:

1. The results indicate that although the Duane model seldom was the best fitting model it almost always fit the data.

2. The IBM model fit airborne data the best....

3. Each of the remaining models was found to be the best fit to the data for specific combinations of environment, equipment type, and aggressiveness of reliability program. [61]

In 1983, McGlone (Pratt & Whitney) conducted a 22-month program to study and analyze the reliability-growth phenomena obtained of electronic and hydromechanical gas turbine control equipment" (49:53). Five mathematical models were evaluated and the conclusions were:

1. ...the Army Materiel Systems Analysis Activity (AMSAA)/Duane model is the best model; however, the Endless-Burn-In model and Time-Series Analysis were also considered acceptable;

2.   ...that AMSAA model parameters should be
      estimated via the method of maximum
      -likelihood; and

3.   ...that data should be tracked continuously on
      an individual and fleet basis.   [49]

In 1986, Gates (The Analytic Sciences Corporation),

analyzed reliability growth data on nine different avionic

systems and 30 equipment items (line replaceable units).

They investigated several reliability growth models and

selected three for the analysis of the data. The findings

were:

1.   Both the Duane and AMSAA models were found to
      yield reasonably good fits to the data sets.
      However, both were found to have limited
      utility as predictive tools because of the
      empirical nature of the model parameters.

2.   The IBM model was found to provide a more
      workable methodology for growth prediction
      because its parameters lend themselves more
      easily to an engineering interpretation.
      [30:ES-1, ES-2]

Reliability models are useful for evaluating or

predicting the reliability potential of a product. In

addition, the "quantification provided by such models is

most valuable for proper management of a reliability

program" (3:11). The application of the growth models will

be addressed in the next paragraph.

Application of Growth Models. Some of the

reliability growth models are:

---predicting whether stated reliability objectives
   will be achieved;

---correlating reliability changes with reliability
　　　　　activities;
　　　　---planning for reliability demonstration tests;
　　　　---planning for a reliability improvement warranty;
　　　　---planning related to maintenance manpower
　　　　　utilization and logistics activities;
　　　　---performing life cycle cost analyses.　[3:11]

Summary of Traditional Ways of Assessing Reliability.

Reliability prediction is used to gain advance knowledge of

the reliability of the new systems/products.　With the

advance knowledge of reliability, forecasts on operational

readiness, support costs, spares requirements, and warranty

costs can be made.　Reliability prediction of highly complex

systems is based on the identification of risks and

assessment of risks.　Testing is crucial to the development

of complex systems in order to reduce the risks and to

identify the problems early.

　　　Reliability development testing (also known as

reliability growth testing) is used to disclose deficiencies

and to verify the effectiveness of corrective actions.

There are numerous reliability growth models developed over

the years.　Which is the "best" one to use?　The next

portion of the literature review will explore some practical

questions concerning reliability growth.

Practical Questions and Answers Associated with The Reliability Gap

The objective of this portion of the literature review was to relate the reliability growth concepts to the theme of this study--the reliability gap. The following questions and answers are based on concepts associated with reliability growth planning. These concepts are from a series of articles written by Dr. Larry Crow and "have proven useful in the planning and evaluation of TAAF program" (19:115).

1. Why is the initial reliability generally lower than the requirement and what can be done to improve it?

2. Are the requirements realistic?

3. Given that the requirements are realistic, how long will it take the initial MTBF to grow to the required MTBF?
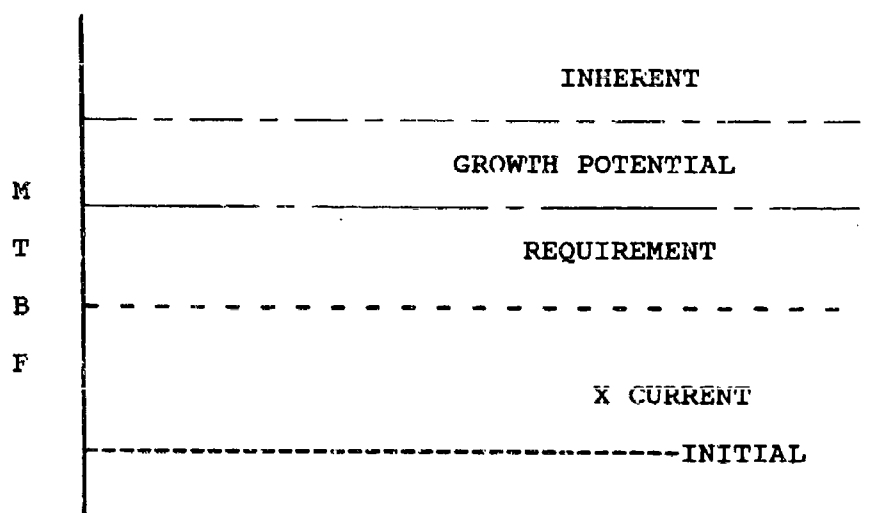
Figure 3. Comparison of Reliability Values (22:387)

Initial Reliability. According to Dr. Crow, former

Chief of the Reliability Methodology Office in the

Reliability Division of the US Army Materiel Systems

Analysis Activity (AMSAA), the building blocks for a new

system design consist of four basic groups:

1. Existing technology used in the same
   environment,

2. Existing technology used in a different
   environment,

3. Existing subsystems in a new configuration, and

4. New research and development. [19:115]

The initial reliability is defined as "the starting

point for system-level reliability growth during development

testing" (19:115). To estimate the initial reliability:

> ...we should consider all available information.
> This may include utilizing previous system,
> subsystem and component test data, historical
> experience, engineering expertise and the
> prediction of the inherent reliability. [19:116]

The inherent reliability is defined as "the reliability

that is determined to be technically achievable for a basic

system design within program time and cost constraints"

(19:115). For new and complex designs, the initial

reliability at the beginning of development testing is

generally lower than the inherent reliability for numerous

reasons, some of which may include:

> ...the customer use environment which is difficult
> to design for, interaction of parts, inaccurate or
> incomplete data bases for predictions and
> laboratory test environments different from the
> use environment. [19:115]

The growth potential is defined as "the maximum
reliability that can be attained with the system design and
reliability growth management strategy" (22:385). The
elements of the management strategy that determine the
growth potential are the classification of Type A and Type B
failure modes and the effectiveness of the fixes for Type B
failure modes (22:383-384).

Type A failure modes are associated with failures with
no corrective actions. The management strategy determined
that it is not cost effective to increase the reliability by
a design change. Type B failure modes are those that,
if seen (usually during reliability testing), a design
change will be attempted. The growth potential of a system
will be attained:

> ...when all Type B failure modes have been found
> and a fix incorporated into the system. For the
> system design and management strategy, this is the
> limiting reliability. The growth potential
> reliability may never actually be achieved in
> practice. [22:385]

Dr. Crow further emphasized the importance of
recognizing that:

> ...the growth potential does not estimate the
> current reliability, but rather, it estimates the
> maximum reliability that will be achieved when all
> Type B failures modes have been found and fixed by
> a corrective action. [22:386]

In the area of reliability growth analysis, Army
experience has indicated that:

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...successful programs usually begin with an
initial MTBF of at least 1/3 or 1/4 of the desired
MTBF ([Initial Operational Capability] IOC
requirement), frequently utilize a fix strategy of
about 95 percent toward failure modes (B mode
fixes) and generally achieve about a 70 percent
fix effectiveness factor. [6:211]

Requirement. In assessing requirement, it is important

to determine:

...whether or not the requirement is below the
growth potential MTBF. If the requirement is not
below the growth potential, then the requirement
cannot be attained with the current system design
and management strategy. [22:385]

Requirements are developed "on the basis of user

experience, projected threat, and system technological

capabilities" (6:210). Not only do requirements need to be

realistic, they "must also be affordable, testable, and

achievable" (6:210).

Growth Rate. Given that the requirements are realistic,

affordable, testable, and achievable, the length of time

needed to grow from the initial MTBF to the required MTBF

depends on the growth rate of the system/equipment. The

growth rate gives an indication of how fast the system

reliability is improving. The growth rate will depend on

"when problems are detected, fixes incorporated into the

system, and how effective the fixes are" (19:117). Morris

and MacDiarmid summarized the growth rate discussion as

follows:

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> The growth rate...is governed by the amount of
> control, rigor, and efficiency by which failures are
> discovered, analyzed, and corrected through design
> and quality actions. A large value of alpha (>0.5)
> reflects a hard-hitting, aggressive reliability
> program with management support spanning all
> functions of a knowledgeable organization, while a
> low value of alpha (<.1) reflects the growth in
> reliability that is due largely to the need to
> resolve obvious problems that impact production,
> and to implement corrective action resulting from
> user experience and complaints. [45:77-78]

They concluded further that a low growth rate does not
necessarily mean a bad design. In fact, "with excellent
design and manufacture, the growth rate could approach
zero" (45:78). In many growth programs, the growth rates
were cited to range from 0.35 to 0.5 (45:78).

Gates identified the following relationships on growth
rates:

> ---alpha = 0.5, for a TAF-type test designed to
>   stimulate equipment failures
>
> ---alpha = 0.35, for a test designed to simulate
>   the mission environment
>
> ---alpha = 0.2, for a benign operational test.
>   [30:7-4]

Summary

The literature review started with the definition of
reliability. The development of reliability engineering
and understanding the problems of unreliability were used to
set the stage for the discussion of the research problem--
the reliability gap. With the reliability gap identified
(Table 2), traditional ways of assessing reliability were

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examined. Specifically, the basic concepts, objectives, and limitations of reliability prediction, reliability testing, and reliability growth were explored. In addition, some practical questions and answers pertaining to the concepts of reliability growth were used to relate to the theme of this study--the reliability gap. The next chapter will address the methodologies of how this study will be accomplished.

III. Methodology

Introduction

This chapter describes the methodology used to
accomplish the research objectives--to examine the existence
of the reliability gap, identify the most significant
contributors, and explore ways on how to minimize the
reliability gap. Data requirement, collection, and analysis
for the three phases of this study will be presented. This
chapter concludes with a summary of the methodology.

Data Requirement

This portion of the study is to identify the data that
will be required to accomplish the research objectives. The
data required for each phase of the research are presented
in the following paragraphs.

Phase I. The data required to examine the existence of
the reliability gap in tactical airborne radars will be the
factory (whether specified, predicted, or demonstrated) and
field MTBFs.

Phase II. The data required to identify and analyze the
major contributors to the reliability gap will be experts'/
practitioners' opinions. In addition, the data obtained

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during the first round of interviews will be validated by all the respondents during the second round of interviews.

Phase III. The data required to explore ways on how to manage the reliability gap will be experts'/practitioners' opinions from the interviews, various studies conducted by the experts/practitioners (DoD & Industry), and appropriate historical studies.

Data Collection

This portion of the study is to describe the methodologies used to collect the data that were identified in data requirement. The data collection techniques for each phase of the research are described below.

Phase I. To examine the existence of the reliability gap on airborne tactical radars, the researcher will collect data from the program offices. Air Force aircraft as well as Navy aircraft will be examined.

Phase II. To identify the major contributors to the reliability gap, the researcher will conduct two rounds of interviews. The first round of interviews will be used to identify the experts'/practitioners' initial opinions. The second round of interviews will be conducted to validate the results obtained from the first round. In order to clarify what data will be collected and how, the following paragraphs will describe the interview process.

Specifically, the development, administration, discussion, and validation of the interview process.

Interview Questionnaire Development. The researcher will review the literature to develop the interview questionnaire. The questionnaire will then be refined by the help of two different program office reliability and maintainability (R&M) engineers and four separate Air Force Institute of Technology (AFIT) faculty members.

The questionnaire will consist of a total of 10 questions. In order to facilitate the free flow of information, most of the questions will be designed to be open-ended. The questionnaire will be used as a guide during the interviews and a sample of the questionnaire can be found in Appendix B.

Interview Administration. It is the intent of the researcher to interview as many reliability experts/ practitioners as time permits. In addition, the researcher intends to interview as wide a spectrum of reliability experts/practitioners as possible. The researcher will use the questionnaire to guide the course of the interviews. A tape recorder will be used during the personal interviews.

The researcher will first administer the interviews to a selective group of attendees at the First Annual Reliability Growth Conference (March 1988). The selection will be based

on the availability and willingness of the attendees to be
interviewed. The rest of the interviews will be conducted
with the following groups of individuals:

1. System program office representatives

2. AFIT professors/instructors.

3. Experts/Practitioners researcher knew from
    previous assignments.

4. References from interviewees.

Interviews Discussion. The researcher selected the
interview method in order to better understand the existence
of the reliability gap problem identified in Phase I of
this study. Furthermore, interviews will allow the
researcher to explore the specific research problem in
greater detail, to probe for additional information with
follow-on questions, and to clarify any ambiguity.

In this study, it is the intent of the researcher to
conduct as many personal interviews as possible. Due to the
geographic separation, the personal interviews will be
supplemented by telephone interviews. There are both
advantages and disadvantages involving both personal and
telephone interviews.

Personal Interviews. Emory (26) defined
personal interviewing as "a two-way conversation initiated
by an interviewer to obtain information from a respondent"
(26:160). In order to be successful, three conditions must

be met. First, the respondents must have access to all relevant information. Second, the respondents must understand their roles. Finally, the respondents must be motivated to cooperate (26:161).

In this study, the requirements identified by Emory will be met at the beginning of each interview session. The researcher will first explain the purpose of the study and why the respondents' participation is so important. The researcher will then explain to the respondents how they can change their answers during the second round of interviews. In addition, the researcher will explain to the respondents that the use of the tape recorder is to capture the enormous flow of information during the interview. The recorder is not used to quote respondents out of context.

Telephone Interviews. Emory identified that the telephone interview possesses some of the same characteristics as the personal interview. The main advantage of telephone interviews is their low cost. Another advantage is that "interviewer bias is reduced by using telephones" (26:170).

Interview Validation. In this study, the results from the first round of interviews will be validated by a second round of interviews. The purpose of the second round is to validate the results obtained from the first round and to give the respondents a chance to provide additional

comment(s) to the summarized results from the first round. The following paragraphs will describe how the validation process of the interviews will be conducted in this study.

The researcher will conduct the interviews and summarize the results from the first round. The summarized results, along with the respondents' initial answers, will be sent back to the participants for additional comment(s). Data will be gathered during both rounds.

Round One. The researcher will first define the reliability gap and ask the interviewees to identify the major contributors to the gap. After the respondents have named the major contributors, the researcher will ask them to rank order the contributors they have identified.

Round Two. During the second round of interviews, the respondents will be asked to validate their initial responses and to provide additional comment(s) to the summarized results from the other respondents.

Phase III. To explore ways on how to minimize the reliability gap, the researcher will collect the experts'/ practitioners' opinions from the same questionnaire used during Phase II of this study. The additional data sources will be various studies conducted by the experts/ practitioners and appropriate historical findings.

Data Analysis

This portion of the study describes how the collected data will be analyzed. The data analysis for each phase of this study will be presented in the following paragraphs.

Phase I. To determine the existence of the reliability gap in airborne tactical radars, the researcher will examine the radars on Air Force as well as Navy aircraft.

Phase II. To identify and analyze the major contributors to the reliability gap, the researcher will use personal and telephone interviews to collect the initial responses. In addition, the researcher will conduct a second round of interviews to validate the results obtained from the first round.

In order to present a detailed description of how the researcher intends to analyze the results using two rounds of interviews, the following paragraphs will describe in detail the objectives and the specific methodologies used for recording, reducing, ranking, and reorganizing the collected data.

Recording the Data. The objective is to record the number of times a particular contributor will be identified by the interviewees. During the interviews, the respondents will be asked to identify the major contributors to the reliability gap. The total number of times a

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particular contributor is mentioned by the respondents will be recorded.

Reducing the Data. The objective is to examine the most significant contributors. From the interviews, the total number of major contributors will be identified. Using the number of responses as the determining factor, the major contributors will be divided into significant and insignificant contributors. Significant contributors will be defined as contributors with a significant number (visually determined) of responses. The number of responses will be classified as significant if they are closely grouped together toward the high end of the scale. If there is an obvious break in the number of responses, the rest of the contributors will be classified as insignificant.

Ranking the Data. The objective is to present the rank order averages of the most significant contributors. During the interviews, the respondents will be asked to rank order the major contributors. From the responses, the researcher will assign a "10" to the number one contributor, a "9" to the number two contributor, etc. Consequently, for any particular contributor, a group of numbers will be assigned. To analyze the relative importance of the major contributors, the averages of the rank order of the contributors will be calculated.

Reorganizing the Data. The objective is to group the data into different categories in order to enhance data analysis. Basically, all the interviewees can be categorized into four different organizations: Air Force, Army, Navy, and Industry. Using the same rank-order procedure described above, the researcher will classify the responses into subcategories (All vs DoD vs Industry) and compare the results.

Phase III. In order to explore ways on how to minimize the reliability gap, the researcher will use the data that will be collected during the interviews. In addition, the researcher will also analyze various studies conducted by the interviewees and appropriate historical studies.

Summary

Various techniques will be used in this study to investigate the research problem--the reliability gap. Table 3 provides a summary of the methodology which will be used in this research. The next chapter presents the findings obtained in this research.

Table 3. Methodology Summary

Phase	Objective	Data Requirement Data Collection Data Analysis
I	To examine the existence of the reliability gap	-Tactical airborne radars on Air Force and Navy aircraft
II	To identify the major contributors to the reliability gap	-Experts'/Practitioners' opinions -Interviews conducted Interviews validated ---Personal ---Telephone -Major contributors analyzed ---Most significant contributors identified and rank ordered
III	To explore ways on how to minimize the reliability gap -Practical guidelines on reliability growth	-Reliability management data -Experts' opinions, various program offices' data, current studies conducted by the interviewees, and appropriate historical studies -Analyze the collected data

IV. Findings

Introduction

This chapter presents the findings used to answer the
research questions--the existence of the reliability gap
in airborne tactical radars, the relative importance of the
major contributors, and practical approaches on how to
minimize the gap. The findings for the three phases of
this study will be presented. This chapter concludes with a
summary of the findings.

Phase I Findings

Both Air Force and Navy aircraft were examined. The
data obtained from NAVAIR is used in this study to present
the existence of the reliability gap in tactical airborne
radars. Figure 4 is a courtesy slide obtained from NAVAIR.
It is interesting to note that when the field MTBF was
better than the specified MTBF, the gap seemed to be very
small. But when the field MTBF was less than the specified
MTBF, the gap seemed to be significantly large. With the
existence of the reliability gap, it becomes obvious to ask
the next set of questions. What causes the gap? What are
the major contributors? What can be done to minimize the
gap and hence maximize operational readiness and optimize
life cycle costs?

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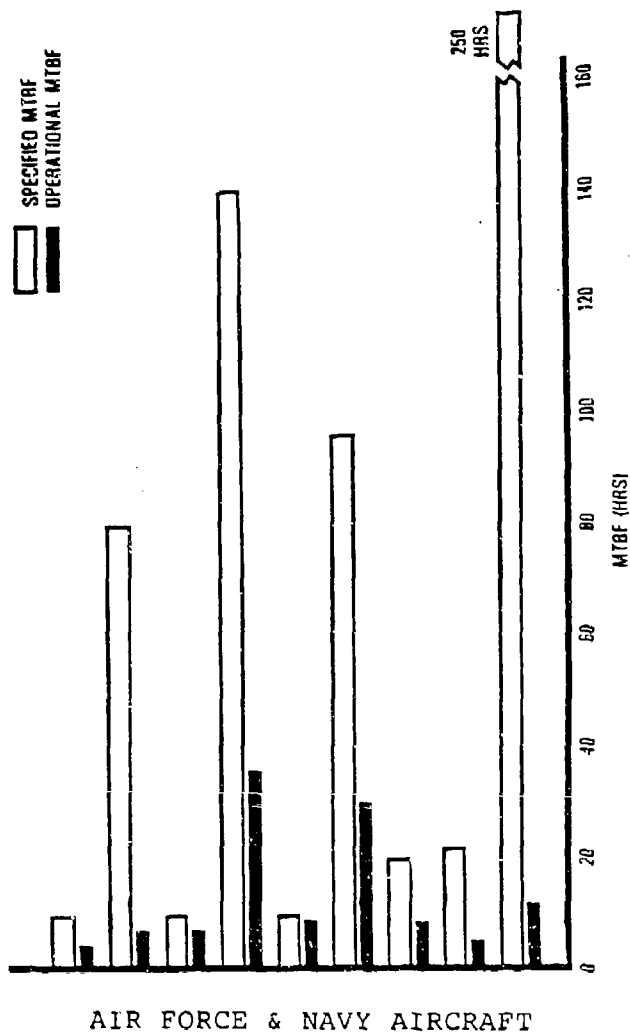
Figure 4. Historical Gap--Tactical Airborne Radars

Phase II Findings

Personal and telephone interviews were conducted. In addition, a second round of interviews was performed to validate the findings from the first round. Experts'/ Practitioners' opinions on the major contributors to the reliability gap were then consolidated.

Both personal and telephone interviews were conducted. In this study, personal interviews constituted 75% of all the interviews. The length of the personal interviews ranged from 30 to 180 minutes, depending on how the individual interviewee responded to the open-ended questions. Most of the personal interviews lasted for 90 minutes. The length of the telephone interviews ranged from 10 to 45 minutes. In this study, most of the telephone interviews were accompanied by mail responses.

A total of 40 experts/practitioners were interviewed. Thirteen were participants (mostly Industry) the researcher met during the First Reliability Growth Conference held in Boston, March 1988. Seven were participants from various program offices and another seven were instructors from AFIT. Nine were participants recommended by the other respondents and the remaining four were experts/ practitioners the researcher knew from previous assignments. The data collected from the interviews were analyzed according to the methodologies described in Chapter III.

The following paragraphs present the findings from the interviews. The findings were grouped into the following categories:

1. Round One of the First 28 Interviewees.

2. Round Two of the First 28 Interviewees.

3. Round One of All 38 Interviewees.

4. Round Two of All 38 Interviewees.

1. Round One of the First 28 Interviewees. The researcher intervi?wed a total of 30 participants. Two of the participants were excluded from the summarized results because of their special expertise. Their responses were highly concentrated in one specific area. The researcher interviewed those people in order to use their expertise in later parts of this study.

In the interest of time, the researcher summarized the results from the first group of 28 interviewees. The researcher then sent the summarized results, along with the respondents' initial answers, back to the participants for feedback. The specific analysis of the collected data of this part of the research was described in Chapter III. Detailed results are attached as Appendices E, F, and G.

2. Round Two of First 28 Interviewees. During the second round of interviews, the participants had the opportunity to modify their initial answers. In addition, the researcher had the opportunity to verify and clarify the

answers. Most of the participants were contacted by telephone during this round of interviews and the researcher was able to get responses from all the participants. Of the 28 participants, only eight changed the rank order of the major contributors. Detailed results are attached as Appendices H, I, and J.

3. Round One of All 38 Interviewees. The additional 10 participants were contacts the researcher made during the early part of this research. Due to the different schedules of both the participants and the researcher, it took some time to conduct the additional interviews.

The additional 10 interviews were conducted in the same manner as the first 28. The participants were first asked to respond to the interview questionnaire. After the researcher received the initial responses from the participants, the summarized results (obtained from the first 28 participants), along with their initial answers, were sent back to the participants for feedback. For the overall analysis, the researcher combined the additional data from the remaining 10 interviewees with the summarized results obtained from the first 28 interviewees. The specific details for the analysis of the collected data were described in Chapter III. Detailed results are attached as Appendices K, L, and M.

4. Round Two of All 38 Interviewees. The second round of interviews for this part was conducted in the same manner as round two for the first 28 interviewees. During this round of interviews, both the participants and the researcher were able to provide feedback on the initial responses. The participants were able to modify their initial answers if they so desired or just clarify their meanings to their initial answers. The researcher was able to verify and clarify the responses and thereby minimize misinterpretation on some of the initial answers. Detailed results are attached as Appendices N, O, and P.

Discussion on the Collected Data. From the collected data, the contributors were recorded, reduced, ranked, and reorganized according to the methodologies described in Chapter III. The following paragraphs describe the specific findings of the collected data.

Recording the Data. From the interviews, the major contributors to the reliability gap were identified and rank ordered. The total number of times a particular contributor was mentioned by the respondents was recorded. Figure 6 (Round One) and Figure 7 (Round Two) present the summaries of the number of responses of the contributor identified by 28 interviewees. Figure 8 (Round One) and Figure 9 (Round Two) present the summaries of the number of responses of the contributor identified by 38 interviewees.

28 Interviewees
(23 DoD/5 Industry)
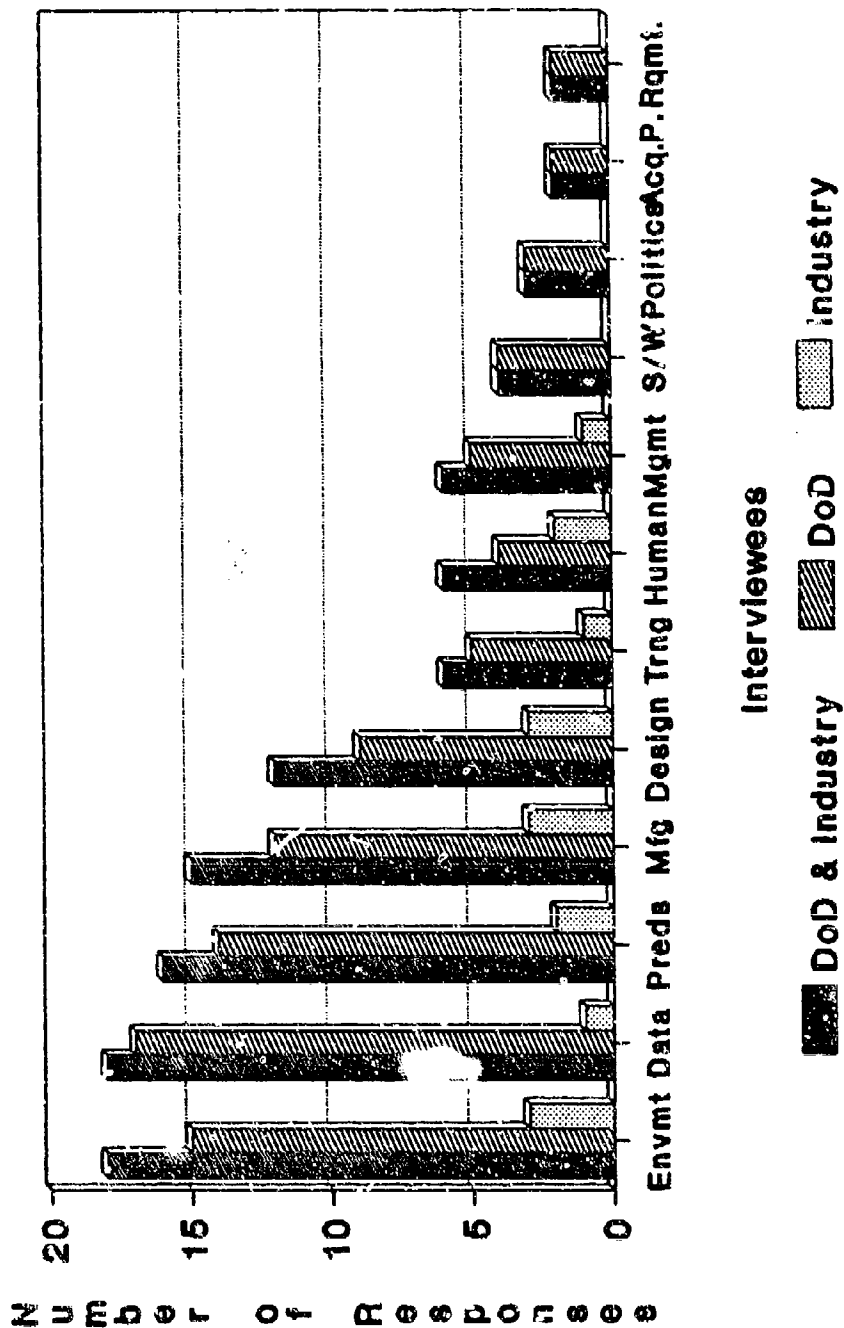
Figure 5. Round One of 28 Interviewees

28 Interviewees
(23 DoD/5 Industry)
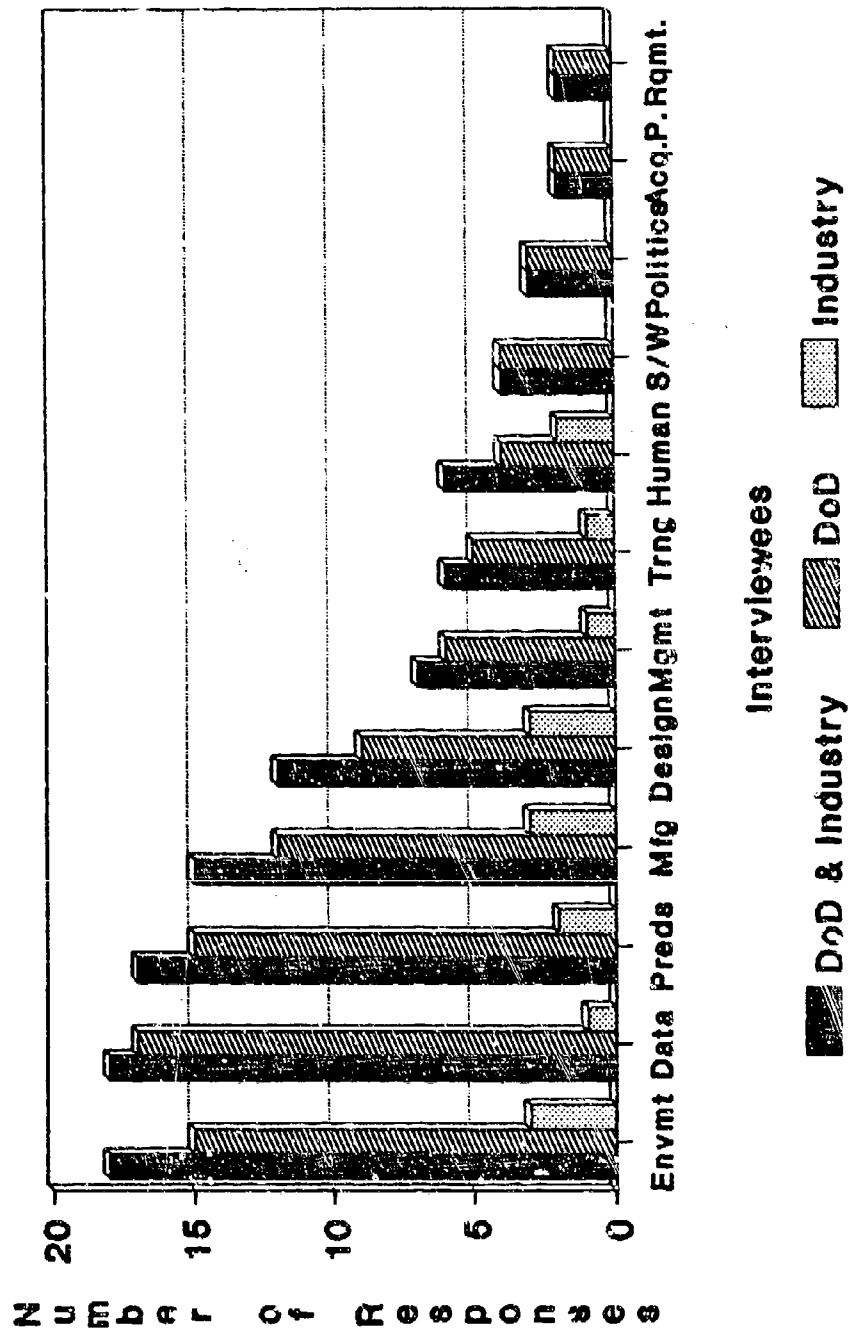
Figure 6. Round Two of 28 Interviewees

38 Interviewees
(28 DoD/10 Industry)
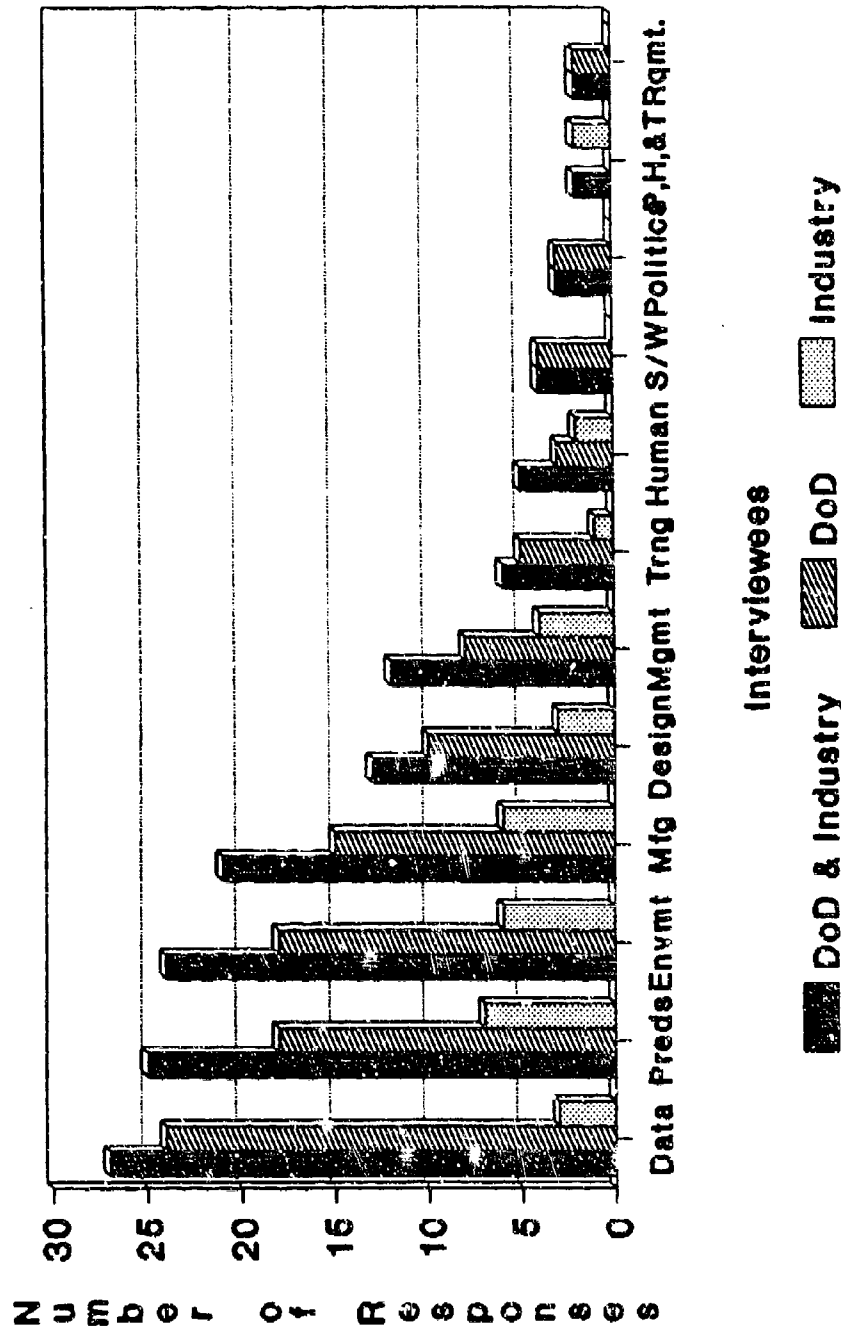
Figure 7. Round One of 38 Interviewees

38 Interviewees
(28 DoD/10 Industry)
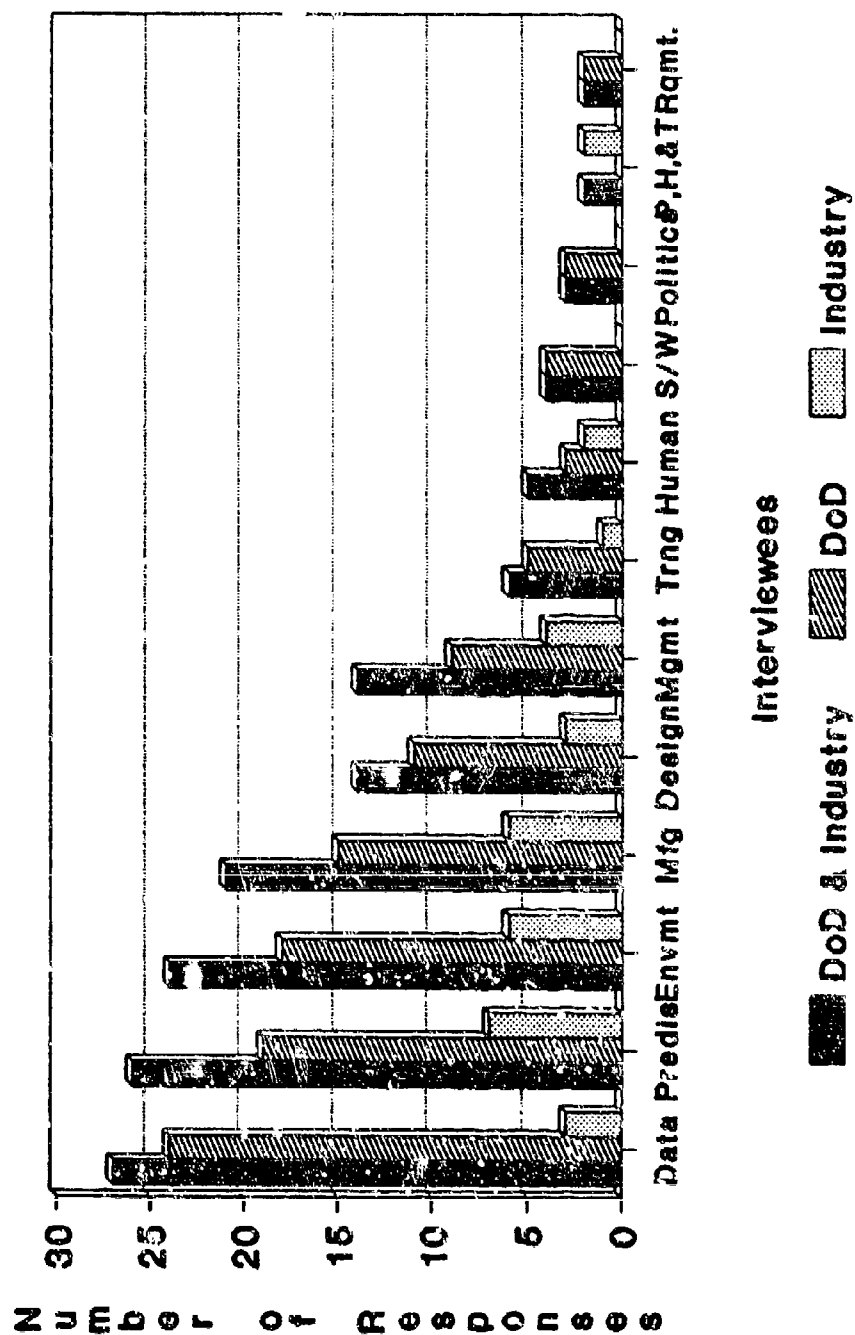
Figure 8. Round Two of 38 Interviewees

<u>Reducing the Data</u>. From the interviews, 12

major contributors were identified. By examining Figures 6

through 9, the major contributors can be grouped into

significant and insignificant contributors. The significant

contributors had a fairly high number of responses and the

insignificant contributors had a fairly low number of

responses. Using the number of responses as the determining

factor, the significant contributors from round one of the

first 28 interviewees were determined to be: Environment,

Data, Prediction, Manufacturing, and Design. However, by

examining Figures 8 and 9, the most significant contributors

were determined to be: Data, Prediction, Environment,

Manufacturing, Design, and Management. An interesting

finding in this study was the difference in the results

between the sample sizes (28 vs 38). This interesting

phenomenon is described in the following paragraphs. The

difference in the results between the sample sizes was not

part of the original intent of this study; however, it is

interesting to note the existing differences. The most

significant differences were in the areas of Management and

Data.

With 28 interviewees, management was not determined

(using the procedures described in Chapter III) as one of

the most significant contributors; however, with 38

interviewees, management was definitely considered as one

of the most significant contributors. By examining the

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rank-order averages of management during round two interviews with both 28 and 38 interviewees, it is interesting to note that management has the highest averages in both cases.

Another interesting contributor was Data. By strictly using the interviewees from Industry (five interviewees) and using the procedures identified in Chapter III, Data would not have been considered as one of the most significant contributors. However, the rank-order averages of data from Industry were as high as those from DoD, if not higher.

Ranking the Data. After the identification of the most significant contributors, the rank-order averages of those contributors were calculated. The specific methodology was described in Chapter III. The rank-order averages were used to analyze the relative importance of the most significant contributors.

The most significant contributors, along with their rank-order averages, from both rounds of interviews of 28 interviewees were determined to be: Environment, Data Prediction, Manufacturing, and Design (see Figures 10 and 11). The most significant contributors from both rounds of interviews of 38 interviewees were determined to be: Environment, Management, Data, Prediction, Manufacturing, and Design (see Figures 12 and 13). To investigate the relative importance of management among 28 interviewees, the researcher included Figures 14 and 15.

28 Interviewees
(23 DoD/5 Industry)
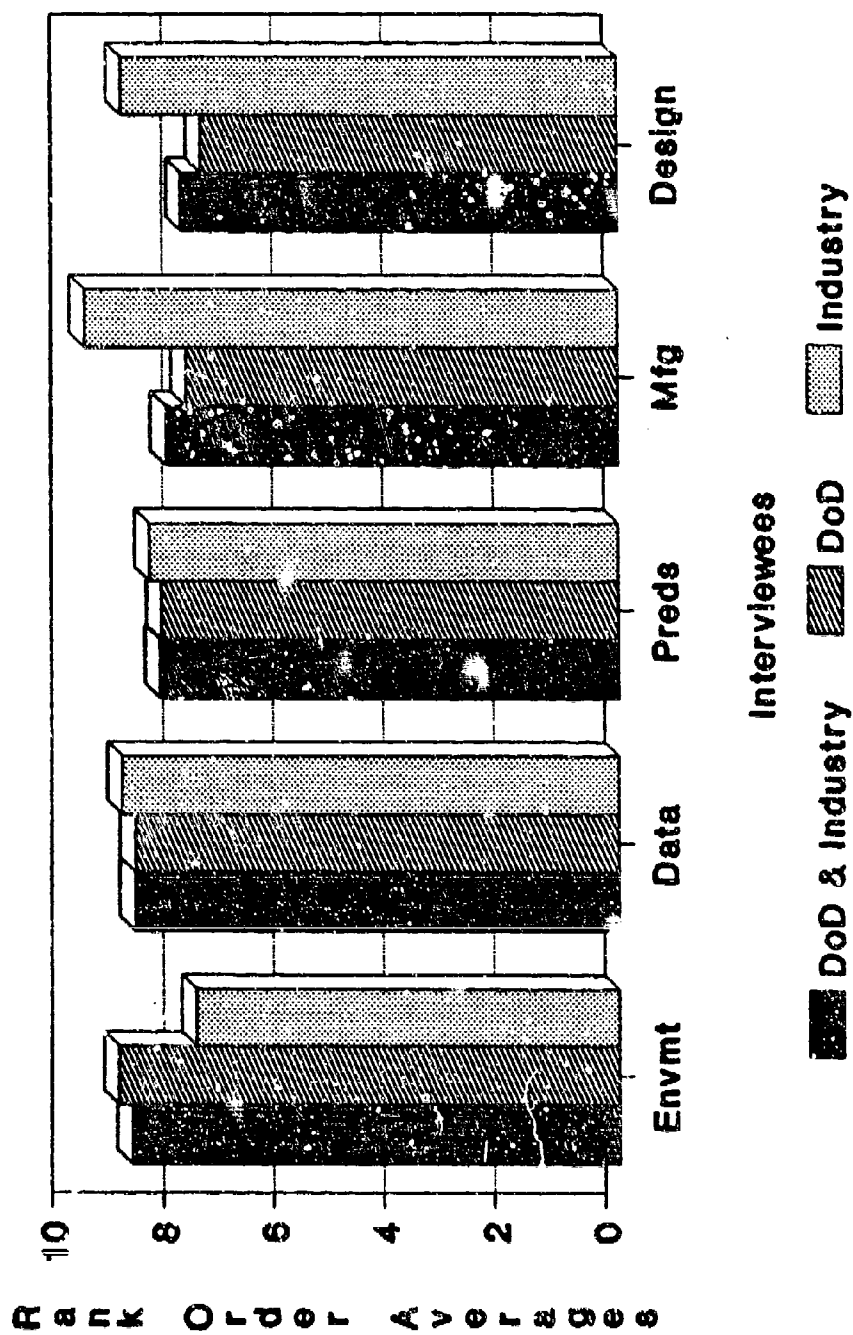
Figure 9. Most Significant Contributors (Round One: 28)

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Figure 10. Most Significant Contributors (Round Two: 28)

Figure 11. Most Significant Contributors (Round One: 38)

38 Interviewees
(28 DoD/10 Industry)
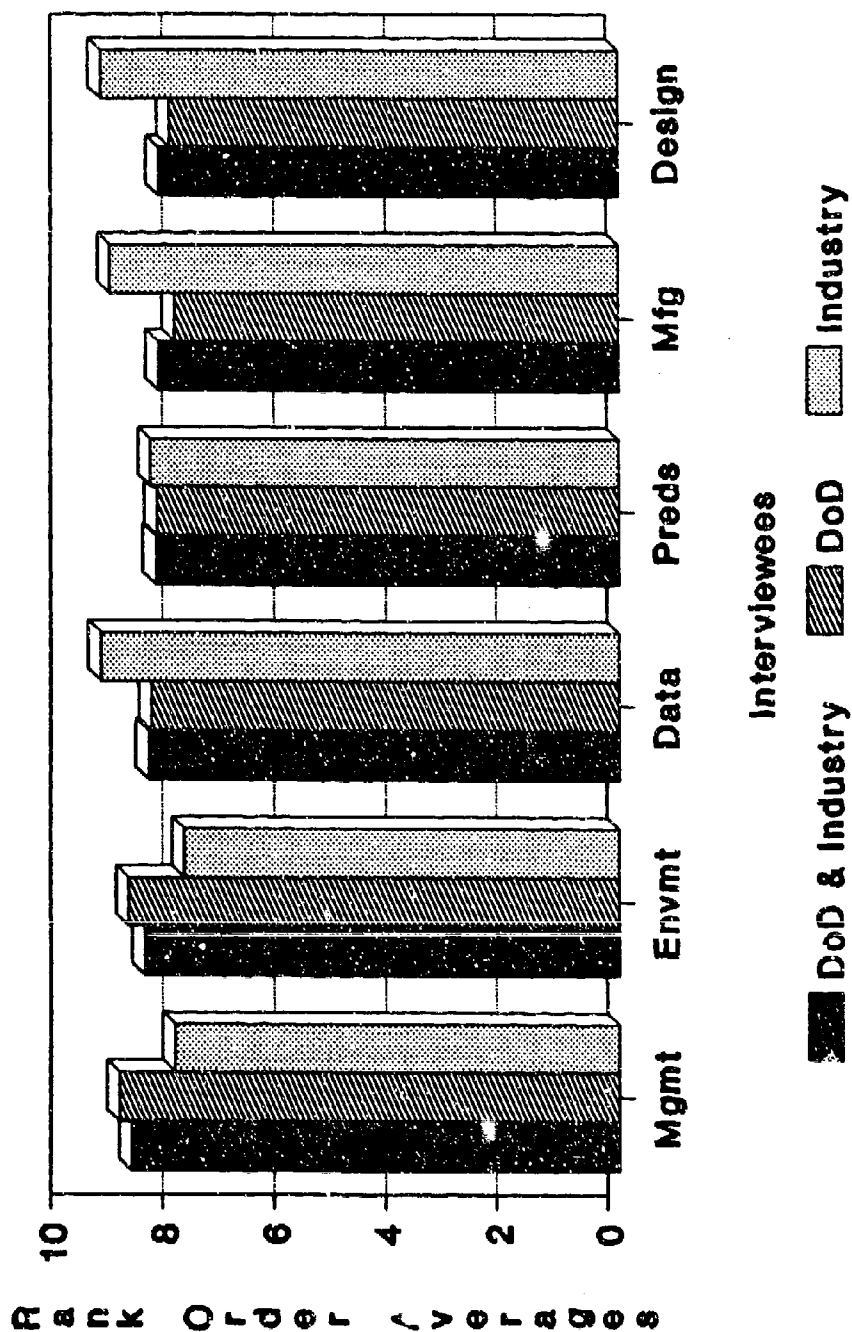
Figure 12. Most Significant Contributors (Round Two: 38)

28 Interviewees
(23 DoD/5 Industry)
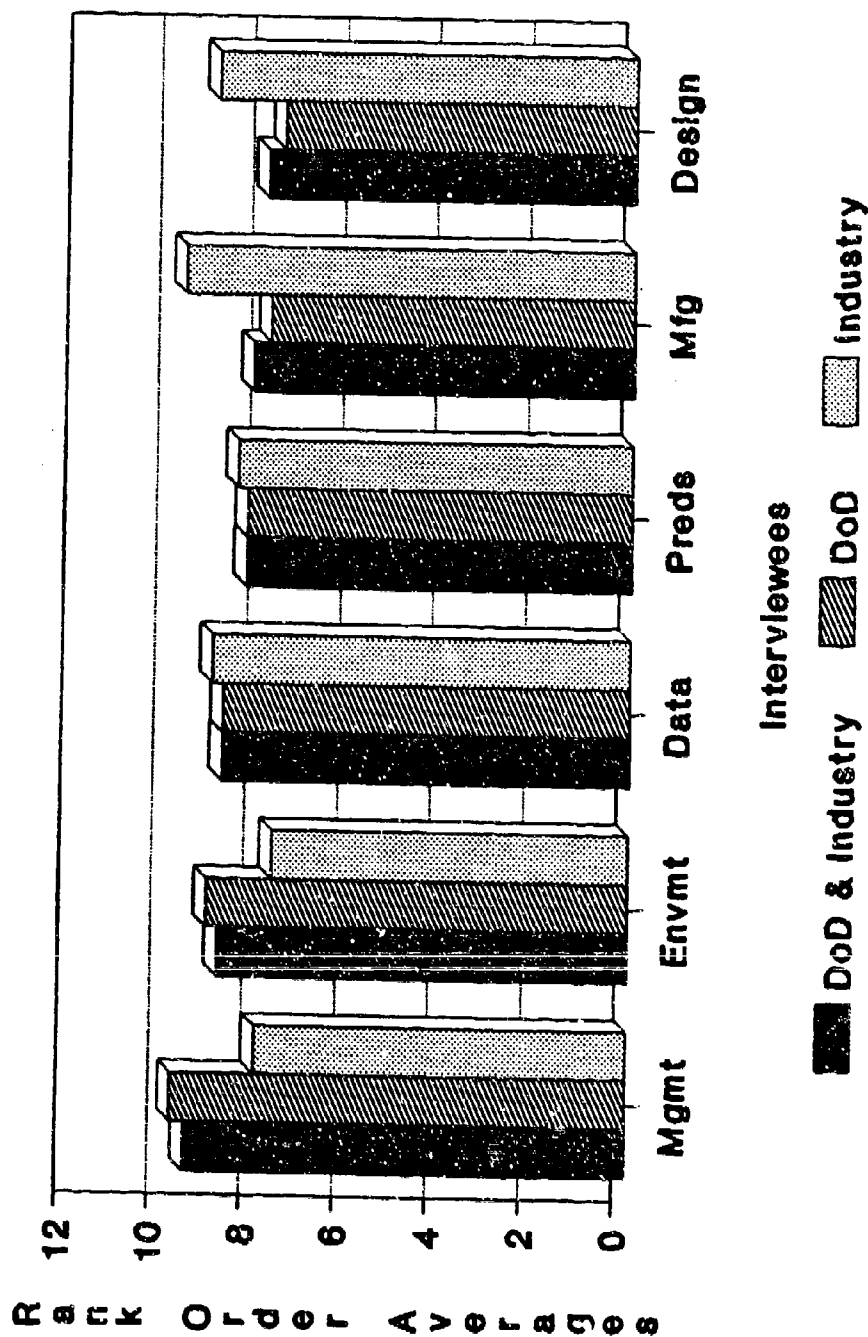
Figure 13. Most Significant Contributors (Round One: 28)

28 Interviewees
(23 DoD/5 Industry)
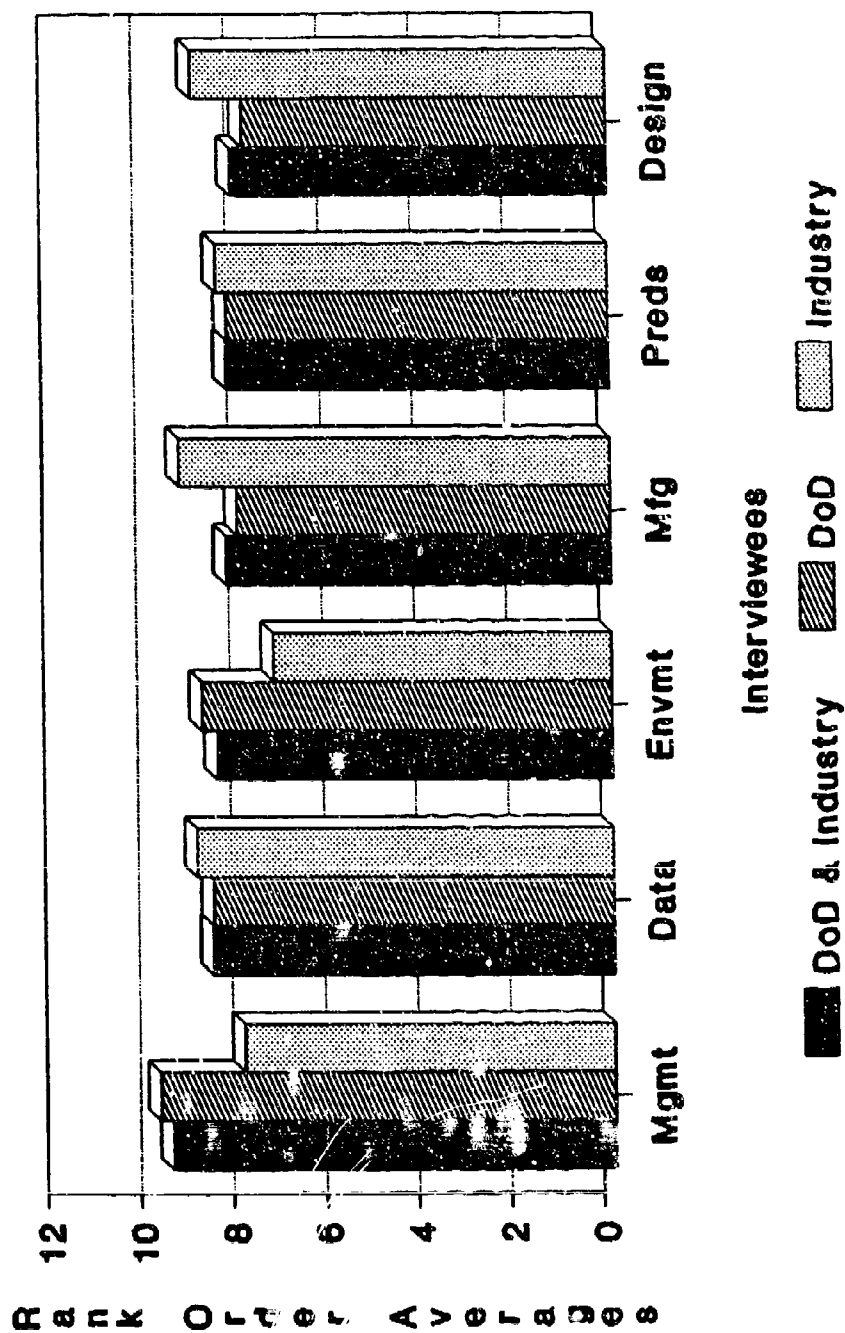
Figure 14. Most Significant Contributors (Round Two: 38)

<u>Reorganizing the Data</u>.   In order to
graphically compare the relative importance of the most
significant contributors, the researcher used the average
rank orders of the contributors to reorganize the data on a
linear scale (0 to 10).   Due to the subjective nature of
this study, the exact location of any contributor on the
linear scale was not as important as its relative location.
For example, when the contributors are closely grouped
together, it is very difficult to distinguish which one is
more important than the other.   However, when there is a
break between the contributors, it often indicates that one
contributor is definitely more important than the other.

By looking at the data, the rank orders of any
contributor did not seem to change much from one round of
interviews to another.   For example, the top-ranking
contributors during the first round of interviews were still
the top ranking contributors after the second round of
interviews.

It is not surprising to note that the DoD rankings match
closely with the Overall (DoD & Industry) rankings
since DoD interviewees constituted 75% of the total
interviewees.   However, it is interesting to note that
between the DoD and Industry rankings, the most significant
difference was in the average rank order for Management and
the number of responses for Data.   Management was ranked
very high among DoD personnel and not so high with Industry

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personnel. In the area of Data, both the DoD and Industry communities ranked it fairly high; however, the number of responses from the two communities differed drastically. For example, 24 of the 28 (86%) DoD respondents mentioned Data as one of the major contributors, whereas only 3 of the 10 (30%) Industry respondents mentioned Data.

The linear scale ranges from 0 to 10 are used to display the most significant contributors. Because the rank-order averages were concentrated toward the top half of the scale, only the numbers from 7 to 10 were labeled on the tables. Table 4 presents the relative importance of the most significant contributors to the reliability gap from the results of the first 28 interviewees. The first column represents the responses from both DoD and Industry participants. The second column represents the responses from DoD participants only, and the third column represents the responses from Industry participants only. The number in parentheses after each contributor represents the number of interviewees responding to that particular contributor. Table 5 presents the relative importance of the most significant contributors to the reliability gap from the results from the second round of interviews of the first 28 interviewees. Tables 6 and 7 present the relative importance of the most significant contributors to the reliability gap from the results from both rounds of interviews of 38 interviewees (see Tables 4 through 7).

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Table 4. Relative Importance of the Most
Significant Contributors to the
Reliability Gap (Round One: 28)

Rank-Order Average	DoD & Industry (28)	DoD (23)	Industry (5)
10.			
.		Mgmt(5)	
.			Mfg(3)
.			
.			
.	Mgmt(6)		
.			
.			
.			
9.		Envmt(15)	Design(3)
.	Envmt(18)	Data(17)	Data(1)
.	Data(18)		
.			Preds(2)
.			
.	Preds(16)	Preds(14)	
.	Mfg(15)		
8.			Mgmt(1)
.	Design(12)		
.		Mfg(12)	
.			Envmt(3)
.		Design(9)	
.			
.			
.			
.			
.			
7.			
.			

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Table 5. Relative Importance of the Most
          Significant Contributors to the
          Reliability Gap (Round Two: 28)

Rank-Order Average	DoD & Industry (28)	DoD (23)	Industry (5)
10.			
.			
.		Mgmt(6)	
.			
.	Mgmt(7)		
.			
.			Mfg(3)
.			
.			
9.			Design(3)
.		Envmt(15)	Data(1)
.			
.	Data(18)	Data(17)	
.	Envmt(18)		
.			Preds(2)
.			
.	Preds(17)	Preds(15)	
.	Mfg(15)		
.	Design(12)	Mfg(12)	
8.			Mgmt(1)
.		Design(9)	
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.			Envmt(3)
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7.			
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Table 6. Relative Importance of the Most
Significant Contributors to the
Relability Gap (Round One: 38)

Rank-Order Average	DoD & Industry (38)	DoD (28)	Industry (10)
10.			
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.			Data(3)
.			Mfg(6)
.		Envmt(18)	
9.		Mgmt(8)	Design(3)
.			
.	Envmt(24)		
.	Mgmt(12)		
.	Data(27)		
.		Data(24)	
.	Preds(25)		Preds(7)
.		Preds(18)	
.	Mfg(21)		
.	Design(13)		
8.			Mgmt(4)
.		Design(10)	
.		Mfg(15)	Envmt(6)
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7.			
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Table 7. Relative Importance of the Most
Significant Contributors to the
Reliability Gap (Round Two: 38)

Rank-Order Average	DoD & Industry (38)	DoD (28)	Industry (10)
10.			
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.			Design(3)
.			Data(3)
.			Mfg(6)
9.		Mgmt(9)	
.			
.	Mgmt(14)	Envmt(18)	
.			
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.	Data(27)		
.	Envmt(24)	Data(24)	Preds(7)
.	Preds(26)	Preds(19)	
.	Mfg(21)		
.	Design(14)	Design(11)	
8.		Mfg(15)	Mgmt(4)
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.			Envmt(6)
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<u>Discussion of the Findings</u>. From the first round of
interviews, a second round was conducted to validate the
findings. For the purpose of trying to understand the
makeup of the different contributors, the following
paragraphs provide a descriptive summary of the comments
cited by the interviewees (also see Appendix C, a summary of
che findings of the first 28 interviewees). In addition,
various studies (conducted by the interviewees) and possible
solutions (suggested by the interviewees) were also included
in the discussion. The contributors are presented in the
order shown in Table 7, using the DoD & Industry column.
Since all the contributors identified are significant, the
contributors with the highest number of responses will be
described first.

<u>Data</u>. Twenty-seven out of 38 interviewees
(71%) identified data as one of the major contributors to
the reliability gap. Most experts felt that the problems
with data were in the areas of data definition and data
collection.

Under the topic of data definition, most respondents
mentioned the difficulty associated with the classification
of failures and scoring procedures. The difficulties
include the determination of relevant vs nonrelevant
failures, the definition of a failure vs a critical
failure, the contractual vs operational failures,

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inherent vs induced failure, Government Furnished Equipment
(GFE) vs non-GFE failures, and hardware vs software
problems. The difficulty also includes the definition of
time, such as flying vs operating hours.

Under the topic of data collection, most of the
interviewees considered the current DoD data collection
system as inaccurate, untimely, and incomplete. They also
mentioned that there is a lack of motivation from the data
collectors. The lack of motivation is mainly due to the
lack of positive feedback and an overwhelming amount of
negative feedback. In addition, most of the respondents
felt that the current data collection system is used as a
manhour accounting system, to ensure the documentation of a
full-day's work, rather than as a system to collect accurate
reliability data.

It is also interesting to note the comments from
Dr. Ben Williams (Director, Center of Excellence for R&M),
who has over 25 years of experience in reliability and
maintainability management. According to him, the problem
is that "...we do not know how to analyze the collected
data." He thinks the current data system is not perfect but
is adequate to provide the necessary information--that is,
the capability to identify where the problem areas are. He
further explained that it is not economically feasible, nor
it is necessary, to investigate every failure, provided that
the failure is not safety-related and does not affect the

operational availability of the weapon system. What is
necessary is to have the right people (preferably R&M
engineers) to analyze the data and identify the failures
that warrant the investigation. That is, the benefits from
corrective action(s) outweigh the resources expended for the
investigation.

Data: Current Studies. An R&M Data
Deficiencies Tiger Team was formed in February 1987 to
investigate the Maintenance Data Collection (MDC) system and
its relationship with R&M requirements (Appendix Q). The
team collectively generated more than 60 recommendations which
were then consolidated into 15 items. Due to the relative
importance of data as compared to the other contributors on
the linear scale, this study included the problem descriptions
of the 15 items as Appendix Q.

Data: Possible Solution. Many solutions
were suggested. From this study, the objective of the
data definition problem is to come up with a set of standard
R&M measurable terms. The objective of the data collection
problem is to come up with a common data base. With the
standard set, the tool for the implementation of the
suggested concepts is a joint data classification board
meeting to clarify the specific classification and
definition. In addition, the joint data classification

board can generate a set of data which can be used as the common data base.

On the more sophisticated side of data collection, Colonel Abrams, former F-15 Deputy Program Manager for Logistics (DPML), suggested the use of an artificial intelligence (AI)-based system. With an AI-based system, real-time data under operational conditions can be accurately captured.

In the meantime, is there a possible solution to the data collection deficiency? It has been suggested that the current data collection system is not perfect, and it never will be. It is, however, adequate to provide the necessary information. The deficiency is not the collected data, per se. The deficiency is in not knowing how to analyze the collected data. A possible solution is to have the "right" people (preferably R&M engineers) analyze the data, identify the magnitude of the problem, and conduct a special study on the problem if the problem has been identified as economically and operationally beneficial.

Prediction. The word "prediction," as used in this phase of the study, refers to the prediction techniques. Twenty-six out of 38 interviewees (68%) identified prediction techniques as one of the major contributors. About half the experts attributed the problem to the techniques used in MIL-HDBK-217. The assumptions on the

prediction techniques in MIL-HDBK-217 were cited by the experts to be questionable. In addition, the predictors in the handbook were considered to be operationally nonrepresentative. The predictors do not consider interconnections, and there are no good predictors for hydromechanical failure rates. Other problems with the prediction technique were stated to be associated with the improper use of reliability models. In addition, most of the experts/practitioners suggested that the prediction techniques accounted for the bulk of the reliability gap.

As far as MIL-HDBK-217 is concerned, both Dr. Crow (18-23) and Mr. Gibson (30) stated that its intended purpose is to serve as a trade-off tool for early design and not to predict the performance of mature systems. According to them, people using MIL-HDBK-217 to make predictions must first understand its intended purpose and use it accordingly.

Prediction: Possible Solution. Through years of experience, Mr. Trakas (NAVAIR: Head, R&M Branch) developed a practical approach of relating the reliability parameters. The objective of this approach is to "provide a repeatable, logical approach toward establishing realistic reliability requirements" (66:103) for the acquisition process. Appendix R is taken from the article written by Mr. Trakas and it outlines this practical approach. It starts with:

> ...the operational requirement defining the minimum
> acceptable value of reliability, in operational
> terms, consistent with meeting the program
> objectives. The operational requirement is then
> translated into the DCP/TEMP (Decision Coordinating
> Paper/Test and Evaluation Master Plan) threshold
> MFHBF (Mean Flight Hours Between Failure) taking
> into account the logistics inputs of MFHBMA (Mean
> Flight Hours Between Maintenance Actions),
> cannibilizations, on-aircraft repair, MFHBR (Mean
> Flight Hours Between Removal) if applicable, and
> the false removal rate.... This reliability is in
> operational terms and must be translated into an
> MTBF (Mean Time Between Failure) requirement for
> the contractor. In order to accomplish this
> translation, an S/F (System/Flight) Ratio must
> first be applied. The S/F ratio takes into account
> the fact that this type of equipment is on and
> operating more than it is flying (assuming a 100%
> duty factor in the aircraft) because of Pre-Flight,
> Flight, Post-Flight, and maintenance activities.
> This ratio then yields an MTBF threshold....an
> experience factor of 25%, based on the Duane
> philosophy, is applied yielding a Lower Test
> MTBF.... In accordance with MIL-STD-781C, assuming
> a typical test using Test Plan IIIC, there is a 2:1
> discrimination ratio. This yields an Upper Test
> MTBF. [66:105]

The safety margin percentage is used as:

> ...the rule of thumb that there is a good chance
> that the specified requirement can be achieved and
> demonstrated if the predicted reliability is 25
> percent greater than the Upper Test MTBF. [66:106]

According to Mr. Trakas, the methodology described is
for avionics. Similar methodologies can be developed for
different systems. In fact, the same type of methodology
was developed and documented in Air Force Logistics Command
Pamphlet (AFLCP) 800-3, April 1973.

Environment. Twenty-four out of 38 interviewees
(63%) identified environment as one of the major

contributors. Most of the participants responded that most of the problems associated with environment are attributed to the misapplication and misinterpretation of the operational environment--the lack of good translational factor between operational and laboratory environment. The operational environment is harsh and difficult to predict. A few of the respondents think that we do not really understand the operational environment, and we do not accomplish adequate testing, to find out about the operational environment. In addition, the predicted reliability is mostly at the parts or subsystems levels. System integration and interfacing is seldom considered. No specific solution was cited.

Manufacturing. Twenty-one of the 38 interviewees (55%) identified manufacturing as one of the major contributors to the reliability gap. Most of the respondents felt that the problem with the manufacturing processes is in the areas of producibility and quality. They felt that a robust design can absorb a lot of the producibility problems. As far as quality is concerned, most of the respondents felt that it is also contractor-dependent, on whether the particular contractor believes in a total quality management program.

Manufacturing: Possible Solution. Several other respondents made the following suggestions:

1. Encourage the design engineers to work closely with the manufacturing engineers by collocating the two work areas.

2. Maximize the use of standardized parts. With the use of standardized parts, the risks to parts performance, costs, etc., can be reduced.

3. Minimize parts count. The reasoning behind this suggestion is with fewer parts, there are fewer failures associated with the parts or interfaces.

In addition, Major Farr (AFIT Professor: Contracting Management), who has more tnan eight years of experience in manufacturing, advocated the use of the Willoughby templates in DoD Directive 4245.7. Willis J. Willoughby, Jr., is the Chairman, Defense Science Board Task Force, Transition from Development to Production. In the area of quality, several respondents mentioned Taguchi's quality philosophy to design. Genichi Taguchi "is frequently mentioned along with W. Edwards Deming, Kaoru Ishikawa, and J. M. Juran" (36:21). The following seven points explain the basic elements of Taguchi's quality philosophy:

1. An important dimension of the quality of a manufactured product is the total loss generated by that product to society.

2. In a competitive economy, continuous quality improvement and cost reduction are necessary for staying in business.

3. A continuous quality improvement program includes incessant reduction in the variation of product performance characteristics about their target values.

4. The customer's loss due to a product's performance variation is often approximately proportional to the square of the deviation of the performance characteristic from its target value.

5. The final quality and cost of a manufactured product are determined to a large extent by the engineering designs of the product and its manufacturing process.

6. A product's (or process') performance variation can be reduced by exploiting the nonlinear effects of the product (or process) parameters on the performance characteristics.

7. Statistically planned experiments can be used to identify the settings of product (and process) parameters that reduce performance variation. [36:21]

Design. Fourteen of the 38 interviewees (37%) identified design as one of the major contributors. Most of the interviewees felt that the wrong selection of parts and components contributed heavily to the problem associated with design. A few of the respondents mentioned that design-caused failures are declining. The major area where design contributes to the gap is a poor understanding of the real operational environment. The other problems associated with design included the use of design tools such as Computer-Aided Design (CAD), which seldom consider R&M parameters.

Design: Possible Solution. Several of the respondents suggested that a more robust design is necessary to withstand the uncertainties associated with the operational environment. Taguchi's method to design was mentioned as an alternative.

Management. Most of the respondents who mentioned
management as one of the major contributors to the
reliability gap ranked it as either the most important
contributor or the second most important contributor. The
average for management is either the highest or second
highest in any set of interviews (see Tables 4 through 7).

It was cited that most managers are worried about short
term benefits rather than long-term gains. Consequently,
fundings in the area of reliability were rarely sufficient
since reliability takes time (one of the findings from the
RCA report from 1955; see Appendix A).

In the area of short-term management, Ralph E. Evans
(27) wrote an editorial and some of his interesting words were:

> Short-term management is the major primary
> bottleneck to achieving the levels of reliability
> that are nominally desired by users. Schedule and
> cost are like water and food--you can't live long
> without them. Reliability (and quality) programs
> are like vitamins--you develop the symptoms (e.g.,
> beri-beri and scurvy for vitamin B & C
> deficiencies). In large part, it is the social,
> economic, and political environments that force
> managers to become oriented to the short-term....
> Short-term managers are anxious and willing to
> confuse form with substance. They have neither the
> time nor inclination to change a company's way of
> life. Instead they go for 1-shot things that have
> lots of hoopla and show, like building a quality-
> productivity center, insisting that everyone
> install the trappings of STATISTICAL quality
> control, and motivational slogans (Quality Is
> Number One).... Short-term managers put middle
> managers in the double bind (damned if you do,
> and damned if you don't) by not allocating
> sufficient resources to them for achieving the
> lofty corporate goals. If middle management takes
> the lofty goals seriously, then it will fail on
> production or schedule. If it keeps to production

and schedule requirements, then it fails on the
lofty corporate goals.... [27]

In addition, the interviewees mentioned that not enough

emphasis is put on training engineers to design systems that

are robust enough to withstand the operational environment.

In the same editorial of Short-Term Management, Ralph Evans

mentioned that:

> Most people need actual (not vicarious) experience
> in other jobs in order to appreciate them....
> A designer needs to experience first-hand what the
> problems of manufacturing and field-service are.
> The manufacturing engineer needs to experience the
> frustrations of design and of living with the junk
> the company ships. [27]

Management: Possible Solution. No specific

solution was cited. However, most respondents mentioned

that somehow management has a "piece of the action" in all

the identified contributors. Without proper managerial

emphasis, none of the other possible solutions is viable. In

addition, Mr. David Weber (General Electric: Lead R&M

Engineer), who has more than 25 years of experience

in the area of reliability, cited that top-management

involvement is needed and "what is also needed are people

who can sustain themselves through the downs as well as the

ups."

Training. The respondents mentioned four

categories of personnel who lack proper training. For the

designers, they mentioned that the R&M parameters are rarely

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taught. In addition, the interviewees contended that the designers do not understand the manufacturing processes and field maintenance to design out producibility and maintenance problems. For the manufacturers, the experts felt that most of them do not have the experience. For the maintainers, the interviewees felt that because they lack proper training, the maintainers themselves induced a lot of the problems. And finally, for the operators, the respondents concluded that operators may induce problems or may have different expectations about the performance of the equipment/system.

Training: Current Studies. Mr. Virgil Rehg (AFIT Professor: Quantitative Methods & Statistics), conducted a couple of surveys, using field people at the operating bases, to identify problems that prevent them from doing their job. Quite a number of people cited training, or the lack of it, prevents them from doing their job better. (Professor Rehg's surveys on "Barriers to Quality").

Training: Possible Solution. Among the responses, a few of the interviewees suggested training people from a system's engineering approach of how each discipline can effectively integrate with the other.

Human Performance. The consensus among the experts was that the inability to predict human performance and

motivation, etc., contributed significantly to the reliability gap.

Human Performance: Possible Solution. The respondents mentioned that human engineering is a possible approach. In addition, a few of the respondents suggested that management emphasis can strongly influence human performance, both positively and negatively.

Software. The few interviewees who mentioned software as one of the major contributors to the reliability gap classified most of the software-related problems as induced. The respondents suggested that we are still in the early stages of software engineering. No specific solution was cited.

Politics. All the respondents agreed that Congressional influences and bureaucratic pressures are unable to predict and greatly impact the possible management emphasis/actions. Most respondents think that management emphasis/actions influence all the other contributors, either directly or indirectly. No one suggested the possibility of a solution in this area.

Packaging, Handling, and Transportation (P,H,&T). This is a unique contributor, mentioned only by Industry personnel. Because of their line of business, most of their

field problems are associated with P,H,&T. No suggested solution was mentioned.

Requirement. Several of the respondents felt that the requirements are usually unclear and poorly defined. A few of the respondents stated that the requirements are fiscally controlled. Rather than planning on how to counter the threat, oftentimes it is planning on "how much we think we can afford." Most of the time, it was mentioned that the stated requirements were not hard-and-firm requirements. Consequently, they were easily overpowered by the constraints of cost and schedule.

Requirement: Possible Solution. In the area of realistic requirement, Mr. McCarty (AFIT Professor: Weapon System Management), who has over 20 years' experience in acquisition, has been advocating for years that there should be a concepts division, where concepts are analyzed in accordance with the identified needs. The stability of the people in the "concepts division" will help establish an ongoing dialogue with the using commands, which in turn will help identify what's achievable and what's optimistic with the given constraints of costs and time. Professor McCarty also mentioned that the people in the concepts division should be divorced from the management of the development of the program in order to have an objective approach to the best answers for the needs.

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Phase III Findings

Experts' opinions, pertaining to Questions 7 and 8 of the Interview Questionnaire, were consolidated. Specifically, opinions on reliability growth model, initial reliability, growth rates, and effectiveness factor were analyzed. The data from the interviews were collected and analyzed according to the methodologies described in Chapter III.

Reliability Growth Model. The question was: If you were to develop a reliability growth plan, what growth model would you use? Most of the responses (DoD & Industry) were Duane or modified Duane (i.e., AMSAA). The reasons were its simplicity and ease of use. Those who chose AMSAA think it is more statistically accurate. A couple of suggestions were made as to how to choose the right model:

1. Use research and computer simulation to find the most appropriate model.

2. Use Duane during the initial stages when the data are scarce. During the mid- and later stages, plot the data, determine the failure distributions, choose a model (parametric or nonparametric) that fits the data the best, and perform a goodness-of-fit test.

Initial Reliability. The question was: If you were to develop a reliability growth plan, what starting reliability value would you use? Would you use a starting reliability value of 10% of the cumulative mean time between maintenance (inherent)? 20%? Most of the experts/practitioners

responded that they would expect an initial reliability close to 10%. However, most of them would like to see an initial reliability closer to 25% or 30%. With a higher initial reliability, they expressed that it does not take as long to reach the mature stage.

Reliability Growth Rate. The question was: If you were to develop a reliability growth plan, what growth rates would you use for the four types of weapon systems: Aircraft, Missile, Spacecraft, and Ground-based complex electronic systems? The responses (averages and modes during the Full-Scale Production Phase of the acquisition process) were as follows:

	Aircraft	Missile	Complex Ground Electronics
Average	0.30	0.33	0.27
Mode	0.30	0.35	0.30

Effectiveness Factor. The question was: If you have identified the corrective actions, what effectiveness factor would you use? For example, 100% effectiveness factor means the corrective action will correct the identified deficiency; it will never happen again. Of the 38 interviewees, 25 responded to this question and the average and the mode were both 70%.

Summary

The findings for each phase were presented separately. Table 8 summarizes the results from each phase. In the next chapter, the conclusions and recommendations of this study will be presented.

Table 8. Summary of Findings

Phase	Findings
I	Reliability gap exists in airborne tactical radars for both Air Force and Navy aircraft. Figure 4.
II	The most significant contributors to the reliability gap were identified and rank ordered. See Tables 4, 5, 6, and 7.
III	Reliability growth responses were consolidated:

III

a. Most popular growth model:

---Duane or modified Duane (i.e., AMSAA)

b. Initial reliability:

---Been experiencing: Close to 10%
---Would like to see: 25% to 30%

c. Growth rate: During Full-Scale Production (average, mode)

---Aircraft: (0.30, 0.30)
---Missile: (0.33, 0.35)
---Complex Ground
   Electronics: (0.27, 0.30)

V. Conclusions and Recommendations

Introduction

This chapter summarizes the results of this study and makes recommendations for future studies. This chapter begins with a review of this research followed by a comparative discussion between the findings from this study and those from the literature review, and concludes with recommendations for future studies.

Review

Over the years, the difference (gap) between factory (whether specified, predicted, or demonstrated) and field reliability has been documented in numerous studies. Historically, the gap in avionics equipment was reported to range from 7:1 to 20:1 (38:231).

The overall objective of this research is to investigate why the actual field reliability is consistently different (usually lower) than the factory reliability. This research begins with an exhaustive literature review. First on the definition of reliability, then the development of reliability engineering, and finally, the problems of unreliability, all to set the stage for the discussion of the research problem--the reliability gap. This inability to accurately relate factory reliability to the field

reliability has a significant impact on operational readiness and life cycle costs. In order to better understand the problem, traditional ways (along with their limitations) of assessing reliability and some practical questions and answers associated with the reliability gap were examined.

To recapitulate, the objectives of this study are:

1. To examine the existence of the reliability gap in airborne tactical radars of Air Force and Navy aircraft.

2. To identify and analyze the major contributors to the reliability gap. Specifically, to identify the most significant contributors.

3. To explore ways of minimizing the reliability gap. Specifically, to examine some practical guidelines on reliability growth.

To accomplish the first objective, tactical airborne radars were examined. The courtesy slide from NAVAIR indicated that the reliability gap for tactical airborne radars existed in both Air Force and Navy aircraft. To accomplish the second objective, personal as well as telephone interviews were conducted. Experts/ Practitioners were asked to rank order the major contributors to the reliability gap. In addition, a second round of interviews was conducted to validate the findings of the first round. The specific findings were documented in Chapter IV. To accomplish the third objective, experts'/ practitioners' opinions, various studies conducted by the experts, and appropriate historical findings were analyzed.

Conclusion: Comparative Discussion

This portion of the chapter compares the findings from
this study to those from the literature review. It follows
the same format as the previous chapters; it is, divided
into three distinct phases, each corresponding to the
appropriate objective of this study.

Phase I. The reliability gap existed in airborne
tactical radars for both Air Force and Navy aircraft.

Phase II. The major contributors identified in this
study were compared to the factors found in the literature
review. By comparing Table 2 (findings from literature
review) and Tables 4 through 7, the results were found to be
comparable. The additional knowledge gained in this study
are:

1. The relative importance of these major contributors.

2. The different perspectives between DoD and Industry
    personnel on these contributors.

Phase III. Various approaches were mentioned on how to
minimize the reliability gap. The responses to Question 6
of the Thesis Questionnaire addressed the kinds of
incentives for contractors to produce more reliable
products. See Appendix C, Question 6. Questions 7 and 8 in
Appendix C address some practical guidelines to reliability
growth. Realizing that reliability growth is not the
panacea to the reliability gap problem, the reliability

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growth program does, however, provide some guidelines on how
to minimize the gap. In this phase, some of the practical
guidelines cited by the experts/practitioners on reliability
growth in the following areas were collected:

1. Reliability growth model

2. Initial reliability

3. Growth rate

4. Effectiveness factor

Reliability Growth Model. From the literature
review, three prominent studies on reliability model were
cited. The analysis for identifying the optimal reliability
growth model is beyond the scope of this study; however,
experts'/practitioners' opinions were gathered on the kind
of reliability growth models that are being used in the
field. The similarity between the findings from the
literature review and this study both concluded that the
Duane or the modified Duane (i.e., AMSAA) is the most
popular model.

Initial Reliability. From the literature review,
the Army identified that most "successful programs usually
begin with an initial MTBF of at least 1/3 or 1/4 of the
desired MTBF" (6:211). Though most experts/practitioners
have been experiencing an initial reliability of less than
10% of the desired reliability, most of them would like to

have an initial reliability 25% to 30% of the desired
reliability.

Growth Rates. From the literature review, the
growth rates were cited to range from 0.35 to 0.5 (45:78).
From this study, Table 8 summarizes the practical growth
rates for each type of weapon system during full-scale
production of the acquisition phase. To some extent, the
ranges for the growth rates may be comparable; however, the
highest rate (mode) identified by the experts/practitioners
in this study was 0.35.

It is important to understand that the risks of the
reliability gap can be minimized if the uncertainties
associated with reliability growth are recognized. The
recommended growth rates for the weapon systems can be used
as a guide for planning purposes. With the findings of this
study, it is hoped that managers will realize that there are
tremendous amount of risks involved in growth rates that are
greater than 0.5. In fact, a few experts/practitioners
commented that during their career (average of fifteen
years), "...0.4 was the fastest that I've seen anything
grow."

Effectiveness Factor. From the literature review,
the Army identified that most failure modes achieved a 70%
fix effectiveness factor (6:211). Some of the experts/
practitioners are aware of the Army's study on effectiveness

factor and also cited a 70% effectiveness factor. Others cited the effectiveness factor to be higher than 70% and some cited lower. However, it is interesting to note that among the 25 out of the 38 interviewees (some did not respond to this particular question), the average and the mode were both 70%.

Several interviewees expressed that the risks of the reliability gap can be minimized if it is recognized that the fix effectiveness for the failure modes is not always 100% effective. As expressed by Dr. Crow, the expert on reliability growth, during the interview: "...in order to do growth testing properly, you must insert the fix before you continue testing because you cannot make the assumption of 100% effectiveness of any fix!"

Recommendations

This study provides some conceptual ideas on how the reliability gap can be minimized in order to maximize operational readiness and optimize life cycle costs. Recommend that continual efforts (i.e., a "rule of thumb" handbook) be made along the lines of practical guidelines in reliability prediction techniques and reliability growth management.

The following recommendations are based on the findings from the literature review and the results from this study. Like the conclusions of this study, it is divided into three distinct phases.

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Phase I. In order to minimize the gap, recommend a closer analysis of the user's requirement (to determine whether it is realistic), the prediction methodology (with the limitations of MIL-STD-217 in mind), the simulated environment during testing (recognizing the difference between laboratory vs operational environment and the unique characteristics of each), and field data collection system.

In the area of development of the initial predicted reliability, recommend that the prediction methodology be refined with field data. It is interesting to note that most of the interviewees from the industry sector cited that the use of field data is the best possible information for refining the prediction methodology. By using the field data, the uncertainties associated with the performance of the equipment in the operational environment can be minimized.

In the area of the actual field reliability data, recommend using the right people (preferably R&M engineers) to analyze the collected data, to identify the problem areas, and to recommend the corrective action(s).

Phase II. Several major contributors have been identified and rank ordered by this study. In order to better understand the various contributors, recommend further analysis of these major contributors.

This study summarized the findings on a linear scale. This is not to suggest that the relationships among the

major contributors are linear. In fact, the effects of some contributors have been suggested to have a significant impact on the other contributors. The overlapping effects of the contributors are beyond the scope of this study. In order to further investigate how each of the contributing factors influences the others, recommend that a formalized factor analysis be conducted. In addition, recommend the major contributors be classified into controllable and uncontrollable contributors by organization. Under each organization, resources ought to be spent only in areas where the contributor(s) can be controlled by that organization.

Phase III. Various approaches have been identified on how to minimize the reliability gap--specifically, to identify some practical guidelines on the type of reliability growth model, the initial reliability, growth rates, and effectiveness factor. Most of the experts/ practitioners believe in growing (improving) reliability, but they also cautioned on the blind application of reliability growth technique. The recommended course of action is to assess each weapon system on a case-by-case basis. Good practices, such as applying the environment correctly, designing the weapon system robustly, assigning the growth rate reasonably, and testing for failures effectively, are recommended approaches in minimizing the reliability gap.

Appendix A: Selective Summary of: Proceedings of
                the Conference on "The Reliability of
                Military Electronic Equipment," RCA,
                August 1955

1. RELIABILITY IS A "SYSTEMS" PROBLEM!
    It involves requirement, specifications, design, test,
    quality control, and "feedback" to mention a few of the
    major aspects.

2. RELIABILITY REQUIRES ORGANIZATION!
    The objective of adequate reliability cannot be achieved
    by happenstance....This dictates the need for an
    internal company organization whose sole interest is
    reliability.

3. RELIABILITY SETS A NEW STANDARD!
    To achieve adequate reliability, we must establish a new
    standard for component and end-item specifications;
    similarly, we must establish a new standard for design
    criteria, quality control, and test procedures....One
    might say that this whole area is the very cornerstone
    on which industry and the military must build if we are
    to be successful in attaining our goal.

4. RELIABILITY REQUIRES ADEQUATE LOGISTIC SUPPORT!
    This involves more than the timely supply of spare parts
    and test equipment to the user; the reliability or
    replacement parts must equal that of the original
    components.

5. RELIABILITY NECESSITATES ADEQUATE USER TRAINING!
    The designer can simplify training requirements through
    modular construction and so on, but user personnel must
    attain an adequate level of training if the full
    benefits of improved apparatus reliability are to be
    realized.

6. RELIABILITY TAKES TIME!
    As a generalization, it might be said that the built-in
    reliability is proportional to the time allowed the
    supplier to design, debug, produce a pilot run, and
    incorporate changes or improvements in production as a
    result of "feedback" from field experience....time is
    the mortar which binds this whole structure of
    reliability together....

7. RELIABILITY REQUIRES MILITARY-INDUSTRY TEAMWORK.

Appendix B: <u>Thesis Questionnaire</u>

Position:
Organization: Years of Experience in Reliability:
Areas (reliability related) of Interest:
Mailing Address:

THESIS TOPIC: Comparison between the theoretically predicted reliability values vs the actual field data of weapon systems.

QUESTIONS:

1. What are the major contributors to the difference between the theoretically predicted values and the actual field data?

2. Why do systems fail?

3. Are most failures related to poor design? Explain why.

4. Are most failures related to poor manufacturing processes? What are the bottlenecks in the manufacturing processes? Explain why.

5. From your personal experience, what is the distribution of the major contributors mentioned in Question 1? If your personal experience is limited, your educated guesses will suffice. If you feel uncomfortable assigning percentages, please rank order the major contributors.

6. What kind of incentives should the government pursue in order to motivate contractors to produce more reliable products?

7. If you were to develop a reliability growth plan, what growth model would you use? What growth rate would you use? What reliability starting point would you use? Would you use a starting reliability value of 10% of the cumulative Mean Time Between Maintenance (Inherent)? 20%? Please answer the questions for the four types of weapon systems: Aircraft, Missile, Spacecraft, and Ground-based complex electronic systems.

8. If you have identified the corrective actions, what effectiveness factor would you use? For example, 100% effectiveness factor means the corrective action will correct the identified deficiency; it will never happen again.

9. What data collection system would you use? What are the
    problems with our current data collection system? What
    changes would you recommend?

10. If you only have enough resources to choose one of the
    two, which one would you choose? Explain.

    a. Reliability demonstration vs Reliability growth
    b. Environmental Stress Screening (ESS) vs Reliability
        growth

Please feel free to call Katherine Ma, AV 785-5435, if you
have any questions. Would like the initial responses back
by 15 Apr 88. Thanks!

Appendix C: Thesis Questionnaire Summary

THESIS TOPIC: Comparison between the theoretically predicted reliability values vs the actual field data of weapon systems.

OBJECTIVES:
---To identify the major contributors to the reliability gap between the predicted vs the actual field data
---To examine ways of minimizing the gap (Questions 1 to 5)
---To recommend some guidelines (experts' point of view) for an effective reliability program (Questions 6 to 10)

        During the interviews, I asked the experts to rank order the major contributors to the reliability gap between the predicted vs the actual field data. I then use the ranking methodology, which I will describe in detail in my thesis, to rank order (from highest to lowest) all the major contributors accordingly. The following is a summary of the result.
        The result is based on the first 30 people I have interviewed (personal & telephone). In order to give a more definitive approach to my thesis, I have taken the privilege of grouping the major contributors into controllable and uncontrollable variables. The criteria for determining what is controllable and what is uncontrollable are totally subjective on my part. My reasoning for classifying a variable as controllable is that, through the course of my literature research and interviews, I have learned of a feasible solution on how to control that variable, and thus minimize the gap between the predicted vs the actual field data. The uncontrollable variables are just that, variables that cannot be controlled and which may have a significant impact on all of the controllable variables. If you do not agree with my classification, please let me know.
        In order to have a clear understanding of what each major contributor represents, I have included the responses from my interviews on the following pages.

Controllable Variables	Uncontrollable Variables
I. DATA	I. TOP MGMT COMMITMENT
II. MANUFACTURING PROCESSES	II. ENVIRONMENT
III. DESIGN-RELATED	III. ACQUISITION PROCESS
IV. REQUIREMENTS	IV. POLITICS
V. PREDICTION TECHNIQUES	V. HUMAN PERFORMANCE
VI. TRAINING	

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MAJOR CONTRIBUTORS TO THE RELIABILITY GAP: (Questions 1-5)

Controllable Variables:

I. DATA:

    ---COLLECTION:
        ---Inaccurate, untimely, and incomplete
        ---Lack of motivation, training, and emphasis

    ---DEFINITION:
        ---Classification of failures: relevant vs
           nonrelevant (3)*
        ---Scoring procedures
        ---Contractual vs operational (2)
        ---Flying vs operating hours (2)
        ---Unclear R&M terms, >60 R&M terms (2)
        ---Reliability vs performance problems

II. MANUFACTURING PROCESSES:

     ---Using processes that are not yet proven
     ---The processes are becoming so microscopic that it
        is difficult to control and inspect
     ---Quality of the components
     ---MIL-HDBK predictions do not take manufacturing
        processes into account
     ---Factory workmanship (training level)
     ---Producibility: Design-related
        -----Proper design can absorb a lot of the problems
     ---Quality:
        -----Contractor-dependent
        -----Does a total quality management program exist

III. DESIGN-RELATED:

      ---Immature technology: For example, Very High Speed
         Integrated Circuit (VHSIC) technology
      ---Mistakes in parts and components selection (3)
      ---Suboptimization
      ---Integration
      ---Complexity
      ---Constrained by time and money
      ---Design tool: CAD rarely include R&M parameters
      ---Software: Induced failures

* Note: The number in parentheses indicates the number of
         experts who gave the same response.

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IV. REQUIREMENTS:

    ---Unclear, not well defined (3)
    ---Requirements are NOT hard, firm requirements
    ---Fiscally constrained
    ---Concession we make to reality, in terms of cost and
       schedule

V. PREDICTION TECHNIQUES:

    ---MIL-STD-217 prediction:
      -----Lack of predictors' failure rates for hydro-
         mechanical and interconnectors and other new
         technologies (2)
      -----Assume perfect design and manufacturing
         processes of components (4)
      -----Mostly are component-level testings
      -----Paper design, all analytical
      -----Too many unknown variables which are average of
         various sources (3)
      -----Some predictors are engineers' opinions
      -----Predictors seldom match the operational
         predictions
      -----Misapplication of the predictors
    ---Inaccurate due to using nonoperational type
      environment (4)
    ---No standard definitions
    ---Do not address interconnections
    ---Assume perfect accessibility for maintainers
      (one-deep) (2)
    ---Improper use of reliability model
    ---Source selection criteria force the contractors to
      always put their best foot forward upfront
    ---Mentality factor: Prediction as a box filling
      exercise
    ---Assume no operator or maintainer-induced failures

VI. TRAINING:

    a. Designers:

        ---Trained to design things to perform rather than
           design things not to fail.
        ---R&M parameters rarely taught
        ---Designers do not understand field maintenance in
           order to design out maintenance problems
        ---Designers do not understand manufacturing
           processes to design out or make the processes
           more producible

b. Maintainers:

   ---Misuse of equipment due to lack of training
   ---Induced problems due to lack of experience
   ---Field personnel not as experienced as laboratory
      engineers
   ---Lack of job proficiency during transfer
   ---Lots of variables in OJT

c. Operators:

   ---Improper air crew expectations of the performance
      of certain pieces of equipment may induce
      additional write-ups
   ---Operators-induced failures

d. Manufacturers:

   ---Lack of experience

Uncontrollable Variables:

I. TOP MANAGEMENT COMMITMENT:

   ---Program management
      -----Program managers (PMs) rarely include any
            funding for reliability growth
      -----Return on investment is too long to have an
            impact on PM's tour
   ---Lack of emphasis on training engineers to design
      things not to fail, rather than to design things
      just to perform
   ---Lack of emphasis on designs that are robust to the
      environment

II. ENVIRONMENT:

   ---Mismatch of operational environment to the design
      envelope (10)
      -----Misapplication of equipment
      -----Change in operational scenario intentionally or
            unintentionally
   ---We do not understand the operational environment (9)
      -----Difficult to predict something we do not
            understand
      -----Inadequate field-type testing to find out more
            about the operational environment
      -----Too expensive to duplicate the operational
            environment

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---Operational environment is harsher than the
   laboratory environment
---Lack of good translational factor between
   operational and
   laboratory environment
---Lack of environmental screening
---Nonapplication of MIL-STD-781C:
   -----Design is not robust to the operational
        environment
---System integration: Interactions of components (2)
   -----GFE interfaces with other equipment
---MIL-HDBK predictors have a lot of uncertainty
---Corrosion control not taken into consideration
---Subjective judgment:
   -----Lead engineers gut feel on new improved
        technology

III. ACQUISITION PROCESS:

   ---Process too long to accommodate the changing threat
   ---Process too short for adequate development of
      certain new technology
   ---Insufficient funds and time
   ---Compromises we made throughout the process
   ---Contradictory approach: Lowest bidder wins the
      contract and yet we want high-quality components

IV. POLITICS:

   ---Bureaucratic pressure
   ---Cost and schedule
   ---Congressional influences

V. HUMAN PERFORMANCE:

   ---Humans are more prone to make mistakes under
      stressful conditions
   ---Inability to predict, level of effort, motivation,
      etc., of the following groups of people:

   a. Designers

   b. Maintainers:
      ---Maintenance practices
         -----Triggering of equipment
         -----Induced errors
         -----False removals
         -----Support equipment

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c. Operators:
    ---Don't fully understand the performance of the
       equipment

d. Manufacturers

e. Contractors:
    ---Contractors' integrity to tell us all the
       problems. Sometimes we do not find the
       problems until the systems are fielded
    ---Contractors, like our designers, know how to
       design to performance, but not to reliability,
       quality, and producibility

THESIS QUESTIONNAIRE: Question 6

What kind of incentives should the government pursue in order to motivate contractors to produce more reliable products?

RESPONSES:

I.   Positive and negative incentives: (20)
        ---Convincing the contractors that the customers are serious
        ---Show the contractors that the government is ready to pay R&M upfront

II.   Monetary: (18)
        ---Purely profit

III.   Need a workable approach: (10)
        a. Specify a mutually (contractor & government) acceptable parameter that is measurable. The parameter (i.e., Mean Time Between Demand) has to be based on operational data.
        b. Need an accurate data collection system that is acceptable to both the contractor and the government.
        c. Conduct data review board to discuss data accuracy. The data review will be attended by both contractor and government representatives.

IV.   Warrant against operational measures and operational environment
        ---Use meaningful terms to tell the contractor what the government really needs.

V.   Use stepwise incentives with time constraints

VI.   Use competition to tie to production or follow-on contracts

VII.   Ensure the contract is well-written so contractors cannot fail to perform. For example, specify R&M as a separate item in the Request For Proposal (RFP).

VIII.   Need to convince contractors that there will be more money involved in producing more reliable products than in just selling spares.

IX.   Government should buy more mature systems.

X.   Encourage contractors to continue reliability growth programs past the end of DT&E and until maturity.

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THESIS QUESTIONNAIRE: Question 7

If you were to develop a reliability growth plan, what
growth model would you use? What growth rate would you use?
What reliability starting point would you use? Would you
use a starting reliability value of 10% of the cumulative
Mean Time Between Maintenance (Inherent)? 20%? Please
answer the questions for the four types of weapon systems:
Aircraft, Missile, Spacecraft, and Ground-based complex
electronic systems.

RESPONSES:

RELIABILITY GROWTH MODEL: The most popular model is Duane,
or modified Duane (i.e., AMSAA).

Other suggestions included:

---Do research and computer simulation to find the most
   appropriate model
---Use Duane during the initial stages. During the mid- and
   later stages, plot the data, determine the failure
   distributions, choose a model (parametric or non-
   parametric) that fits the data best, and perform a
   goodness-of-fit test

RELIABILITY GROWTH RATE: A function of redesign and
manufacturing corrections. Highly dependent on management
attention. A couple of experts expressed that "0.4 was the
fastest that I've seen anything grow."

	FSD NEW DESIGN	PRODUCTION NEW DESIGN
Aircraft	0.26	0.1
Missile	0.28	---
Spacecraft	0.43	---
Avionics	???	???
Engines	???	???
Airborne computers	???	???
Complex Grd. electronics	0.24	???
Mechanical	???	???
Structural (applicable?)	???	???

INITIAL STARTING POINT: Cumulative MTBM (I)

---Mostly have been experiencing: <10%
---Would like to see: 25-30%

THESIS QUESTIONNAIRE: Question 8

If you have identified the corrective actions, what
effectiveness factor would you use? For example, 100%
effectiveness factor means the corrective action will
correct the identified deficiency; it will never happen
again.

RESPONSES:

Overall % = 70%

Other %:

---Design: 85%
---Manufacturing processes: 73%
---Human factors and others: 70%
---Avionics: 73%
---Mechanical: 98%
---Electronics and structural: 73%

A few of the experts expressed that: "Discount failures
with identified corrective actions is a great idea if the
corrective actions work. In most cases, the implementation
of the identified corrective actions takes too long and it's
too costly."

In response to the above comments, I have asked a few experts
the following questions. Please provide your answers so I
can get a larger sample size.

1. How long and how much does it cost to identify a
    corrective action?

2. How long and how much does it cost to do the failure
    analysis?

3. How long and how much does it cost to implement the
    corrective action?

THESIS QUESTIONNAIRE: Question 9

What data collection system would you use?   What are the
problems with our current data collection system?   What
changes would you recommend?

RESPONSES:

For the first group of experts (the ones I interviewed at
the First Reliability Growth Conference held in Boston, 7-9
March 1988), I didn't ask you this question. If any of you
would like to add to the following set of responses, please
feel free to do so.

The choices of the data collection systems are: Maintenance
Data Collection (MDC), Maintenance Operations Data Access
System (MODAS), Core Automated Maintenance System (CAMS) (as
advertized), F-16's Centralized Data System (CDS),
Comprehensive Engine Management System (CEMS), and System
Effectiveness Data System (SEDS). The most popular choice
was F-16's CDS. Some experts would like to hire a
contractor, and yet others would like to develop their own
data collection system.

The most cited problems with our current systems are:

---Inaccurate, incomplete, and untimely
---No motivation for data collectors to do better
---Lack of feedback system for better data
---AFTO Form 349s are used more as man-hour accounting
   system than anything else
---Logistically driven, not design driven
      -----No information on what piece/part failed?
            How it failed? What caused the failure?

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THESIS QUESTIONNAIRE: Question 10

If you only have enough resources to choose one of the two,
which one would you choose? Explain.

a. Reliability demonstrations vs reliability growth
b. Environmental Stress Screening (ESS) vs reliability
    growth

RESPONSES:

a. With limited resources, most experts favored
    reliability growth. They think it will provide the
    most payback.

b. Most experts think that in order to have an effective
    reliability program, both ESS and reliability growth
    are needed. When limited resources are emphasized,
    most experts chose reliability growth over ESS, but
    most of them expressed that it's not an either-or
    situation. In fact, one expert told me that if he had
    to choose between the two, he would QUIT his job first!

Appendix D: List of Interviewees & Their Organizations

Department Of Defense (DoD)

Abrams, Lt Col Fred L.   Director Tactical Logistics
                                AFLC LOC/TL

Akhbari, Hamid   Product Assurance Engineer
                                B-1B SPO, ASD/B1ESI

Andrews, Capt Richard A.   AFIT Instructor
                                AFIT/LSY

Arnold, Gary M.   R&M Engineer
                                F-16 SPO, ASD/YPEX

Babcock, Paul F.   Electronics Engineer, GS-12
                                Department of the Navy
                                Navy Space Program Detachment

Campbell, Capt Clint   Instructor of Quantitative
                                Methods & Statistics
                                AFIT/LSQ

Edwards, Jerry L.   Product Assurance Engineer
                                F-15 SPO, ASD/VFES

Ellner, Paul PhD.   Director USAMSAA
                                AMXSY-RM

Farr, Major Michael   Director, Graduate Contracting
                                Management Program
                                AFIT/LSY

Fleeger, Major (Ret.)   Product Assurance Services
                                Consultant

Hartman, Lt Col Roger   Chief, Logistics Studies and
                                Analysis
                                AFOTEC/LG4

Keller, Major Fred D.   AF-1 Deputy PM for Logistics
                                Director of Transport and
                                Trainer Programs SPO
                                ASD/SDCBL

Lapp, John   SCADC Program Manager
                                ASD/AEAA

LaSala, Kenneth P.	Chief, R&M Division Product Assurance Engineering HQ AFSC/PLER
Lilius, Walter A.	U.S. AMETA AMXOM-QA
Mangan, Tom	Product Assurance Engineer Propulsion SPO ASD/YZEX
Mauldin, Colonel Thad	Aircraft Systems Division Directorate of Maintenance and Supply HQ USAF DCS/L & E
Miller, Major Phillip E.	Director of Graduate Programs AFIT/LSG
Morris, Seymour F.	Electronic Reliability Engineer RADC/RBER
McCarty, Dyke	Professor of Weapon System Management AFIT/LSY
Olson, Glenn	R&M Engineer AFALC/OA-OL
Paige, Lt Col Alan (Ret.)	Directorate of R&M and Evaluation AFALC/ERR
Rehg, Virgil	Professor of Quantitative Methods & Statistics AFIT/LSQ
Robinson, Capt David G.	Assistant Professor AFIT/ENY
Rostokowski, Frank	R&M Engineer Department of the Navy Naval Air Systems Command HQ
Trakas, Robert	Head, R&M Branch Department of the Navy
Widenhouse, Carrol	Assistant Professor of Quantitative Methods & Statistics AFIT/LSQ

Williams, Ben, PhD   Director, Center of Excellence
           for R&M
           AFIT/CERM

Wlazlo, Capt Tom   Former F-16 Engine Manager
           ASD/ENE (GIMADS)

Young, David   OASD (P&L/MD)
           Pentagon

Industry

Chenoweth, Halsey B., PhD Fellow Engineer
           Westinghouse Electric Corp.

Crow, Larry, H., PhD   Supervisor
           Reliability Methods Group
           AT&T Bell Laboratories

Gibson, Gregory J.   Manager: Reliability Engineering
           The Analytic Sciences Corp.
           (TASC)

Healy, John D.   District Mgt-R&M Methods
           Bellcore

Horne, Robin A.   Staff Engineer
           Product Reliability
           Product/Process Assurance
           Delco Electronics
           -subsidiary of GM Hughes
            Electronics

Muddiman, Matt W.   Statistical Development Corp.
           Product & Process Assurance
           Delco Electronics Corp.

Seusy, Cliff   Quality Engineer
           Hewlett Packard

Spangler, Lester   Field Engineer
           Dynamics Research Corp. (DRC)

Tracy, Terry A.   Product/Process Assurance
           Product Reliability Supervisor
           Delco Electronics

Weber, David P.   Lead Engineer
           Reliability & Safety Engineering
           Aircraft Engine Business Group
           General Electric (GE)

Appendix E: <u>First Round One of 28 Interviewees</u>
                <u>(DoD & Industry)</u>

ENVMT	DATA	PREDS	MFG	DESIGN	MGMT	TRNG
10	10	10	10	10	10	10
10	10	10	10	10	10	9
10	10	10	10	9	10	8
10	10	10	10	9	10	8
10	10	9	9	8	9	8
9	10	9	9	8	8	6
9	9	9	9	8		
9	9	9	9	8		
9	9	8	8	7		
9	9	8	8	7		
9	9	8	7	6		
9	8	7	7	5		
9	8	7	6			
8	8	7	6			
8	8	6	5			
8	7	6				
7	7					
6	7					

	ENVMT	DATA	PREDS	MFG	DESIGN	MGMT	TRNG
Average	8.83	8.78	8.31	8.2	7.92	9.5	8.17
# of Resp.	18	18	16	15	12	6	6

HUMAN	POLITICS	S/W	ACQ.P.	RQMT.
8	10	6	10	9
8	8	6	7	6
7	7	6		
7		4		
7				
6				

	HUMAN	POLITICS	S/W	ACQ.P.	RQMT.
Average	7.17	8.33	5.5	8.5	7.5
# of Resp.	6	3	4	2	2

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<u>First Round One of 23 Interviewees (DoD)</u>

DATA	ENVMT	PREDS	MFG	DESIGN	MGMT	TRNG
10	10	10	10	10	10	9
10	10	10	10	9	10	8
10	10	10	9	8	10	8
10	10	9	9	8	10	8.
10	10	9	9	8	9	6
10	9	9	8	7		
9	9	9	8	7		
9	9	8	7	6		
9	9	8	7	5		
9	9	8	6			
8	9	7	6			
8	9	7	5			
8	8	6				
8	8	6				
7	7					
7						
7						

	DATA	ENVMT	PREDS	MFG	DESIGN	MGMT	TRNG
Average	8.77	9.07	8.29	7.83	7.56	9.8	7.8
# of Resp.	17	15	14	12	9	5	5

HUMAN	POLITICS	S/W	ACQ.P.	RQMT.
8	10	6	10	9
7	8	6	7	6
7	7	6		
6		4		

	HUMAN	POLITICS	S/W	ACQ.P.	RQMT.
Average	7.00	8.33	5.5	8.5	7.5
# of Resp.	4	3	4	2	2

Appendix G: First Round One of 5 Interviewees (Industry)

	MFG	DESIGN	ENVMT	PREDS	HUMAN	TRNG	DATA
	10	10	9	10	8	10	9
	10	9	8	7	7		
	9	8	6				
Average	9.67	9.0	7.67	8.5	7.5	10	9
# of Resp.	3	3	3	2	2	1	1

	MGMT
	8
Average	8
# of Resp.	1

Appendix H: First Round Two of 28 Interviewees
                    (DoD & Industry)

DATA	ENVMT	PREDS	MFG	DESIGN	MGMT	TRNG
10	10	10	10	10	10	10
10	10	10	10	9	10	9
10	10	10	10	9	10	8
10	10	10	10	9	10	8
10	9	9	9	9	10	8
10	9	9	9	9	9	7
9	9	9	9	8	8	
9	9	9	9	8		
9	9	8	8	7		
9	9	8	8	7		
8	9	8	7	7		
8	9	8	7	6		
8	8	7	7			
8	8	7	6			
8	8	7	6			
7	7	6				
7	6	6				
6	5					

	DATA	ENVMT	PREDS	MFG	DESIGN	MGMT	TRNG
Average	8.67	8.56	8.29	8.33	8.17	9.57	8.33
# of Resp.	18	18	17	15	12	7	6

HUMAN	POLITICS	S/W	ACQ.P.	RQMT.
8	10	6	10	9
8	8	6	7	6
8	7	6		
8		5		
7				
6				

	HUMAN	POLITICS	S/W	ACQ.P.	RQMT.
Average	7.5	8.33	5.75	8.5	7.5
# of Resp.	6	3	4	2	2

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Appendix I: <u>First Round Two of 23 Interviewees (DoD)</u>

DATA	ENVMT	PREDS	MFG	DESIGN	MGMT	TRNG
10	10	10	10	10	10	9
10	10	10	10	9	10	8
10	10	10	9	9	10	8
10	10	9	9	8	10	8
10	9	9	9	8	10	7
10	9	9	9	7	9	
9	9	9	8	7		
9	9	8	7	7		
9	9	8	7	6		
8	9	8	7			
8	9	8	6			
8	9	7	6			
8	8	7				
8	8	6				
7	5	6				
7						
6						

	DATA	ENVMT	PREDS	MFG	DESIGN	MGMT	TRNG
Average	8.65	8.87	8.27	8.08	7.89	9.83	8.00
# of Resp.	17	15	15	12	9	6	5

HUMAN	POLITICS	S/W	ACQ.P.	RQMT.
8	10	6	10	9
8	8	6	7	6
8	7	6		
7		5		

	HUMAN	POLITICS	S/W	ACQ.P.	RQMT.
Average	7.75	8.33	5.75	8.50	7.50
# of Resp.	4	3	4	2	2

Appendix J: <u>First Round Two of 5 Interviewees</u>
             <u>(Industry)</u>

	MFG	DESIGN	ENVMT	PREDS	HUMAN	TRNG	DATA
	10	9	9	10	8	10	9
	10	9	7	7	6		
	8	9	6				
Average	9.33	9.0	7.33	8.5	7.0	10	9
# of Resp.	3	3	3	2	2	1	1

	MGMT
	8
Average	8
# of Resp.	1

Round One of 38 Interviewees (DoD & Industry)

DATA	ENVMT	PREDS	MFG	DESIGN	MGMT	TRNG
10	10	10	10	10	10	10
10	10	10	10	10	10	9
10	10	10	10	10	10	8
10	10	10	10	10	10	8
10	10	10	10	9	10	8
10	10	10	9	8	8	6
10	10	9	9	8	8	
10	9	9	9	8	8	
9	9	9	9	8	8	
9	9	9	9	7	8	
9	9	9	9	7	8	
9	9	9	8	6	6	
9	9	9	8	5		
9	9	8	8			
9	9	8	7			
8	9	8	7			
8	9	8	7			
8	8	8	6			
8	8	7	6			
8	8	7	6			
8	7	7	5			
7	7	7				
7	7	6				
7	6	6				
7		6				
7						
5						

	DATA	ENVMT	PREDS	MFG	DESIGN	MGMT	TRNG
Average	8.56	8.79	8.36	8.19	8.15	8.67	8.17
# of Resp.	27	24	25	21	13	12	6

HUMAN	POLITICS	S/W	P,H,&T	RQMT.
8	10	6	9	9
7	8	6	9	6
7	7	6		
7		4		
6				

	HUMAN	POLITICS	S/W	P,H,&T	RQMT.
Average	7.0	8.33	5.5	9.0	7.5
# of Resp.	5	3	4	2	2

Appendix L: Round One of 28 Interviewees (DoD)

DATA	ENVMT	PREDS	MFG	DESIGN	MGMT	TRNG
10	10	10	10	10	10	9
10	10	10	9	10	10	8
10	10	10	9	10	10	8
10	10	10	9	8	10	8
10	10	9	9	8	10	6
10	10	9	9	8	8	
10	9	9	8	7	8	
9	9	9	8	7	6	
9	9	9	8	6		
9	9	9	7	5		
9	9	8	7			
9	9	8	7			
8	9	8	6			
8	9	7	6			
8	9	7	5			
8	8	6				
8	8	6				
8	7	6				
7						
7						
7						
7						
7						
5						

	DATA	ENVMT	PREDS	MFG	DESIGN	MGMT	TRNG
Average	8.46	9.11	8.33	7.80	7.90	9.00	7.80
# of Resp.	24	18	18	15	10	8	5

POLITICS	S/W	HUMAN	RQMT.
10	6	7	9
8	6	7	6
7	6	6	
	4		

	POLITICS	S/W	HUMAN	RQMT.
Average	8.33	5.5	6.67	7.5
# of Resp.	3	4	3	2

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Appendix M: Round One of 10 Interviewees (Industry)

	PREDS	MFG	ENVMT	MGMT	DATA	DESIGN	P,H,&T
	10	10	10	8	10	10	9
	10	10	9	8	9	9	9
	9	10	8	8	9	8	
	8	10	7	8			
	8	9	7				
	7	6	6				
	7						
Average	8.43	9.17	7.83	8.00	9.33	9.00	9.00
# of Resp.	7	6	6	4	3	3	2

	HUMAN	TRNG	RQMT.
	8	10	9
	7		
Average	7.5	10	9
# of Resp.	2	1	1

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Appendix N: Round Two of 38 Interviewees (DoD & Industry)

DATA	PREDS	ENVMT	MFG	MGMT	DESIGN	TRNG
10	10	10	10	10	10	10
10	10	10	10	10	10	9
10	10	10	10	10	10	8
10	10	10	10	10	9	8
10	10	10	10	10	9	8
10	10	9	9	10	9	7
10	9	9	9	10	9	
10	9	9	9	8	8	
10	9	9	9	8	8	
9	9	9	9	8	7	
9	9	9	9	8	7	
9	9	9	8	8	7	
9	9	9	8	7	7	
9	8	9	8	6	6	
8	8	9	7			
8	8	9	7			
8	8	8	7			
8	8	8	7			
8	8	8	6			
8	7	7	6			
7	7	7	6			
7	7	7				
7	7	6				
7	6	5				
7	6					
6	6					
5						
Average 8.48	8.35	8.54	8.29	8.79	8.29	8.33
# of Resp. 27	26	24	21	14	14	6

HUMAN	POLITICS	S/W	P,H,&T	RQMT.
8	10	6	9	9
8	8	6	9	6
8	7	6		
7		5		
6				
Average 7.40	8.33	5.75	9.00	7.50
# of Resp. 5	3	4	2	2

Appendix O: Round Two of 28 Interviewees (DoD)

DATA	ENVMT	PREDS	MFG	DESIGN	MGMT	TRNG
10	10	10	10	10	10	9
10	10	10	9	10	10	8
10	10	10	9	10	10	8
10	10	10	9	9	10	8
10	9	9	9	8	10	7
10	9	9	9	8	10	
10	9	9	9	7	8	
10	9	9	8	7	7	
9	9	9	8	7	6	
9	9	9	7	7		
9	9	8	7	6		
8	9	8	7			
8	9	8	7			
8	9	8	6			
8	8	7	6			
8	8	7				
8	8	6				
8	5	6				
7		6				
7						
7						
7						
6						
5						

	DATA	ENVMT	PREDS	MFG	DESIGN	MGMT	TRNG
Average	8.42	8.83	8.32	8.00	8.09	9.00	8.00
# of Resp.	24	18	19	15	11	9	5

POLITICS	S/W	HUMAN	RQMT.
10	6	8	9
8	6	8	6
7	6	7	
	5		

	POLITICS	S/W	HUMAN	RQMT.
Average	8.33	5.75	7.67	7.50
# of Resp.	3	4	3	2

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Appendix P: Round Two of 10 Interviewees (Industry)

	PREDS	MFG	ENVMT	MGMT	DESIGN	DATA	P,H,&T
	10	10	10	8	10	10	9
	10	10	9	8	9	9	9
	9	10	8	8	9	9	9
	8	10	7	8			
	8	9	7				
	7	6	6				
	7						
Average	8.43	9.17	7.83	8.00	9.33	9.33	9.00
# of Resp.	7	6	6	4	3	3	2

	TRNG	HUMAN
	10	8
		6
Average	10	7.00
# of Resp.	1	2

Appendix Q: Selective R&M Data Deficiencies Tiger
              Team Meeting Minutes

The Fifteen Problem Descriptions are:

1.   The Air Force lacks an overall focal point for
logistics-related data systems. Responsibility and
authority is fragmented in terms of requirements, design
responsibility, and resources.

2.   R&M terms and definitions vary in Air Force documents
(e.g., MIL-STD-721C and AFP 57-9) and in the Reliability &
Maintainability Information System (REMIS) Functional
Description (FD).

3.   In order to measure and report the status of weapon
system reliability and maintainability, and to assess the
impact of R&M modifications relative to R&M 2000 goals,
there must be a standard set of R&M indicators from which
analysis can be performed.

4.   There is no structure to the process of identifying raw
data elements which are necessary for identification and
analysis of R&M problems in the Air Force.

5.   Policies in the Air Force do not adequately cover serial
number tracking to derive reliability information.

6.   Present field data systems do not capture the necessary
BIT data to effectively identify fault-isolation problems.

7.   Currently depot maintenance does not report within the
Maintenance Data Collection (MDC) systems.

8.   The current MDC system and the Core Automated
Maintenance system (CAMS) experience a loss of some of the
on-equipment data.

9.   The CAMS/REMIS data outputs will not be available to the
acquisition community until 1992 or later. The present R&M
data systems (AFTO Form 349, DO56B, DO56T, and [Maintenance
Operations Data Access System] MODAS), could be
significantly improved with a coordinated effort, thus
"filling-the-gap" until REMIS becomes operational.

10.   Several weapon systems currently have the capability to
provide Maintenance Integrated Data Access System (MIDAS)
and Functionally Integrated Designating and Referencing
(FINDER) information. However, our current maintenance data

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collection system is not geared towards collecting maintenance fault codes, job guide function numbers, or reference designators.

11. The Air Force R&M community, as well as contractors, do not have access to the data that will provide the effect of failures on weapon system capability (i.e., critical failure).
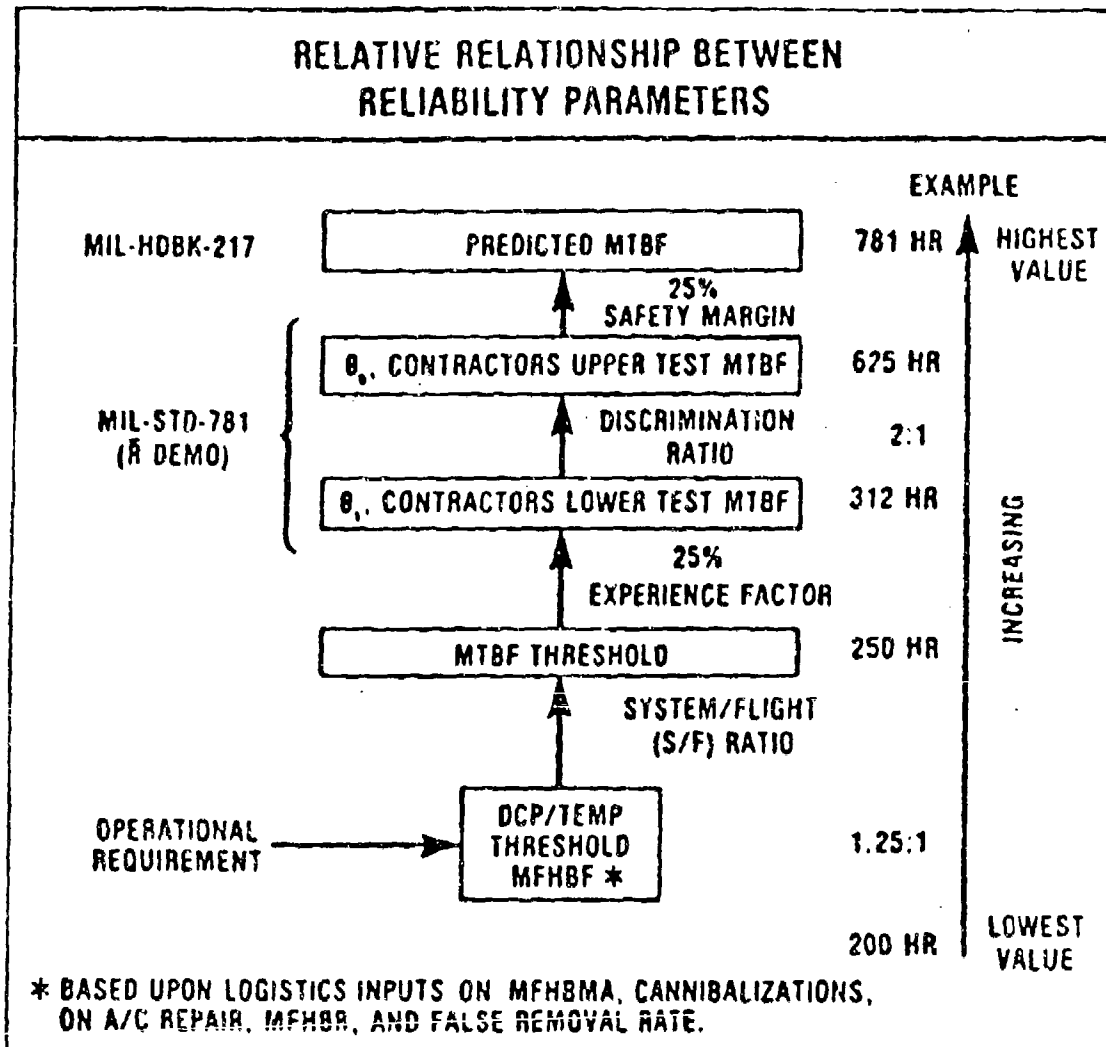
12. Data in the current MDC systems are suspect.

13. CAMS has a limited MDC correction capability. Early experience with CAMS at Dyess and Ellsworth AFBs shows a high MDC error rate (in the 30 percent range). There is a need to be able to correct these data prior to their transmission to AFLC.

14. While there are a vast amount of R&M data, accurate failure/fix information is not collected due to the failure of the organizational and intermediate level personnel to properly document their actions. There is a significant amount of emphasis across the operational commands on time accounting. This emphasis does not originate from the MAJCOMS. However, no amount of contrary information has been able to change the perception that it is necessary to document "8 hrs/day per man."

15. The present data systems cannot capture R&M Time Stress Measurement Device (TSMD) data that will be available on all LRU's by 1990. The data could be useful for warranty and R&M administration.

Appendix R: Relative Relationship Between Reliability Parameters (66:106)

RELATIVE RELATIONSHIP BETWEEN
RELIABILITY PARAMETERS

		EXAMPLE	
MIL-HDBK-217	PREDICTED MTBF	781 HR	HIGHEST VALUE
	25% SAFETY MARGIN		
MIL-STD-781 (R DEMO)	θ, CONTRACTORS UPPER TEST MTBF	625 HR	
	DISCRIMINATION RATIO	2:1	
	θ, CONTRACTORS LOWER TEST MTBF	312 HR	
	25% EXPERIENCE FACTOR		INCREASING
	MTBF THRESHOLD	250 HR	
	SYSTEM/FLIGHT (S/F) RATIO		
OPERATIONAL REQUIREMENT	OCP/TEMP THRESHOLD MFHBF *	1.25:1	
		200 HR	LOWEST VALUE

* BASED UPON LOGISTICS INPUTS ON MFHBMA, CANNIBALIZATIONS, ON A/C REPAIR, MFHBR, AND FALSE REMOVAL RATE.

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VITA

Captain Katherine C. L. Ma was born on 25 November 1954 in Shanghai, China. She was graduated from Grover Cleveland High School in Portland, Oregon. From the University of Oregon, she received her first Bachelor of Science degree (Biology) in 1977 and her second Bachelor of Science degree (Medical Technology) in 1978. After receiving her commission from the Officer Training School in January 1980, she completed her Communications Electronics Officer Technical School at Keesler AFB, Mississippi in October. She was assigned to the 2148th Communications Squadron at Ellsworth AFB, South Dakota from October 1980 to January 1983. Prior to entering the Air Force Institute of Technology (AFIT) in Systems Management at the School of Systems and Logistics, she worked as the Logistics Evaluation Manager at the Air Force Operational Test and Evaluation Center (AFOTEC) in Albuquerque New Mexico, where she also had the opportunity to complete her Master of Business Administration (MBA) from New Mexico Highlands University.

> Permanent Address: 6041 S.W. 47th Avenue
> Portland, OR   97221

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Over the years, the reliability of fielded weapon systems has consistently been less than what was predicted. In the area of avionics equipment, the reliability gap between "predicted mean-time-between-failures (MTBFs)" and "field MTBFs" was reported to range from 7:1 to 20:1 (38:231). The inability to accurately relate factory (whether specified, required, or demonstrated) reliability to the field reliability of weapon systems/subsystems has a significant impact on operational readiness and life cycle costs.

To study the reliability gap between factory and field reliability, this research is divided into three distinct phases, with the following objectives:

1. To examine the existence of the reliability gap in airborne tactical radars.

2. To identify and analyze the major contributors to the reliability gap. Specifically, to identify the most significant contributors.

3. To explore practical guidelines on how to minimize the reliability gap. Specifically, to identify some practical guidelines on reliability growth.

To examine the existence of the reliability gap, this thesis obtained the data from NAVAIR and examined the radars on Air Force and Navy aircraft. Using experts'/ practitioners' (DoD & Industry) opinions, contributors to the reliability gap were identified. In addition, some practical guidelines on reliability growth management were also identified. This thesis consolidated some of the best currently available thinking on the major contributors to the reliability gap and some of the practical guidelines on reliability growth.